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土壤－植物系统钾素管理

Potassium Management in Soil-Plant System

主　编：周健民　Hillel Magen
Chief Editors：J.M. Zhou, H. Magen

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INTERNATIONAL POTASH INSTITUTE

Institute of Soil Science, Chinese Academy of Sciences

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前　言

肥料在中国粮食安全保障方面的作用是非常清楚的。由于大多数农田土壤肥力较低，且集约化种植程度较高，所以大量施肥便成为获得高产的先决条件。然而，当前所有肥料养分的利用率均较低，尤其是氮素，这便带来了环境风险和经济损失。

钾在中国农业的很多方面均有很重要的作用。华东和东南地区土壤较为缺钾，而华中地区由于作物高产的需求，其农田土壤中也出现了缺钾的情况。钾在蔬菜和果树种植中的作用更为突出，据国际肥料组织的研究，中国有大约一半的钾肥用在了果树和蔬菜种植方面。由于作物吸收的钾大部分存在于非收获部分，因此农业废弃物的处理对于钾肥管理影响重大。中国很多研究工作表明，钾在提高氮的利用率方面有很重要的影响和作用。

国际钾肥所(IPI，瑞士)和中国科学院南京土壤研究所合作多年，在中国钾素研究方面进行了很多的交流和讨论，并共同举办了多次国际学术会议，最近的一次会议是 2012 年 7 月 25～27 日在成都举办的“第 12 届 ISSAS-IPI 植物-土壤系统钾素管理国际学术研讨会”。本次会议的主要议题包括了养分利用率、作物秸秆还田与钾素管理、典型作物施钾效应及钾肥施用的经济价值等方面。

非常感谢《*Journal of Plant Nutrition and Soil Science*》的协助！本次会议中提交的不少论文被接受并发表于该刊的特刊中(2013 年 6 月第 176 卷第 3 期)。

Hillel Magen

国际钾肥所所长

Preface

Fertilizers' role in achieving and assuring food security in China is clear; large agricultural areas of agricultural land have relatively low soil fertility and high cropping intensity. As a result, intensive fertilization is a prerequisite for achieving high yields. However, current nutrient use efficiencies for all major nutrients, in particular nitrogen, are relatively low, which leads to environmental damage and economic losses.

The role of potassium in Chinese agriculture is essential in many ways. Potassium is deficient in soils in East and South-East China, but also in more fertile soils in Central China where it is needed to support high yielding cereals. Potassium is crucial for growing vegetables and fruit. According to the International Fertilizer Association approximately half of potassium fertilizers consumption in China is in the fruit and vegetable sector. As potassium is largely taken by non-productive plant parts, the management of crop residues has a strong effect on potassium fertilization. Potassium has a significant effect and role in improving nitrogen use efficiency, as shown in various research work from across China.

The International Potash Institute (IPI), Switzerland and the Institute of Soil Science, Chinese Academy of Sciences (ISSAS), China have a long record of scientific cooperation and conducting joint symposia. This includes over decades of sharing and discussing potassium research in China. The last IPI-ISSAS joint symposium: 'The 12th ISSAS-IPI international symposium on management of potassium and soil systems in China' took place on 25-27 July, 2012 in Chengdu. The symposium focused on topics such as nutrient use efficiency, potassium management under various crop residues management practices, typical response of various crops to potassium fertilization, and economic considerations related to potassium application.

IPI are pleased to acknowledge our collaboration with the *Journal of Plant Nutrition and Soil Science*, which has led to a number of the 12th ISSAS-IPI international symposium papers being published in a special edition of the Journal (volume 176, issue 3, June 2013).

Contents 目录

第一部分　土壤与作物的钾素动态测定与施肥指导
Potassium dynamics, determination in soil and plant, and fertilization recommendation

不同土壤钾素淋溶特性的初步研究
…… 董艳红，王火焰，周健民，任正文　2

水旱轮作条件下不同类型土壤供钾能力及钾素动态变化研究
…… 占丽平，李小坤，鲁剑巍，丛日环，王　瑾，王　筝，廖志文　9

Potassium dynamics in plant and soil as affected by soil sodicity
…… *Abdul Wakeel*　17

小麦体内钾含量变化特征及诊断叶、鞘位的研究
…… 安林林，王火焰，董彩霞，陈智慧　33

基于可见/近红外反射光谱的梨树叶片钾含量的快速测定研究
…… 赵化兵，董彩霞，徐阳春　39

不同基因型甘蔗钾吸收动力学研究
…… 陈迪文，卢颖林，江　永，黄　莹，敖俊华，周文灵，黄振瑞，李奇伟　45

不同钾素水平对水稻不同部位含钾量的影响
…… 陈智慧，王火焰，周健民，安林林，陈小琴，杜昌文　49

柱花草属不同种钾含量研究
…… 文　稀，郇恒福，刘国道，黄冬芬，虞道耿，唐　军　57

Long-term effect of fertilizer and rice straw on mineral composition and potassium adsorption in a reddish paddy soil
…… *Liao Yulin*, *Zheng Shengxian*, *Nie Jun*, *Xie Jian*, *Lu Yanhong*, *Qin Xiaobo*　67

Acid-extractable potassium in agricultural soils: Source minerals assessed by differential and quantitative X-ray diffraction
…… *Ylva Andrist-Rangel*, *Magnus Simonsson*, *Ingrid Öborn*, *and Stephen Hillier*　86

Potassium uptake requirement in relation to grain yield and genotypic improvement of irrigated lowland rice in China
…… *Zhang Yi*, *Zhang Chaochun*, *Yan Peng*, *Chen Xinping*, *Yang Jianchang*, *Zhang Fusuo*, *and Cui Zhenling*　102

Improving potassium acquisition and utilisation by crop plants
…… *Philip J. White*　110

Citrus leaf nutrient-status: A critical evaluation of guidelines for optimal yield in Israel
…… *Eran Raveh*　127

第二部分　钾肥管理
Potassium management

Potassium fertilizer management in winter oilseed rape production in China
…… *Ren Tao*, *Lu Jianwei*, *Li Hui*, *Zou Juan*, *Xu Huali*, *Liu Xiaowei*, *and Li Xiaokun* 140

Potassium management in tea plantations: its uptake by field plants, status in soils and efficacy on yields and quality of teas in China
…… *Ruan Jianyun*, *Ma Lifeng*, *and Shi Yuanzhi* 156

钾氮配施对湖南丘陵双季稻区钾肥效应及钾素平衡的影响
…… 廖育林，鲁艳红，聂　军，周　兴，谢　坚，杨曾平 170

长期不同施肥对高原小麦产量和土壤钾素的影响
…… 张亚丽，陈占全，李月梅 177

Current potassium management status and grain yield response of Chinese maize to potassium application
…… *Wu Liangquan*, *Ma Wenqi*, *Zhang Chaochun*, *Wu Liang*, *Zhang Weifeng*, *Jiang Rongfeng*, *Zhang Fusuo*, *Cui Zhenling*, *and Chen Xinping* 181

Potassium management in rice-maize systems in South Asia
…… *J. Timsina*, *V. K. Singh*, *and K. Majumdar* 192

沿江平原稻麦轮作系统维持钾素平衡和作物高产的钾肥运筹研究
…… 刘　枫，吴传洲，朱克保，奚　波，韩韦东 211

五年定位试验钾肥用量对双季稻产量和施钾效应的影响
…… 鲁艳红，廖育林，聂　军，谢　坚，杨曾平，周　兴 217

Field-scale K and P fluxes in the bioenergy crop switchgrass: Theoretical energy yields and management implications
…… *Patrick Woodson*, *Jeffrey J. Volenec*, *and Sylvie M. Brouder* 224

湖北省莲藕钾肥合理用量与运筹方式研究
…… 刘冬碧，张富林，张过师，段小丽，余延丰，吴茂前，熊桂云 241

贵州马铃薯钾肥施用研究与应用状况回顾与展望
…… 肖厚军，秦　松，苟久兰，何佳芳 247

不同类型紫色土含钾量及对烤烟钾分布规律的影响
…… 唐先干，韩　延，何宽信，李祖章 251

华南蔬菜钾肥推荐施用技术研究
…… 李淑仪，廖新荣，王荣萍，丁效东 255

第三部分　钾肥效应与功能
Effects and function of potassium fertilization

The effects of potassium fertilization on water-use efficiency in crop plants
…… *Witold Grzebisz*, *Andreas Gransee*, *Witold Szczepaniak*, *and Jean Diatta* 261

Potassium and stress alleviation: Physiological functions and management of cotton
…… *Derrick M. Oosterhuis*, *Dimitra A. Loka*, *and Tyson B. Raper* 287

UV-B 辐射增强下施钾对大麦光合及蒸腾生理日变化的影响
…… 娄运生，曾志平，韩　艳，吴　蕾，孟　艳 306

Simulating the effect of potassium fertilization on carbon sequestration in soil
…… *Bnayahu Bar-Yosef and Jiftah Ben Asher* 313
钾对不同基因型甘蔗生长、光合特性及叶绿素荧光参数的影响
…… 李奇伟，周文灵，卢颖林，江　永，敖俊华，陈迪文，黄　莹，黄振瑞，唐湘如 328
Assessment of economic and environmental impacts of two typical cotton genotypes with contrasting potassium efficiency
…… *Hao Yanshu*, *Wang Xiaoli*, *Xia Ying*, *Wu Lishu*, *and Jiang Cuncang* 336
甘蔗及其近缘属植物钾效率差异研究
…… 敖俊华，卢颖林，黄　莹，陈迪文，周文灵，江　永，黄振瑞，李奇伟 345
内蒙古马铃薯施肥效应及养分利用率研究
…… 段　玉，李焕春，赵沛义，妥德宝，张　君，姚俊卿，付贵锁 351
不同钾肥用量对生姜生长和营养品质的影响
…… 李录久，王家嘉，姚殿立，吴萍萍，柳希玉，丁　楠 357
不同钾用量对山东褐土夏玉米产量、效益及钾素平衡的影响
…… 魏建林，张英鹏，崔荣宗，杨　果，马　征 362

第一部分
土壤与作物的钾素动态测定与施肥指导

Potassium dynamics, determination in soil and plant, and fertilization recommendation

不同土壤钾素淋溶特性的初步研究[①②]

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摘　要：通过室内土柱淋溶试验，研究降雨情况下不同土壤钾素的淋溶特性及其与土壤性质的关系，结果表明：未施钾的自然土壤，在降雨量较小时（87 mm），决定钾素淋溶状况的主要土壤因子是土壤质地，质地越轻，K^+ 淋溶量越大；降雨量较大时（435 mm），决定钾素淋溶状况的主要因子则为速效钾，田间速效钾含量愈大，淋溶风险愈大。外源钾施入土壤后，在降雨量较小时（87 mm），钾素淋溶状况主要受土壤粉粒和缓效钾的影响，粉粒含量和缓效钾越大，淋溶量越小；降雨量较大时（435 mm），钾素淋溶状况主要受全钾和缓效钾的影响，其值越大淋溶量越小。在降雨量充足、田间排水不畅的情况下，短时间内（2 h）土壤钾肥表观淋出率仅与粉粒含量呈显著负相关关系，土壤的质地是影响钾淋溶的主要因子；长时间（24 h）淋溶后钾肥表观淋出率则与土壤 pH，粉粒、全钾、缓效钾和长石含量均呈显著负相关关系，其中全钾和粉粒的影响作用最大。

关键词：钾淋溶；降雨；土壤性质；质地

中图分类号：S151.9+3

钾作为植物生长必需的元素，对农作物的高产、优质和抗逆性有着举足轻重的作用。植物所吸收的钾主要来自于土壤，而土壤中的钾元素以离子形态为作物提供营养，其较强的移动性决定了钾素的淋溶损失是农田土壤钾素损失的重要部分。已有研究表明，淋失作用是导致化肥利用率低的主要原因，尤其是在降雨量大、渗透率低、阳离子交换量低的土壤中[1]。在我国钾肥资源匮乏、国际钾肥进口成本增加[2]的多重压力下，研究土壤的钾素淋溶特性，减少钾素淋溶损失，提高肥料利用率显得尤为重要。

农田土壤养分淋失的影响因素很多[3-6]，可以概括为外界影响因素（降雨、施肥、作物及耕作措施等）和土壤性质因素两个方面。钾元素作为可溶性养分，其移动和淋失与水分同步，降雨成为影响钾素淋溶的重要外界因素之一[7-8]。而在外界因素相同的状况下，影响钾素淋溶的土壤性质则主要有土壤 pH[8]、矿物类型[9]、交换性钾的含量[10]、质地组成[11]等。但是，已有的关于土壤钾素淋溶的研究结果由于研究条件不同而各有差异，对于影响土壤钾素淋溶的主要土壤性质没有得出统一的结论，基于多种土壤的系统研究则更为罕见。

本研究选取 14 种土壤进行室内土柱淋溶试验，模拟不同降雨情况下农田土壤钾素的淋溶状况，研究不同土壤钾素淋溶特性的差异，分析土壤性质与淋溶特性的关系，进而确定影响钾素淋溶特性的主要土壤因子。

1　材料与方法

1.1　供试土壤及基本性质测定方法

供试的 14 种土壤分别采自湖南长沙、江西鹰潭、湖北蕲春、湖北潜江、安徽芜湖、黑龙江海伦、河南封丘、安徽广德、安徽怀宁、山东莱阳、江苏常熟、江苏盐城、重庆、河北衡水。土壤样品经风干后过 2 mm 筛。按照鲁如坤[12]的《土壤农业化学分析方法》测定土壤的基本理化性质：土壤 pH 测定采用 Sartorius 普及型（PB-10）pH 计（水土比为 2.5∶1）；阳离子交换量（CEC）测定采用乙酸铵交换法；有机质（OM）测定采用重铬酸钾容量法；全钾测定采用氢氟酸-高氯酸消煮法；速效钾测定采用乙酸铵提取法；缓效钾测定采用硝酸煮沸法；土壤体积质量与饱和含水量测定采用环刀法；土壤质地组成测定采用吸管法；采用 X'PERT PRO X 射线衍射仪（HX041）测定土壤的矿物类型，并将其分别按照长石、非长石含钾矿物及含钾矿物总量等进行归类。土壤基本理化性质见表 1。

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② 发表于《土壤》，2014，46（2）：225-231.

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表 1　供试土壤的基本性质

Table 1　Basic properties of the tested soils

采样点	土壤类型	pH	CEC (cmol/kg)	SOM (g/kg)	全钾 (g/kg)	速效钾 (mg/kg)	缓效钾 (mg/kg)	体积质量 (g/cm³)	饱和含水量 (g/kg)	砂粒 (g/kg)	粉粒 (g/kg)	黏粒 (g/kg)	长石 (g/kg)	非长石钾矿物 (g/kg)	含钾矿物总量 (g/kg)
湖南长沙	水稻土	4.63	10.9	32.2	12.3	26.8	191	1.30	385	104	554	342	30.0	250	280
江西鹰潭	水稻土	4.93	10.4	15.4	10.5	87.7	143	1.31	339	402	322	276	0.0	175	175
湖北蕲春	水稻土	5.08	9.75	25.9	14.2	37.4	256	1.30	387	227	548	224	100.0	125	225
湖北潜江	水稻土	5.31	9.63	36.1	8.6	44.0	151	1.29	392	290	452	257	0.0	250	250
安徽芜湖	水稻土	4.99	10.6	21.4	17.0	33.0	302	1.29	385	206	572	222	75.0	150	225
黑龙江海伦	黑土	5.69	49.1	147	15.2	196	565	0.94	627	180	641	179	225.0	125	350
河南封丘	潮土	8.06	8.11	12.9	17.9	77.1	615	1.44	288	611	320	69	225.0	125	350
安徽广德	水稻土	6.06	7.15	0.78	12.9	49.3	303	1.46	299	264	588	148	50.0	175	225
安徽怀宁	水稻土	4.63	12.2	24.9	18.8	36.9	210	1.31	343	365	414	222	150.0	150	300
山东莱阳	潮土	4.69	7.77	6.89	16.3	42.6	813	1.53	256	650	259	91	275.0	175	450
江苏常熟	水稻土	5.15	20.2	45.3	17.0	47.6	334	1.30	39.2	120	576	304	150.0	200	350
江苏盐城	潮土	8.37	7.64	13.0	18.0	48.4	656	1.31	36.6	96	862	42	200.0	200	400
重庆	紫色土	7.78	22.5	13.5	19.0	73.9	513	1.44	32.2	294	572	134	150.0	175	325
河北衡水	潮土	8.27	13.7	15.5	18.1	82.2	882	1.31	30.8	150	740	109	175.0	175	350

1.2　淋溶方法

试验设施钾(K)与不施钾(CK)两个处理，每个处理 3 个重复。施钾的处理为在整个土柱中加入等量的氯化钾，施钾量为 200 mg/kg(以纯 K 计)。试验所用土柱为内径 5.4 cm，高25 cm的 PVC 管，淋溶液于底部收集。每个土柱装土 297.728 g，使用相同力度均匀装入土壤。土柱顶部和底部均放置 200 目尼龙网，分别起到减少加水对土壤的搅动影响及防止土壤渗漏到淋出液中的作用。装填土柱时特别注意将土柱边缘的土壤压实，确保无贴壁水流入渗，尽量减少管壁效应的产生。土柱装填结束后加入足量的水使土壤饱和，第二天开始用去离子水淋洗土柱。淋溶液每 10～50 ml 收集一次，并记录淋溶时间，采用 M410 型火焰光度计测定淋溶液中 K^+ 含量。有关数据分析与统计采用 Excel 和 SPSS 19.0 进行。

2　结果与讨论

2.1　不同降雨量下各土壤钾素淋溶状况

在不考虑水分蒸发与作物吸收的情况下，模拟田间不同降雨量下(87、131、218、435 mm)不同土壤钾素淋溶状况，其中 87 mm 和 435 mm 分别代表田间降雨量较小和降雨量较大的情况。87 mm 和 435 mm降雨量下各土壤的淋溶指标见表 2。

表 2　降雨量为 87 mm 和 435 mm 时各土壤的钾素淋溶指标

Table 2　Soil K leaching index under 87 mm and 435 mm rainfall

采样点	不施钾处理淋溶液 K^+ 平均浓度(mg/L)		施钾处理淋溶液 K^+ 平均浓度(mg/L)		淋溶液体积 (ml)		不施钾处理 K^+ 累积淋溶量(mg/kg)		施钾处理 K^+ 累积淋溶量(mg/kg)		钾肥表观淋出率(%)	
	87 mm	435 mm	87 mm	435 mm	87 mm	435 mm	87 mm	435 mm	87 mm	435 mm	87 mm	435 mm
湖南长沙	2.69	0.77	83.7	24.9	85	885	0.77	2.29	23.9	74.1	11.6	35.9
江西鹰潭	4.66	3.85	75.2	24.8	99	899	1.55	11.6	25.0	75.0	11.7	31.7
湖北蕲春	2.39	1.46	45.7	22.8	85	885	0.68	4.33	13.1	67.8	6.19	31.8
湖北潜江	2.55	0.85	57.9	19.7	83	883	0.71	2.52	16.1	58.3	7.71	27.9
安徽芜湖	2.01	1.20	37.1	16.0	85	885	0.57	3.56	10.6	47.7	5.01	22.1
黑龙江海伦	19.5	7.85	82.2	19.6	13	813	0.85	21.4	3.59	53.5	1.37	16.0
河南封丘	3.46	1.53	35.0	12.6	114	914	1.33	4.69	13.4	38.7	6.03	17.0
安徽广德	2.22	0.91	38.0	11.4	111	911	0.83	2.80	14.2	34.8	6.67	16.0
安徽怀宁	2.76	0.65	51.3	10.6	98	898	0.91	1.97	16.9	32.1	7.99	15.1
山东莱阳	2.70	0.77	24.7	6.30	124	924	1.12	2.39	10.3	19.6	4.59	8.58
江苏常熟	1.46	0.75	14.1	6.05	83	883	0.41	2.23	3.92	18.0	1.76	7.86
江苏盐城	1.94	0.65	15.3	4.70	91	891	0.59	1.96	4.69	14.1	2.05	6.05
重庆	1.45	0.78	4.76	2.19	104	904	0.51	2.37	1.66	6.64	0.58	2.13
河北衡水	0.90	0.36	4.68	1.55	108	908	0.33	1.09	1.70	4.73	0.69	1.82

注：钾肥表观淋出率＝(施钾处理 K^+ 累积淋溶量－不施钾处理 K^+ 累积淋溶量)/施钾量(200 mg/kg)×100，下表同。

由表 2 可以看出，随降雨量增大，两个处理的 K^+ 淋溶液体积、K^+ 累积淋溶量及钾肥表观淋出率逐渐增大，淋溶液 K^+ 平均浓度逐渐降低。降雨量较小(87 mm)时，江西鹰潭的土壤钾肥表观淋出率最大，为 11.7%，重庆土壤的最小，为 0.85%，14 种土壤平均淋出率为 5.28%。降雨量较大(435 mm)时，湖南长沙的土壤钾肥表观淋出率最大为 35.9%，河北衡水土壤的最小，为 1.82%，14 种土壤平均淋出率为 17.1%，是 87 mm 时淋出率的 3.24 倍。降雨量 87 mm 和 435 mm 时，不施钾处理 K^+ 累积淋溶量最大的分别为江西鹰潭和黑龙江海伦；施钾处理 K^+ 累积淋溶量最大的均为江西鹰潭。

这可能是由于江西鹰潭和黑龙江海伦的土壤速效钾含量较高，而速效钾能够反映土壤钾的投入和残余量[10]，因此其土壤溶液中易淋溶的 K^+ 浓度较高，土壤钾较易淋溶。重庆及河北衡水的土壤缓效钾含量相对较高。缓效钾是指存在于膨胀性层状硅酸盐矿物层间和颗粒边缘上的一部分钾[13]，缓效钾含量高，土壤固钾及缓冲能力较强，淋溶液 K^+ 平均浓度较低，故淋溶量较小。另外，土壤类型也是影响 K^+ 淋溶量的重要因素。取自江西鹰潭和湖南长沙的土壤是红壤发育的水稻土，富含 1∶1 型高岭组黏土矿物[14]，由一层硅氧四面体和一层铝氧八面体组成的晶层结构决定其不能形成闭合的孔穴，同时同晶置换产生的负电荷量很小，吸附阳离子能力很弱，所以 K^+ 易淋溶损失。

2.2 不同降雨量下土壤钾素淋溶的影响因素

降雨量较小(87 mm)和降雨量较大(435 mm)时各淋溶指标及钾肥表观淋出率与土壤性质的 Pearson 相关系数列于表 3。

表 3 87 mm 和 435 mm 降雨量时土壤钾素淋溶指标与土壤性质的 Pearson 相关系数

Table 3 The correlation coefficient between soil K leaching index and soil properties under 87 mm and 435 mm rainfall

土壤性质	不施钾处理 K^+ 累积淋溶量		不施钾处理淋溶液 K^+ 平均浓度		施钾处理 K^+ 累积淋溶量		施钾处理淋溶液 K^+ 平均浓度		钾肥表观淋出率	
	87 mm	435 mm	87 mm	435 mm	87 mm	435 mm	87 mm	435 mm	87 mm	435 mm
速效钾	0.169	0.884**	0.889**	0.893**	−0.345	0.036	0.277	0.080	−0.363	−0.175
pH	−0.244	−0.158	−0.129	−0.152	−0.576*	−0.606*	−0.604*	−0.605*	−0.581*	−0.616*
SOM	−0.074	0.816**	0.922**	0.840**	−0.242	0.256	0.496	0.310	−0.245	0.079
CEC	−0.176	0.758**	0.842**	0.781**	−0.468	−0.020	0.233	0.034	−0.473	−0.204
体积质量	0.164	−0.742**	−0.789**	−0.760**	0.142	−0.359	−0.529	−0.407	0.139	−0.208
饱和含水量	−0.174	0.761**	0.836**	0.783**	−0.179	0.368	0.533*	0.420	−0.177	0.213
砂粒	0.738**	−0.004	−0.057	−0.026	0.259	−0.019	−0.018	−0.043	0.233	−0.020
粉粒	−0.761**	−0.048	0.050	−0.022	−0.569*	−0.334	−0.301	−0.308	−0.551*	−0.348
黏粒	−0.028	0.095	0.017	0.089	0.537*	0.640*	0.580*	0.639*	0.554*	0.667**
全钾含量	−0.327	−0.225	−0.115	−0.209	−0.661*	−0.752**	−0.665**	−0.745**	−0.664**	−0.757**
缓效钾	−0.162	−0.034	0.079	−0.018	−0.692**	−0.706**	−0.592*	−0.692**	−0.704**	−0.753**
长石	−0.037	0.095	0.253	0.114	−0.651*	−0.631*	−0.456	−0.610*	−0.668**	−0.703**
含钾矿物总量	−0.169	−0.108	0.094	−0.085	−0.607*	−0.687**	−0.482	−0.671**	−0.617*	−0.715**

注：* 表示相关性达到 $p<0.05$ 显著水平，** 表示相关性达到 $p<0.01$ 显著水平。

不施钾处理，降雨量 87 mm 时 K^+ 累积淋溶量与土壤砂粒含量呈极显著正相关关系，与土壤粉粒含量呈极显著负相关关系；而降雨量 435 mm 时，累积淋溶量与土壤质地无相关关系，而与土壤速效钾、有机质、阳离子交换量及土壤饱和含水量呈显著正相关关系，与土壤体积质量呈显著负相关关系。对这些土壤性质与降雨量 435 mm 累积淋溶量作回归分析，回归方程为：不施钾处理 435 mm 降雨量时的累积淋溶量 $=0.112\times$速效钾含量-2.429，回归系数 $r=0.884$，系数的 t 检验 $p<0.1$，故其累积淋溶量与速效钾含量存在一定偏相关性。由此，未施钾的自然土壤，在降雨量较小时，决定钾素淋溶状况的主要土壤因子是土壤质地，质地越轻，K^+ 淋溶量越大；降雨量较大时，决定钾素淋溶状况的主要因子则为速效钾含量，田间速效钾含量越大，土壤溶液中易交换的 K^+ 浓度越高，淋溶风险越大。

降雨量 87 mm 及 435 mm 时，钾肥表观淋出率及施钾处理 K^+ 累积淋溶量及淋溶液 K^+ 平均浓度均与土壤黏粒含量呈显著正相关关系，与土壤 pH，全钾、缓效钾及含钾矿物含量呈显著负相关关系。此外，87 mm 降雨量时钾肥表观淋出率及施钾处理的 K^+ 累积淋溶量还与土壤粉粒含量呈显著负相关关系。将这些淋溶指标与相关的土壤性质作回归分析，其方程见表 4。可见，降雨量较小时淋溶指标与粉粒和缓效钾含量有一定偏相关性，且粉粒对其影响最大；而降雨量较大时的淋溶指标则与全钾和缓效钾含量有更强的相关性，全钾对其影响更大。由此可知，外源钾施入土壤后，在降雨量较小时，钾素淋溶状况主要受土壤粉粒和缓效钾含量的影响；降雨量增大后，钾素淋溶状况主要受全钾和缓效钾含量的影响。

表 4　87 mm 和 435 mm 降雨量时淋溶指标与土壤性质的回归方程(n=14)

Table 4　Regression equations between soil K leaching index and soil properties under 87 mm and 435 mm rainfall

回归方程(逐步回归方法)	回归系数	系数 t 检验显著性
施钾处理 87 mm 降雨量时累积淋溶量=29.6−0.018×缓效钾−0.198×粉粒	r=0.808	$p<0.05$
降雨量 87 mm 钾肥表观淋出率=14.0−0.009×缓效钾−0.091×粉粒	r=0.807	$p<0.05$
施钾处理 435 mm 降雨量时累积淋溶量=126−56.3×全钾	r=0.752	$p<0.01$
降雨量 435 mm 时钾肥表观淋出率=51.6−16.5×全钾−0.021×缓效钾	r=0.843	$p<0.05$

在降雨量较小时,土壤质地决定了钾素淋溶状况,砂粒含量越高,质地越轻,钾淋溶量越大。Rosolem 等[11]也发现相对黏质土、砂质黏壤土耕层以下钾的淋失量随施钾量增加而增加的趋势更显著。并且已有研究发现钾的固定一般随黏粒含量的增多而有加强的趋势[15-17]。因此,土壤黏粒含量越高,土壤钾淋溶风险越小。可见,土壤质地是影响土壤钾素淋溶的重要因素之一。这是因为 K^+ 等可溶性养分在土壤中的淋溶与土壤水分的运动状况密不可分,而土壤质地决定了土壤固相物质各粒级土粒的配合比例,它通过对土粒的表面能、土壤孔隙尺度和分布的影响,对土壤水分入渗能力产生影响。土壤质地越重,黏粒质量分数越高,颗粒越细微,固体相比表面积越巨大,表面能高、吸附能力越强,粒间孔隙越小,吸水、保水性能越强[18],淋溶液淋出速率越慢,K^+ 的淋溶量则越小。另外发现,土壤黏粒含量与钾肥表观淋出率呈显著正相关关系,这是由于江西鹰潭和湖南长沙的土壤,其为红壤发育的水稻土,富含铁铝氧化物及高岭石,质地黏细,对土壤钾的固定能力较弱,钾淋溶量较大,导致整体相关分析结果存在偏差。将这两种土壤剔除后分析得另外 12 种土壤黏粒含量与87 mm及 435 mm 降雨量时钾肥表观淋出率的相关系数分别为 0.261 和 0.482,均未达到显著水平。同时研究发现土壤黏土矿物类型不同,其固钾能力有明显差异[9, 16]。因此,分析土壤钾的淋溶不仅要关注土壤的粒径组成,还应该考虑土壤的黏土矿物的类型。

降雨量较大时,土壤孔隙中水分呈现饱和状态,对水分阻滞作用增强,质地的影响作用变弱,这时,土壤溶液中残余的 K^+ 浓度则决定了土壤钾的淋溶量。未施钾的自然土壤,其速效钾含量(反映土壤中 K^+ 的残余量)影响了钾素的淋溶;外源钾施入土壤后,相当部分进入矿物晶层转变为缓效钾[19],未被固定的部分 K^+ 才能够随水淋溶。对于本文采用的自然耗竭土壤而言,其全钾及缓效钾含量越高,说明其土壤固持钾素的潜力越大,同时含钾矿物含量越多,对 K^+ 的保持能力也越强,因此土壤钾的淋溶量越小。

降雨量较大及较小两种情况下,14 种土壤的钾肥表观淋出率均与土壤 pH 呈显著负相关关系,即土壤 pH 越小,酸性越强,钾的淋溶量越大;土壤 pH 越大,碱性越强,钾的淋溶量越小,这与林涛等[8]研究的紫色土钾淋失量与土壤 pH 的关系规律基本相同,并基本符合我国南方酸性土壤持钾能力弱、北方中碱性土壤持钾能力强的现状。这是由于酸性土壤的水化铝离子常聚合成为大型的多价阳离子,吸附于黏粒矿物表面,一方面对晶片表面的蜂窝状空穴产生阻塞作用,防止 K^+ 进入空穴内,同时又发挥“楔子”作用,把相邻两晶片撑住,使它们不能闭合在一起,从而增大了晶片之间的距离,使酸性土壤固定钾的能力小于碱性土壤[20]。此外,沈钦华等[21]也研究发现盐酸对各种矿物的促释作用最强,表明酸性条件能够引起土壤矿物中钾的大量释放,从而导致钾淋溶量的增大。

2.3　不同淋溶时间各土壤钾素淋溶状况

自然条件下一次降雨量很大或者多次降雨总量很大时,如果田块排水不畅,雨水会在农田中积累,并随时间的推移慢慢下渗。此时,农田土壤中的养分容易随着雨水的下渗而产生淋溶,从而导致养分的淋失,降低肥料的利用率。为模拟自然条件农田排水不畅时不同时间(2、6、12、24 h)土壤中钾的淋溶情况,用保持 5 cm 深的去离子水对土柱进行等强度的淋溶。选取 2 h 和 24 h 分别代表短时间及长时间的淋溶,其土壤钾淋溶状况见表 5。

表 5　淋溶 2 h 和 24 h 各土壤的钾素淋溶指标

Table 5　Soil K leaching index within 2 and 24 hours

采样点	不施钾处理淋溶液 K^+ 平均浓度(mg/L)		施钾处理淋溶液 K^+ 平均浓度(mg/L)		不施钾处理淋溶液体积(ml)		施钾处理淋溶液体积(ml)		不施钾处理 K^+ 累积淋溶量(mg/kg)		施钾处理 K^+ 累积淋溶量(mg/kg)		钾肥表观淋出率(%)	
	2 h	24 h	2 h	24 h	2 h	24 h	2 h	24 h	2 h	24 h	2 h	24 h	2 h	24 h
湖南长沙	4.10	1.35	139	52.1	31	179	19	287	0.42	1.26	8.59	30.8	4.09	14.8
江西鹰潭	7.28	4.41	143	45.0	25	206	23	230	0.62	3.41	11.0	31.2	5.18	13.9

续 表

采样点	不施钾处理淋溶液 K^+ 平均浓度(mg/L)		施钾处理淋溶液 K^+ 平均浓度(mg/L)		不施钾处理淋溶液体积(ml)		施钾处理淋溶液体积(ml)		不施钾处理 K^+ 累积淋溶量(mg/kg)		施钾处理 K^+ 累积淋溶量(mg/kg)		钾肥表观淋出率(%)	
	2 h	24 h	2 h	24 h	2 h	24 h	2 h	24 h	2 h	24 h	2 h	24 h	2 h	24 h
湖北蕲春	5.41	2.35	113	51.2	12	72	8	90	0.22	0.70	3.16	12.3	1.47	5.81
湖北潜江	3.23	1.16	79.3	28.7	45	434	44	465	0.49	1.81	11.7	41.8	5.60	20.0
安徽芜湖	4.61	1.54	90.9	31.9	8	101	7	132	0.12	0.68	2.16	10.7	1.02	5.01
黑龙江海伦	19.5	14.3	82.2	56.0	5	39	5	41	0.35	1.97	1.49	7.36	0.57	2.70
河南封丘	5.27	2.15	65.2	20.2	37	311	34	330	0.65	2.38	7.44	21.1	3.39	9.35
安徽广德	4.54	2.36	110	43.1	10	89	7	109	0.15	0.82	2.74	12.8	1.30	6.01
安徽怀宁	3.14	0.63	63.7	11.9	82	745	69	975	0.86	2.05	14.6	29.2	6.86	13.6
山东莱阳	3.08	0.73	30.2	5.88	106	1 039	96	1 139	1.08	2.78	9.68	20.5	4.30	8.87
江苏常熟	2.67	1.09	26.7	10.8	20	167	18	165	0.18	0.60	1.63	6.00	0.73	2.70
江苏盐城	4.82	1.78	43.1	15.4	8	92	8	103	0.14	0.61	1.11	4.71	0.49	2.05
重庆	3.10	1.72	11.1	6.39	8	55	6	65	0.08	0.38	0.22	1.13	0.07	0.38
河北衡水	1.73	0.59	10.0	3.35	30	193	25	238	0.17	0.47	0.82	2.16	0.32	0.84

由表 5 可知，随淋溶时间增加，两个处理的淋溶液体积、K^+ 累积淋溶量及钾肥表观淋出率逐渐增大，淋溶液 K^+ 浓度逐渐减小。施钾处理的 K^+ 累积淋溶量及淋溶液 K^+ 浓度均显著高于不施钾处理，而淋溶液体积则为不施钾处理略大于施钾处理，但其差异未达到显著水平。淋溶 2 h 和 24 h 后钾肥表观淋出率的最大值分别为安徽怀宁 6.86%、湖北潜江 20%；同时，最小值则均为重庆的紫色土，其值分别为 0.07% 及 0.38%。

短时间淋溶(2 h)，两个处理的土壤 K^+ 累积淋溶最大的分别为安徽怀宁和山东莱阳的土壤。淋溶 2 h 后，14 种土壤淋溶液平均淋出体积为 28 ml，而安徽怀宁和山东莱阳的土壤由于砂粒含量较高，淋溶液淋出较快，平均淋溶液体积分别达到 76 ml 和 101 ml，使得 K^+ 淋溶量相对较大。就淋溶体积而言，黑龙江海伦的土壤在两个淋溶时间内淋溶液体积均最小，这可能与其土壤有机质含量高(147 g/kg)有关。长时间淋溶(24 h)，两个处理的土壤 K^+ 累积淋溶最大的则分别为江西鹰潭和湖北潜江的土壤，与此两种土壤固钾能力差有关。江西鹰潭土壤速效钾含量高，又是红壤发育而来的水稻土，故钾较易淋溶。湖北潜江的土壤缓效钾含量较低，为 151 mg/kg，土壤固钾及缓冲能力较弱，因此淋溶量较大。

2.4 不同淋溶时间下土壤钾素淋溶的影响因素

降雨量充足，排水不畅时，各土壤在不同淋溶时间下的淋溶特性存在显著差异，其淋溶体积、淋溶液 K^+ 平均浓度、累积淋溶量及钾肥表观淋出率的大小与土壤的基本性质密切相关，用 SPSS 进行相关统计分析，短时间淋溶(2 h)和长时间淋溶(24 h)时土壤各淋溶指标与土壤性质的 Pearson 相关系数分别列于表 6。

表 6 淋溶 2 h 和 24 h 时土壤钾素淋溶指标与土壤性质的 Pearson 相关系数

Table 6 The correlation coefficient between soil potassium leaching index and soil properties within 2 and 24 hours

土壤性质	不施钾处理 K^+ 累积淋溶量		不施钾处理淋溶液 K^+ 平均浓度		不施钾处理淋溶体积		施钾处理 K^+ 累积淋溶量		施钾处理淋溶液 K^+ 平均浓度		施钾处理淋溶体积		钾肥表观淋出率	
	2 h	24 h	2 h	24 h	2 h	24 h	24 h	24 h	2 h	24 h	2 h	24 h	2 h	24 h
速效钾	−0.060	0.246	0.867**	0.911**	−0.294	−0.313	−0.276	−0.279	−0.055	0.266	−0.261	−0.287	−0.288	−0.313
pH	−0.408	−0.370	−0.097	−0.062	−0.352	−0.382	−0.528	−0.547*	−0.542*	−0.437	−0.328	−0.355	−0.530	−0.546*
SOM	−0.087	0.091	0.875**	0.889**	−0.258	−0.250	−0.183	−0.117	0.097	0.454	−0.245	−0.251	−0.187	−0.130
CEC	−0.199	−0.032	0.788**	0.839**	−0.320	−0.313	−0.367	−0.369	−0.155	0.223	−0.304	−0.310	−0.374	−0.385
体积质量	0.238	0.011	−0.784**	−0.784**	0.399	0.380	0.180	0.085	−0.220	−0.504	0.397	0.407	0.173	0.089
饱和含水量	−0.262	−0.046	0.836**	0.833**	−0.431	−0.405	−0.238	−0.114	0.225	0.560*	−0.423	−0.419	−0.234	−0.116
砂粒	0.780**	0.719**	−0.102	−0.128	0.663**	0.638*	0.540*	0.373	−0.069	−0.250	0.695**	0.687**	0.517	0.335
粉粒	−0.805**	−0.790**	0.103	0.128	−0.652*	−0.627*	−0.744**	−0.651*	−0.235	0.000	−0.665**	−0.652*	−0.731**	−0.621*

续 表

土壤性质	不施钾处理 K^+ 累积淋溶量		不施钾处理淋溶液 K^+ 平均浓度		不施钾处理淋溶体积		施钾处理 K^+ 累积淋溶量		施钾处理淋溶液 K^+ 平均浓度		施钾处理淋溶体积		钾肥表观淋出率	
	2 h	24 h	2 h	24 h	2 h	24 h	24 h	24 h	2 h	24 h	2 h	24 h	2 h	24 h
黏粒	−0.027	0.063	0.008	0.011	−0.081	−0.080	0.319	0.467	0.556*	0.476	−0.119	−0.127	0.339	0.486
全钾含量	−0.103	−0.358	−0.143	−0.141	0.051	0.081	−0.404	−0.677**	−0.713**	−0.649*	0.044	0.060	−0.420	−0.683**
缓效钾	0.036	−0.106	0.024	0.050	0.158	0.115	−0.423	−0.582*	−0.716**	−0.552*	0.180	0.166	−0.450	−0.603*
长石	0.242	0.030	0.183	0.179	0.382	0.357	−0.263	−0.512	−0.690**	−0.511	0.315	0.318	−0.294	−0.541*
含钾矿物总量	0.246	−0.027	−0.011	−0.004	0.294	0.282	−0.183	−0.374	−0.757**	−0.620*	0.397	0.396	−0.210	−0.391

由表 6 可知，无论长时间还是短时间的淋溶，不施钾处理的 K^+ 平均浓度与土壤速效钾含量、有机质含量及阳离子交换量呈极显著正相关，而施钾处理 K^+ 平均浓度则与土壤全钾含量、缓效钾含量、长石含量及含钾矿物总量呈显著负相关。这是由于大部分外源钾被土壤矿物所固定[20]，影响了土壤溶液中 K^+ 的平衡，从而使得淋溶浓度与缓效钾含量等显著相关。

同时，不施钾处理 2 h 和 24 h 内 K^+ 累积淋溶量均与土壤砂粒含量呈极显著正相关，与土壤粉粒含量呈极显著负相关，且随淋溶时间增加相关系数变小。施钾处理淋溶 2 h 的 K^+ 累积淋溶量与土壤砂粒含量呈显著正相关，与粉粒含量呈显著负相关。施钾处理淋溶 24 h 的累积淋溶量则与砂粒含量相关性不显著。淋溶 2 h 的钾肥表观淋出率只与土壤粉粒含量呈极显著负相关，而淋溶 24 h 的钾肥表观淋出率与土壤 pH，粉粒、全钾、缓效钾和长石含量均呈显著负相关。相应回归方程为：施钾处理淋溶 24 h 后累计淋溶量＝69.8－ 21.2×全钾－0.389×粉粒，r＝0.836*；淋溶 24 h 后钾肥表观淋出率＝32.7－10.3×全钾－0.173×粉粒，r＝0.822*。因此，在降雨量充足、田间排水不畅的情况下，短时间内钾的淋溶状况主要受土壤质地的影响，长时间内钾的淋溶状况则主要受土壤全钾和粉粒含量影响。

3 结论

(1) 未施钾的自然土壤，在降雨量较小时(87 mm)，决定钾素淋溶状况的主要土壤因子是土壤质地，质地越轻，K^+ 淋溶量越大；降雨量较大时(435 mm)，决定钾素淋溶状况的主要因子则为速效钾含量，田间速效钾含量越大，土壤溶液中易交换的 K^+ 浓度越高，淋溶风险越大。

(2) 外源钾施入土壤后，在降雨量较小时(87 mm)，钾素淋溶状况主要受土壤粉粒和缓效钾含量的影响，粉粒和缓效钾含量越大，淋溶量越小；降雨量较大时(435 mm)，钾素淋溶状况主要受全钾和缓效钾含量的影响，其值越大淋溶量越小。

(3) 在降雨量充足、田间排水不畅的情况下，短时间内(2 h)土壤钾肥表观淋出率仅与粉粒含量呈显著负相关，土壤质地是影响钾淋溶的主要因子；长时间(24 h)淋溶后钾肥表观淋出率则与土壤 pH，粉粒、全钾、缓效钾和长石含量均呈显著负相关，其中全钾和粉粒的影响作用最大。

(4) 不同降雨量及淋溶时间，钾肥表观淋出率均与土壤 pH 呈显著负相关，基本符合我国南方酸性土壤持钾能力弱、北方中碱性土壤持钾能力强的现状。另外，分析土壤钾的淋溶不仅要关注土壤的粒径组成，还应该考虑土壤黏土矿物的类型。

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Preliminary study on potassium leaching characteristicsof different soils

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Abstract: A soil leaching column experiment was conducted to investigate K leaching from various soils and to reveal the relationship between K leaching and soil properties. The results showed that under light rain (87 mm), soil texture was the main factor in determining K leaching for the soils without application of K fertilizer. The lighter the soil texture, the greater the amount of the K leached. Under heavy rain (435 mm), soil available K was the main factor in determining how much K could be released from the unfertilized soils. When 200 mg/kg K was applied to the soils, both the content of silt fraction and slowly available K (SAK) were the main factors influencing K leaching under light rain (87 mm). As the content of soil silt or the SAK increased, the K leaching from the soil decreased. But soil total K and SAK were the main factors in determining K leaching under heavy rain (435 mm). When the rain-fall was much higher, the apparent K fertilizer leaching ratio (AKLR) within 2 h was negatively correlated to soil silt content. However, AKLR within 24 h was negatively correlated to pH, silt, total K, SAK and feldspar content in soils, and the silt and total K content were more closely related to AKLR than other factors.

Key words: K leaching, Rainfall, Soil properties, Soil texture

水旱轮作条件下不同类型土壤供钾能力及钾素动态变化研究①

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摘　要：采用盆栽试验，研究了黑麦草—水稻轮作条件下不同类型土壤供钾能力及钾素动态变化，以期为土壤供钾机制研究及合理的钾素调控提供依据。结果表明：不施钾条件下（NP处理），潮土上种植作物的生物量和吸钾量最高，黄褐土次之，红壤最低；施钾条件下（NPK处理），三种土壤上种植作物的生物量无显著差异，作物吸钾量为黄褐土＞潮土＞红壤。整个轮作期，红壤、黄褐土和潮土NPK处理的作物生物量比NP处理分别增加55.6%、45.2%和23.2%，作物吸钾量分别增加368.8%、166.8%和74.5%。轮作前季（黑麦草季），NP处理的三种土壤水溶性钾含量和交换性钾含量均降低，潮土非交换性钾含量明显降低，红壤和黄褐土非交换性钾含量在前期变化不大，中期有升高的趋势，后期显著降低；NPK处理的土壤钾含量均高于NP处理，且各种形态钾含量的变化趋势与NP处理基本相同。轮作后季（水稻季），NP处理的三种土壤水溶性钾含量变化不大，交换性钾含量呈先降低后升高的趋势，非交换性钾含量呈先升高后降低的趋势；NPK处理的土壤交换性钾含量在水稻生长前期明显升高，中期下降，后期有略微上升，水溶性钾和非交换性钾含量有先升高后降低的变化趋势。综上所述，在不施钾条件下，轮作期内各土壤钾素消耗量较大，水溶性钾和交换性钾含量降低，并促进了非交换性钾的释放；施钾能提高土壤水溶性钾和交换性钾含量，并使其向非交换性钾方向转化，施钾对黑麦草和水稻有显著增产效果，可以有效地提高土壤供钾水平。

关键词：土壤供钾能力；黄褐土；潮土；红壤；黑麦草；水稻

中图分类号：S153.6

水旱轮作是我国重要的耕作制度。随着吸钾量大的高产作物品种的推广、复种指数的增加和农业集约化程度的提高，作物收获时每年从农田中带走的钾量逐渐增加，而对钾肥的投入远不能维持钾素平衡，农田钾素输出与投入不平衡加剧；另一方面，水旱轮作区，水热资源丰富，钾素流失严重[1]。土壤缺钾面积不断增加，土壤钾素耗竭日趋严重[2]。土壤钾素的缺乏常常造成作物因生理失调而减产[3]，农田钾素亏缺已成为农业生产持续发展的限制因素之一[4]。施用钾肥是缓解土壤钾素亏缺的重要途径[5]。但是，我国钾肥资源匮乏[6]，目前我国本土钾肥供给远远不能满足需求[7]。在钾肥资源短缺的形势下，需要高效利用钾素来充分发挥作物的产量潜力和进一步改善产品品质。因此，开展水旱轮作条件下的土壤供钾能力研究对合理施用钾肥和高产节源具有重要意义。

土壤中的钾有多种形态，一般将其分为四部分。第一部分是不易被植物吸收利用的钾，即结构钾，主要是长石和白云母中的钾；第二部分是非交换性钾，包括黑云母中的钾和黏土矿物所固定的钾；第三部分是吸附于土壤胶体表面并能被溶液中的阳离子在短时间内代换的钾，即交换性钾；第四部分是土壤溶液中的钾，即水溶性钾[8,9]。韩真[10]研究了不同土壤类型钾形态与钾素供应情况，廖育林等[11]通过大田试验研究了长期施钾对红壤水稻土钾素状况的影响。雷永振等[12]研究表明，不施钾处理土壤中的速效钾含量明显降低，而施钾处理则有所增加；土壤缓效钾与速效钾含量的变化趋势相同，但缓效钾含量的变化没有速效钾含量的变化明显。土壤中钾的固定与释放是影响整个平衡体系的关键，同时也是影响土壤供钾能力的原因。水旱轮作条件下，由于作物对钾素的吸收利用以及干湿交替、温度等外界环境条件的影响，土壤各种形态钾之间可以相互转化并处于动态平衡。研究钾在土壤中的形态变化有助于了解钾的土壤化学行为，从而指导合理施肥。本文采用盆栽试验，研究水旱轮作条件下不同类型土壤的供钾能力及不同形态钾素含量动态变化特征，以充分发挥土壤的供钾能力，为维持作物高产和土壤钾素可持续利用以及钾肥的合理施用提供依据。

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1 材料与方法

1.1 试验材料

供试土壤为红壤(RS)、黄褐土(YCS)和潮土(AS)。其中,红壤采自湖北省赤壁市,由第四纪红壤母质发育而成,质地为壤土;黄褐土采自湖北省襄阳市,由第四纪黄土母质发育而成,质地为黏土;潮土采自湖北省赤壁市,由第四纪红壤母质发育而成,质地为砂土。采样深度为0~20 cm,风干后过2 mm筛,其基本理化性质如表1所示。盆栽试验采用黑麦草—水稻轮作方式进行,供试作物品种为"超高"一年生黑麦草(Lolium multiflorum cv. Chaogao),杂交水稻两优036(Oryza sativa L. cv. Liangyou036)。

表1 供试土壤基本理化性质

Table 1 Physiochemical properties of tested soils

土壤类型 Soil type	pH	CEC (cmol/kg)	有机质 Organic matter (mg/kg)	水溶性钾 Sol-K (mg/kg)	交换性钾 Ex-K (mg/kg)	非交换性钾 Nonex-K (mg/kg)	全钾 Total-K (g/kg)	砂粒 Sand (g/kg)	粉粒 Silt (g/kg)	黏粒 Clay (g/kg)
红壤 Red soil	4.7	15.7	7.7	15.5	66.6	43.5	13.0	51.8	894.0	54.2
黄褐土 Yellow cinnamon soil	7.0	19.9	15.1	8.8	119.7	553.2	15.6	90.9	884.1	25.1
潮土 Alluvial soil	8.3	5.1	9.4	40.5	60.7	503.5	18.5	524.1	462.9	13.0

1.2 试验设计

试验设两个处理,分别为:①NP(不施钾);②NPK(施钾)。各处理4次重复。

水旱轮作前季种植黑麦草,每千克土施N 0.24 g、P_2O_5 0.15 g、K_2O 0.20 g,$MgSO_4 \cdot 7H_2O$ 0.25 g、$CaCl_2$ 0.10 g。肥料品种分别为分析纯尿素、$NH_4H_2PO_4$、KCl、$MgSO_4 \cdot 7H_2O$和$CaCl_2$。微量元素肥料采用1 000倍阿农营养液配方[13],每千克土加1.0 ml。氮肥总用量的55.0%作基肥,余下的均分为3次,在每次刈割后追施,磷、钾、钙、镁、微肥等均一次性基施。轮作后季种植水稻,每千克土施N 0.28 g、P_2O_5 0.15 g和K_2O 0.20 g,肥料种类及中、微量元素肥料用量同黑麦草。氮肥总用量的25.0%作基肥,余下的均分为3次追施,其他养分施用方法同黑麦草。

黑麦草于2010年10月17日施基肥、播种,播种量为25粒种子/盆,15 d后定苗20棵,根据黑麦草的生长状况分别于2011年1月18日、3月17日、4月17日刈割并追肥,5月14日收获。水稻于2011年5月30日施基肥、播种,播种量为3粒种子/盆,15 d后定苗1棵,10月10日收获。

土壤样品的获取:采用长450 mm、直径为6 mm的圆柱形螺旋取样器垂直插入土壤,随机取点9个,混合均匀后风干、过筛。黑麦草季取土壤样品4次,分别在黑麦草施基肥播种后、第1次刈割后、第2次刈割后和收获后,具体取样时间为2010年10月17日,2011年1月20日、3月18日和5月14日。水稻季取土样3次,前2次根据作物的生长情况(生物量大小)来确定取样时间,第3次在作物收获后,具体时间为2011年8月16日、9月16日、10月10日。水稻季获取土壤样品之前,控制浇水,使土壤有一定程度的落干,保证土样能够成功获取。

盆栽试验采用12 cm×15 cm(直径×高)塑料桶进行,每桶装风干土6 kg,将土壤与氮、磷、钾肥拌匀后装盆,中、微量元素养分以营养液的方式施入。追施的氮肥以营养液的形式施入。

1.3 测试分析方法

黑麦草样品首先在105℃烘箱中杀青30 min,然后60℃烘48 h至恒重,称量干样质量。水稻样品分成稻草和稻谷两部分,分别烘干至恒重。将烘干的植物样磨碎,经浓H_2SO_4-H_2O_2消化,用火焰光度法测定植物钾含量[14]。

钾素吸收量(g/盆)=作物干物质量(g/盆)×相应植株的钾含量

土壤pH采用电位法、用pH计测定(水土比2.5∶1);土壤有机质采用重铬酸钾容量法测定;土壤机械组成用吸管法测定;土壤水溶性钾按10∶1水土比用去离子水浸提,速效性钾按10∶1水土比用1.0 mol/L中性NH_4OAc浸提,酸溶性钾按10∶1水土比用1.0 mol/L的热HNO_3浸提,全钾用NaOH熔融浸提,过滤后用火焰光度法测定[14]。土壤交换性钾=速效性钾-水溶性钾;土壤非交换性钾=酸溶性钾

一速效性钾。

1.4 数据处理

试验数据统计分析和作图利用 SPSS Statistics 17.0 软件和 Microsoft Office 软件。试验数据的差异显著性水平($p < 0.05$)通过最小显著法(LSD)进行检验。

2 结果与分析

2.1 水旱轮作条件下不同类型土壤的供钾能力

2.1.1 生物量

从图 1 可以看出,水旱轮作条件下,三种土壤施钾(+K)处理的作物生物量均高于不施钾(−K)处理,红壤、黄褐土和潮土+K 处理的黑麦草生物量与−K 处理相比,分别增加 25.9%、22.0%和 12.4%;水稻生物量分别增加 88.9%、81.8%和 35.9%。说明钾肥的施用能显著提高作物的生物量。轮作前季(黑麦草季)的施钾增产效果低于轮作后季(水稻季),说明黑麦草—水稻轮作轮作方式下,三种土壤在轮作前季种植黑麦草时供钾较充足,而后季种植水稻时供钾不足。所以在后季种植水稻时,需要补充足够用量的钾肥以保证作物的产量。

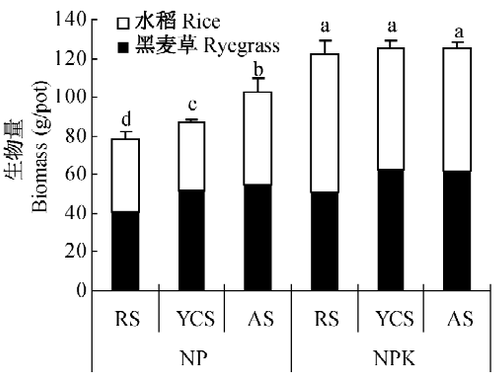

图 1 黑麦草—水稻轮作条件下不同类型土壤的作物生物量(g/盆)

Fig. 1 Crop biomass of the different types of soil under ryegrass-rice rotation (g/pot)

注:不同小写字母表示 $p < 0.05$ 水平上差异显著(下同)

−K 处理潮土上种植作物的生物量最大,与黄褐土和红壤相比分别增加 18.1%和 29.9%,说明在基础地力条件下,潮土的生产能力最高,黄褐土次之,红壤最差,这可能与土壤本身的供钾能力有关。潮土的水溶性钾含量和非交换性钾含量较高,随着作物吸钾,非交换性钾向水溶性钾和交换性钾转化,潮土的质地偏砂,养分释放速度较快,所以能获得较高的生物量,红壤的水溶性钾、交换性钾和非交换性钾的含量均较低,所以获得的生物量最低;黄褐土的水溶性钾含量较低,交换性钾和非交换性钾含量较高,其作物的生物量高于红壤,低于潮土。+K 处理的三种土壤上种植作物的生物量无显著差异($p > 0.05$),说明在施钾条件下,三种土壤的生产能力没有差异。

整个轮作期,红壤、黄褐土和潮土+K 处理的作物生物量比−K 处理分别增加 55.6%、45.2%和 23.2%。三种土壤的施钾增产率大小顺序表现为红壤>黄褐土>潮土,三种土壤的施钾效果有所不同,说明不同土壤施钾有效的临界指标是不同的。

2.1.2 钾素吸收量

不施钾条件下(见图 2),潮土上种植作物的吸钾量比黄褐土和红壤分别增加 37.8%和 263.5%,说明基础地力条件下,潮土的供钾能力最强,黄褐土次之,红壤最低。施钾后,黄褐土上种植作物的钾素吸收量最高,比潮土和红壤分别增加 5.9%和 49.4%,而三者的生物量无显著差异,说明施钾条件下,黄褐土和潮土的供钾强度过高,且作物存在钾的奢侈吸收现象。

红壤、黄褐土和潮土+K 处理的作物钾素吸收量与−K 处理相比,分别增加 368.8%、166.8%和 74.5%,说明外源钾的施入显著提高了土壤的供钾能力。

从图 2 还可看出,无论施钾与否,前季黑麦草的钾素吸收量均高于水稻,可能与黑麦草的钾含量高、吸钾强度大有关[15],同时也说明水旱轮作条件下应注重钾的合理分配。

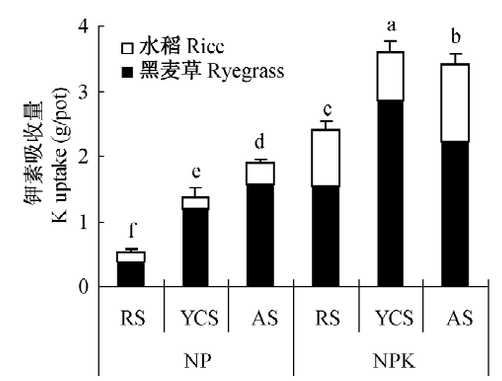

图 2 黑麦草—水稻轮作轮作条件下不同类型土壤的钾素吸收量(g/盆)

Fig. 2 K uptake by crop of the different types of soil under ryegrass-rice rotation (g/pot)

2.2 水旱轮作条件下土壤钾素变化

2.2.1 水溶性钾

黑麦草—水稻轮作轮作条件下,红壤、黄褐土和潮土−K 处

理的水溶性钾含量在轮作前季(黑麦草季)有降低的趋势(见图 3),在轮作后季(水稻季)前期(黑麦草播种后 223～299 d,水稻播种后 0～76 d)有略微升高的趋势,水稻季后期(黑麦草播种后 300～353 d,水稻播种后 77～130 d)有略微降低的趋势,变化不大,说明当土壤的水溶性钾含量降低到一定程度后不再降低或略有增加,这可能与土壤本身的水溶性钾含量和其他形态钾素向水溶钾的转化有关。红壤、黄褐土和潮土＋K 处理的水溶性钾含量在水稻季前期(黑麦草播种后 223～299 d,水稻播种后 0～76 d)呈明显升高趋势,说明钾肥的施用显著提高了土壤的水溶性钾含量,施入的钾肥对土壤水溶性钾含量的影响大于水稻生长对钾素吸收的影响,后期由于水稻不断吸钾,水溶性钾含量有降低趋势。轮作结束时,－K 处理的红壤、黄褐土和潮土的水溶性钾含量与试验前土壤相比分别降低 10.7、3.4、27.9 mg/kg,＋K 处理的红壤、黄褐土和潮土的水溶性钾含量与试验前土壤相比分别降低 5.3 mg/kg、升高 3.2 mg/kg 和降低 19.7 mg/kg。

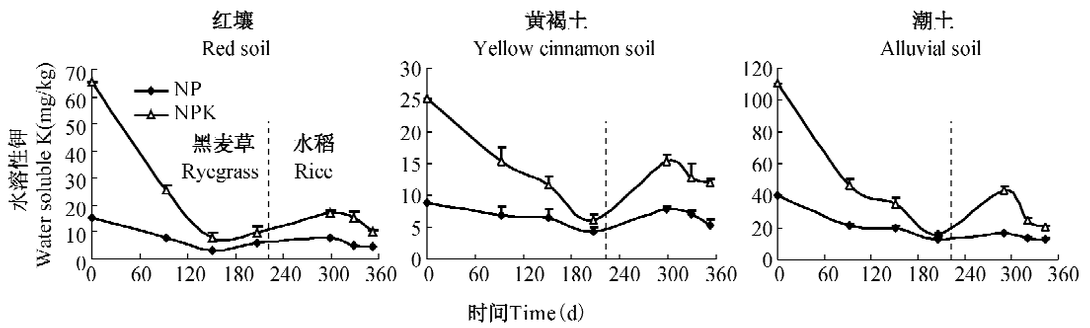

图 3　黑麦草—水稻轮作轮作条件下土壤水溶性钾变化

Fig. 3　Dynamics of water soluble K of the different types of soil under ryegrass-rice rotation (mg/kg)

由图 3 看出,三种类型土壤＋K 处理的水溶性钾含量明显高于－K 处理。不论施钾与否,土壤水溶性钾含量在作物生长过程中不是固定不变的,而是一个波动的过程。黑麦草试验期末期(黑麦草播种后 207 d),红壤、黄褐土、潮土＋K 和－K 处理的水溶性钾含量比前期(黑麦草播种后 0 d)分别降低 55.4、19.3、95.1 mg/kg 和 9.4、4.4、27.5 mg/kg,说明随着黑麦草的生长,水溶性钾首先被作物吸收利用,其含量不断降低。不同土壤水溶性钾的变化特征有所不同,这可能与土壤本身的理化性质和供钾能力有关。各土壤＋K 处理的水溶性钾含量降低程度显著高于－K 处理($p<0.05$),这可能与＋K 处理的黑麦草吸钾量高有关,说明施钾能增加作物的钾素吸收,提高土壤的供钾能力。结果表明,土壤的水溶性钾含量不仅受外界因素的影响(施钾、作物生长、水作、旱作等),还受到土壤本身理化性质的影响(钾含量、钾素平衡、颗粒组成等)。

2.2.2　交换性钾

图 4 表明,轮作前季(黑麦草季),无论＋K 或－K 处理,随着黑麦草的生长和吸钾强度的增加,交换性钾向水溶性钾转化并被吸收利用,各土壤交换性钾含量都显著降低($p<0.05$),潮土＋K 处理的交换性钾含量呈先略微升高(黑麦草播种后 0～93 d)、后明显降低(黑麦草播种后 94～207 d)的变化趋势,这可能与潮土交换性钾含量较低和水溶性钾含量较高有关。黑麦草季前期,作物首先吸收水溶性钾,所以施钾首先提高潮土交换性钾含量,随着水溶性钾的消耗,交换性钾向水溶性钾转化以供黑麦草的正常生长。

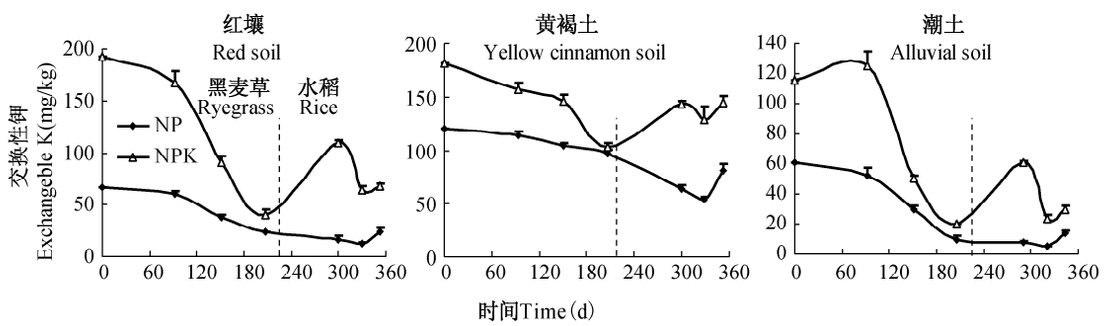

图 4　黑麦草—水稻轮作轮作条件下土壤交换性钾变化

Fig. 4　Dynamics of exchangeble K of the different types of soil under ryegrass-rice rotation (mg/kg)

轮作后季(水稻季),红壤、黄褐土和潮土－K 处理的交换性钾含量呈先降低(黑麦草播种后 223～

329 d，水稻播种后 0～106 d）、后升高（黑麦草播种后 330～353 d，水稻播种后107～130 d）的趋势，说明随着水稻的生长和吸钾强度的增加，－K 处理土壤的交换性钾含量逐渐降低；＋K 处理的土壤由于钾肥的施用，在水稻季前期（黑麦草播种后 223～299 d，水稻播种后 0～76 d）有明显升高趋势，说明在水稻生长前期，施入的钾肥对土壤交换性钾含量的影响大于水稻生长对钾素吸收的影响；水稻季中期（黑麦草播种后 300～329 d，水稻播种后77～106 d），随着作物的生长，交换性钾向水溶性钾转化并被吸收利用，其含量明显降低；－K 和＋K 处理的三种土壤交换性钾含量在水稻季末期（黑麦草播种后 330～353 d，水稻播种后 107～130 d）有上升趋势，可能由于土壤中水稻可利用的交换性钾减少，打破钾素平衡，促进矿物钾或非交换性钾向交换性钾的转化。轮作结束时，－K 处理的红壤、黄褐土和潮土的交换性钾含量与试验前土壤相比分别降低 42.5、39.2、46.6 mg/kg，＋K 处理的红壤、黄褐土和潮土的交换性钾含量与试验前土壤相比分别升高 0.7 mg/kg、升高 25.2 mg/kg 和降低 31.1 mg/kg。

2.2.3　非交换性钾

黑麦草—水稻轮作轮作条件下，红壤、黄褐土和潮土不同处理的非交换性钾含量变化如图 5 所示。红壤和黄褐土－K 处理的非交换性钾含量在轮作前季（黑麦草季）前期（黑麦草播种后 0～93 d）变化不大，在黑麦草季中期（黑麦草播种后 94～151 d）有升高的趋势，黑麦草季后期（黑麦草播种后 152～207 d）有降低的趋势，潮土－K 处理的非交换性钾含量在轮作前季（黑麦草季）有降低的趋势；三种土壤－K 处理的非交换性钾含量在轮作后季（水稻季）有先升高再降低的趋势；轮作结束时，－K 处理的红壤、黄褐土和潮土的非交换性钾含量与试验前土壤相比分别降低 14.3、77.3、169.0 mg/kg。

黑麦草季，红壤和黄褐土＋K 处理的非交换性钾含量有先升高后降低的趋势，潮土有降低的趋势；水稻季，红壤和黄褐土＋K 处理的非交换性钾含量有先升高后降低的趋势；潮土在水稻季前期（黑麦草播种后 223～299 d，水稻播种后 0～76 d）变化不大，水稻季中期（黑麦草播种后 300～329 d，水稻播种后 77～106 d）有升高的趋势，水稻季后期（黑麦草播种后 330～353 d，水稻播种后 107～130 d）有降低的趋势，轮作结束时，＋K 处理的红壤、黄褐土和潮土的非交换性钾含量与试验前土壤相比分别升高 3.6 mg/kg、降低 3.2 mg/kg 和降低 93.9 mg/kg。

轮作前季（黑麦草季）前期，红壤和黄褐土－K 处理的非交换性钾含量变化不大，说明前期土壤非交换性钾对黑麦草的贡献很小；随着作物的生长，土壤矿物态钾向非交换性钾转化使得黑麦草季中期土壤的非交换性钾含量升高，黑麦草季后期非交换性钾又向交换性钾转化以供作物的吸收利用，因此有下降的趋势。红壤和黄褐土＋K 处理的非交换性钾含量呈先升高后降低的趋势，说明除了土壤本身的钾素转化作用外，施用的外源钾也分配于非交换性钾，施入的钾肥对非交换性钾含量的影响大于作物的吸收，随着黑麦草的生长吸钾，非交换性钾向速效钾释放以供作物正常生长，黑麦草季后期黄褐土＋K 处理土壤非交换性含量比－K 处理有所降低，说明黄褐土在施钾条件下黑麦草的吸钾强度更大；潮土＋K 和－K 处理的非交换性钾含量呈明显降低趋势，说明对于潮土来说非交换性钾对作物的贡献较大。

轮作后季（水稻季），各土壤－K 和＋K 处理的非交换性钾含量有上升趋势，这可能是由于钾肥的施用以及温度升高促进了土壤矿物态钾向非交换态钾的转化；随着水稻生长的进行，又有降低的趋势，可能与作物钾素吸收和土壤中钾素平衡有关。

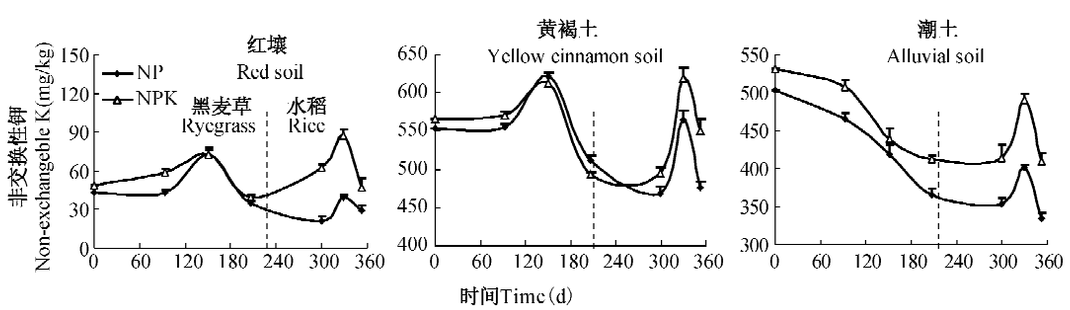

图 5　黑麦草—水稻轮作轮作条件下土壤非交换性钾变化

Fig. 5　Dynamics of non-exchangeble K of the different types of soil under ryegrass-rice rotation (mg/kg)

3　讨论与结论

黑麦草—水稻轮作轮作条件下，三种土壤的供钾能力有所不同。不施钾条件下，各土壤供钾能力顺序

为潮土>黄褐土>红壤，施钾条件下各土壤供钾能力顺序为黄褐土>潮土>红壤，说明土壤类型不同，其供钾能力会有差异，外界因素如施肥等也会影响到土壤的供钾能力。对于三种土壤，钾肥施用可以显著提高作物的生物量，特别是在钾素肥力较低的土壤上，增产效果最显著，这与很多研究结果一致[5, 16-20]。三种土壤的施钾增产效果有差异，顺序为红壤>黄褐土>潮土，且种植方式之间也有差异，黑麦草季（旱作）的施钾增产效果低于水稻季（水作），这与钾在作物上的产量效应受多种因素的影响有关。在氮、磷养分相同的基础上，钾肥在作物上的产量效应除受气候、灌水、作物等因素的影响外，土壤本身的性质及作物的种植方式对钾肥在作物上的产量效应也有重要的影响[21]。潮土质地偏砂，养分释放速度较快，土壤钾素供应较快，所以施钾增产效果最低。因此，在水旱轮作中重视钾肥施用的同时，要根据土壤本身的性质来进行钾肥的合理分配，从而获得最佳产量效应。

整个轮作期，+K 处理的作物吸钾量与－K 处理相比显著增加。所以在实际生产中种植黑麦草和水稻时，不仅要施用钾肥，还要施够钾肥，这样才能满足作物对钾素的需求，并且保持耕地的养分平衡，避免掠夺性种植[22]。但是钾肥也不能过量，否则会造成作物的钾素奢侈吸收，导致钾素资源的浪费。从研究结果还可以看出，黑麦草对钾素的需求量比水稻高，因此，在实际的轮作种植生产中，应该根据作物的实际需要来施用钾肥。施用钾肥是影响土壤钾素状况的外源因素之一，适量施钾能使土壤钾素明显增加[23]，黑麦草—水稻轮作轮作条件下，+K 处理的土壤钾含量高于－K 处理，说明施钾能提高不同时期的土壤钾含量，改善土壤钾素状况，培肥地力，对可持续农业具有深远的意义。

土壤中各形态钾之间可以相互转化，并处于一个动态的平衡体系中。土壤的干湿状况和肥料施用等因素影响着这一平衡[24]。作物首先吸收利用土壤中的水溶性钾和交换性钾，非交换性钾是作物吸收速效钾（水溶性钾和交换性钾）的最直接来源。土壤速效钾被作物吸收后，土壤非交换性钾就会释放出来供作物吸收[25]。三种土壤各种形态钾的动态变化有相同的地方，也有不同的地方。不施钾条件下，试验后三种土壤的水溶性钾、交换性钾和非交换性钾含量与试验前土壤相比都下降，其中红壤的交换性钾含量降低最多，说明红壤的交换性钾对作物的贡献最大，黄褐土和潮土的非交换性钾含量降低最多，说明黄褐土和潮土的非交换性钾对作物的贡献最大。施钾条件下，三种土壤的各种形态钾含量变化趋势有所不同。肥料施入土壤后，有一部分被作物吸收，一部分被土壤吸附固定，由于特定土壤中钾的吸附位点是一定的，不同吸附位点对钾离子的吸附能力不同[26]。施钾后，土壤含钾量发生变化，土壤中的吸附位点变化，致使不同土壤对钾肥的保持能力不同，且作物对钾素的吸收量也不同，所以试验后土壤的各形态钾含量与试验前土壤相比有升高也有降低。黑麦草季和水稻季的各土壤钾素变化特征不同，说明种植方式（水作和旱作）对土壤各形态钾之间的转化具有明显影响[27]。

水分直接影响土壤各形态钾之间的相互转化[28]。长期以来，人们在测定土壤钾素含量时，一般先将土壤样品风干后再测定，土样的风干过程是一个由湿到干的过程，干湿变化势必会引起土壤不同形态钾素之间的相互转化。Luebs 等研究表明，将田间采集的湿土进行干燥处理可以降低交换性钾含量，也可以增加交换性钾含量，湿土中的交换性钾含量与作物效应的相关性比在干土中高[29]。但也有研究表明，土壤样品的风干处理对土壤交换性钾含量的影响不大[30]，能够反应出土壤钾素含量与施钾增产效果的关系。评估淹水条件下土壤真实有效养分是目前研究中的一个难题，如何准确测定其土壤有效钾素含量的方法还有待进一步研究。

水旱轮作条件下，钾肥的施用不仅可以在提高作物产量上发挥巨大潜力，还能提高土壤钾素含量，对保护耕地质量有积极的作用。红壤、黄褐土和潮土的钾素动态变化不同，说明不同的土壤其供钾能力及钾素保持能力不同。因此，未来应加强钾素在作物-土壤体系内的循环等问题的研究，摸清不同土壤的供钾能力及钾肥与其他肥料配合施用的有效施用条件，完善化肥的分配、管理体制，最大限度地减少钾肥损失，提高利用率和经济效益，使有限的资源发挥最大可能的经济效益。

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Supply capacity and dynamic of potassium in different types of soils under paddy-upland rotation

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Abstract: Potassium (K) supply capacities and K dynamics were studied through a pot experiment in different types of soils under ryegrass-rice rotation, aiming to provide evidence for research on soil K supplying mechanism and reasonable K

control. Results showed that both aboveground biomass and K uptake by crops were highest in Alluvial soil (AS) without K treatment (NP), followed by Yellow cinnamon soil (YCS), then the Red soil (RS). However, for treatments with K fertilization, aboveground biomass indicated no significant difference ($p>0.05$) among these three type of soils whereas K uptake by crops varied with the types of soil, showing an order of YCS > AS > RS. The crop biomass in the NPK treatment were much higher than that in the NP treatment, increasing by 55.6%, 45.2% and 23.2% for RS, YCS and AS, respectively. Similarly, K uptake amounts were also increased by 368.8%, 166.8% and 74.5%, respectively in the NPK treatments as compared with NP treatments. In the ryegrass growth season, the concentrations of water soluble K and exchangeable K of the soils were all decreased under the NP treatment. The non-exchangeable K of AS was clearly reduced under the NP treatment in the whole growing period. However, for YCS and RS, non-exchangeable K remained relatively stable at first, then increased at medium stage and clearly decreased at later stage of ryegrass growth. For the NPK treatment, the water soluble K, exchangeable K and non-exchangeable K were all higher than that in the NP treatment during the period of ryegrass growth. During the nice growing period, water soluble K of the soils were little changed in the NP treatment, soil exchangeable K decreased at first and then increased, and non-exchangeable K increased at first and then decreased. For the NPK treatment, soil exchangeable K clearly increased at early stage of rice growth, and decreased at medium stage, then increased at later stage of rice growth. The dynamic changes of soil water soluble K and non-exchangeable K increased at first and then decreased. Overall, our study revealed that both soil water soluble K and exchangeable K would decrease with no K fertilization, resulting in the release of non-exchangeable K. The application of K fertilizer would enhance K supply capacity by improving the concentrations of water soluble K, exchangeable K and non-exchangeable K, thus increasing the yield of ryegrass and rice significantly.

Key words: Potassium supply capacity, Yellow cinnamon soil, Alluvial soil, Red soil, Ryegrass, Rice

Potassium dynamics in plant and soil as affected by soil sodicity §

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Abstract: Salt stress refers to the excessive amount of soluble salts in the root zone which induce osmotic stress and ion toxicity in the growing plant. Among toxic ions, sodium (Na^+) has the most adverse effects on plant growth by its detrimental influence on plant metabolism in inhibiting enzyme activities. An optimal K^+ : Na^+ ratio is vital to activate enzymatic reactions in the cytoplasm necessary for maintenance of plant growth and yield development. Although most soils have adequate amounts of potassium (K^+), in many soils available K^+ has become insufficient because of large amounts of K^+ removal by high-yielding crops. This problem is exacerbated under soil-sodic conditions as a consequence of $K^+ - Na^+$ antagonism. Here K^+ uptake by plants is severely affected by the presence of Na^+ in the nutrient medium. Due to its similar physicochemical properties, Na^+ competes with K^+ in plant uptake specifically through high-affinity potassium transporters (HKTs) and non-selective cation channels (NSCCs). Membrane depolarization caused by Na^+ makes it difficult for K^+ to be taken up by K^+ inward-rectifying channels (KIRs) and increases K^+ leakage from the cell by activating potassium outward-rectifying channels (KORs). Minimizing Na^+ uptake and preventing K^+ losses from the cell may help to maintain a K^+ : Na^+ ratio optimum for plant metabolism in the cytoplasm under salt-stress conditions. It would seem a reasonable assumption therefore that an increase in the concentration of K^+ in salt-affected soils may support enhanced K^+ uptake and reduce Na^+ influx via HKTs and NCCSs. Although very useful information is available regarding $K^+ - Na^+$ homeostasis indicating their antagonistic effect in plants, current knowledge in applied research is still inadequate to recommend application of potassium fertilizers to alleviate Na^+ stress in plants under sodic and saline-sodic conditions. Nevertheless some encouraging results regarding alleviation of Na^+ stress by potassium fertilization provide the motivation for conducting further studies to improve our understanding and perspectives for potassium fertilization in sodic and saline-sodic environments.

Key words: Salt-stress, K-Na homeostasis, K fertilizers, ameliorating effect of K

1 Introduction

The ever increasing world population is worrisome in relation to fulfilment of global food requirements that may double by 2050 (*Tilman* et al., 2011), while over the same period natural resources are predicted as limiting because of rapid global climate change. Owing to use of brackish irrigation water, waterlogging and natural subsoil salinity, fertile soils are becoming salt-affected and a major threat to sustainable food production in arid and semi-arid areas of the world *Qadir* et al. (2006). The term salinity refers to the accumulation of the specific amount of soluble salts (EC$\geqslant$4 dS m^{-1}) in the root zone which inhibit plant growth. Soils in which the sodium (Na^+) concentration is increased (SAR$\geqslant$13) at the exchangeable sites of the soil particles but with low concentration of total soluble salts (EC $<$ 4 dS m^{-1}) are described as sodic soils. Those soils with high soluble salt concentrations EC$\geqslant$4 dS m^{-1} and SAR$\geqslant$13 are termed saline-sodic soils (*Qadir* et al., 2007).

Physiological and biochemical studies have revealed that generally salt stress includes osmotic stress and ion toxicity, but is multifactorial and complex (*Munns*, 1993; *Tarczynski* et al., 1993; *Schubert*, 2011). In relation to $K^+ - Na^+$ plant interactions in salt stress, interest has focused on the understanding of salt stress-induced potassium (K^+) efflux as being highly critical in the development of salt-resistant

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plants. The recent model suggested by *Shabala* (2009) proposes that Na^+-induced K^+ efflux via membrane depolarization causes a massive decrease in cytosolic K^+ concentration, and an increase in cytosolic Ca^{2+} concentration which in turn leads to raised reactive oxygen species (ROS) causing programmed cell death (PCD). Similar to animal counterparts, a plasma-membrane hydroxyl radical (HR)-activated K^+ channel is responsible for PCD by extruding K^+ from the root cells by ROS generation during salt stress (*Demidchik* et al., 2010). The most toxic ion in salt-affected soils is Na^+ which inhibits cell metabolic processes by affecting the activities of several vital enzymes in the cell cytoplasm (*Barkla* and *Blumwald*, 1992; *Schroeder* et al., 1994; *Murguia* et al., 1995). The osmotic stress is similar to drought stress which certain plant species are able to withstand by adaptive response mechanisms, as by developing a deeper and larger root system to increase water uptake (*Gowda* et al., 2011) and/oraccumulation of osmolytes and osmoprotectants (*Farooq* et al., 2009) which may contribute to osmotic stress caused by salinity. Generally, in salt resistance of plants there is the possibility to tolerate high concentrations of toxic ions and/or to exclude toxic ions. The metabolic processes occurring in the plant cell are mostly intolerant to high concentration of toxic ions in the cell cytoplasm, even salt-resistant plants (Flowers et al., 1977). Salt-resistant plants either exclude toxic ions at the root surface by minimizing their uptake or sequester them in the vacuoles of root and shoot cells (*Flowers* et al., 1977; *Schubert* and *Läuchli*, 1990; *Schubert* et al., 2009; *Plett* and *Moller*, 2010). As most of the salt-affected soils contain toxic concentrations of Na^+, plants possessing mechanisms to resist Na^+ either at root level or in the shoot are categorized as salt-resistant. For plants growing at high concentrations of Na^+ in the nutrient medium, a significant decrease in K^+ concentration and K^+ : Na^+ ratio has been observed in the plant tissue(*Maathuis* and *Amtmann*, 1999; *Shabala* et al., 2006). Thus to enhance plant growth in sodic and saline-sodic soils, both Na^+ uptake has to be decreased and K^+ uptake increased. The higher uptake of Na^+ by plants due to elevated Na^+ concentration in soils is achieved by utilization of non-selective cation channels (NSCCs; *White*, 1999; *Tester* and *Davenport*, 2003) and of K^+ by high-affinity K^+ transporters (HKTs) (*Shabala* and *Cuin*, 2008). Hence Na^+ competes with K^+ uptake by the plants and increasing K^+ concentration in the root zone may support K^+ in this competition. This may not only decrease Na^+ uptake, but also increase K^+ uptake. This interaction between K^+ and Na^+ has been reported by several researchers from their studies on absorption, uptake, root-to-shoot translocation and vacuolar sequestration (*Maathuis* and *Amtmann*, 1999; *Demidchik* and *Tester*, 2002; *Cuin* et al., 2003; *Cuin* and *Shabala*, 2005; *Chen* et al., 2007a) as well as those works substituting non-specific functions of K^+ by Na^+ in halophytic crop species (*Wakeel* et al., 2010a, 2011a). A comprehensive analysis of K^+ and Na^+ interaction in soil and plants is necessary to unveil the mechanisms of their uptake and transport in plants under sodic and saline-sodic soils. The present review aims to provide a critical analysis of $K^+ - Na^+$ interactions in soil and plant necessary to enhance plant growth by maintaining the K^+/Na^+ ratio in plant tissues under saline-sodic conditions. Furthermore, reviewing the ameliorating effect of K-fertilization allows conclusions to be drawn on prospects of high rates of potassium fertilization in sodic and saline-sodic soils.

2 K^+ and Na^+ dynamics in soil

Potassium concentration in the earth's crust is about 2.6% and it is one of the most abundant plant nutrient in most soils. The greatest part of soil potassium, however, is bound to primary and secondary minerals, and thus not available to plants. Its availability to plants depends upon the concentration present in the soil solution and its transfer from exchangeable and fixed form to the soil solution. Typically, there are four forms of K^+ in soil: Non-exchangeable K^+, exchangeable K^+, soil mineral K^+ and solution K^+ (*Sparks*, 1987). The dynamic reactions for equilibrium between these different K^+

forms are important for K^+ availability to plants where non-exchangeable K^+ is an important pool of K^+ in soils and makes a significant contribution to plant K^+ supply (*Mengel* and *Uhlenbecker*, 1993; *Jalali* and *Zarabi*, 2006). A continuous refill of soil solution is required by adding potassium fertilizers and/or K^+ release from weathering K^+ reserves for optimal plant growth (*Sparks*, 1987). Capacity is the total amount of K^+ present in the soil, whereas intensity is the concentration of K^+ in soil solution available to plants. The transfer rate from capacity to intensity shows the kinetic factor of renewal of potassium from fixed to available form (*Barber*, 1984).

Micas and alkali feldspars are the major natural sources of soil K^+ which contain 6 - 9% and 3.5 - 12 % K^+, respectively. During growth plants take up K^+ and reduce its concentration in the root zone releasing exchangeable and non-exchangeable K^+ into the soil solution from K^+-containing minerals. Solution K^+ from the non-root zone area may also diffuse to the root zone under flooded conditions. During K^+ release, micas are converted progressively to the secondary 2 : 1 clay minerals illite, vermiculite and smectite (*Havlin* et al., 1999).

Some of the applied potassium fertilizer to such soils often becomes unavailable or slowly available to the plants (*Scott* and *Smith*, 1987) due to fixation of K^+ by soil particles. This fixed K^+ may be released from soil particles into soil solution when the concentration of K^+ is lowered in soil solution although this release is often too slow to meet the plant's requirement. The release of K^+ depends on the physicochemical properties of the soil, and type of clay minerals. The cation exchange capacity (CEC) of vermiculite clays is 1.2 - 1.5 mol kg^{-1} soil with layer thickness of 1.4 - 1.5 nm and a layer charge of 0.6 - 0.9 moles per formula unit, while smectites have CEC 0.8 - 1.2 mol kg^{-1} soil, layer thickness 1.0 - 2.0 nm and layer charge 0.2 - 0.6 moles per formula unit (*Bohn* et al., 2001).

Besides the concentration of solution K^+ and the type of clay minerals present in the soil, K^+ release from clay minerals also depends on the concentration of other cations especially Ca^{2+}, Mg^{2+} and Na^+. High concentrations of Ca^{2+}, Mg^{2+} and Na^+ in irrigation water lead to K^+ desorption and leaching (*Jalali* and *Merrikhpour*, 2008). The desorbed K^+ can easily leach and even be lost from the soil profile. However, it does become more readily available to plant roots over a specific time period. Irrigation water high in Na^+ can desorb and leach inherited and applied K^+ from the soil (*Bartal* et al., 1991). High-yielding crops and crop production systems in which entire above-ground plant parts are removed from the field in the form of crops have a very high demand for K^+. This can only be met by frequent applications of potassium fertilizers, the slow release of K^+ from soil clay minerals providing only a very small fraction of the supply required.

Sodium comprises approximately 2.8% of earth's crust, a little higher than K^+. The hydrated Na^+ ion has a radius of 0.358 nm, whereas the hydrated ion radius of K^+ is 0.331 nm. Sodium concentration is 0.1 to 1.0 mM in the soil solution in temperate zones and in arid and semi-arid areas its concentration is 50 to 100 mM which is detrimental to soil physicochemical properties (*Qadir* et al., 2006). Low-quality irrigation water makes a greater contribution to Na^+ accumulation in such areas. Increased Na^+ concentration deteriorates the soil aggregates due to its greater hydrated radius and cause hardness and poor aeration in the soils, increases the soil pH and decreases the water potential. Decreased water potential causes osmotic stress to the plants which affects the whole plant metabolism, and the increased pH decreases the availability of most of the nutrients including K^+. In sodic soils competition of Na^+ with other essential cations also decreases their availability to plants.

3 K^+ and Na^+ uptake by plants

Epidermal and cortical cells of the roots acquire K^+ from the soil solution. The lipid bilayer of cell membranes is impermeable to ions. Thus, K^+ entry into cells is mediated by transporters located in the plasma membrane. More than 40 years ago *Epstein* et al. (1963) explained the kinetics of K^+ uptake in

barley by means of two mechanisms. Subsequent studies on other plant species confirmed that two transport systems are indeed responsible for K^+ uptake by plant cells, namely a high-affinity transport system (HATS) previously referred to as "Mechanism 1", an active process, and a channel-mediated low-affinity transport system (LATS), earlier called "Mechanism 2" (*Maathuis* and *Sanders*, 1996; *Rodriguez-Navarro*, 2000; *Britto* and *Kronzucker*, 2008).

Commonly, high-affinity K^+ uptake is mediated either by the HKT family such as the TaHKT1 in wheat (*Schachtman* and *Schroeder*, 1994) or the KT/HAK/KUP family such as the HvHAK1 in barley (*Santa-Maria* et al., 2000). These transporters function at low external K^+ concentrations (i.e. -0.2 mM) usually mediated by H^+/K^+ symport with 1∶1 stoichiometry (*Maathuis* and *Sanders*, 1994; *Britto* et al., 2008). The HATS are strongly down-regulated under K^+ replete conditions and up-regulated under K^+ starvation (*Kochian* and *Lucas*, 1982). The motive force is provided by plasma membrane proton pumps in the form of a H^+ electrical gradient across the membrane (*Palmgren*, 2001). Generally, the low-affinity transport system comes into play when the external K^+ concentration is higher than 1 mM (*Wang* and *Wu*, 2010). However, the electrochemical K^+ gradient is of decisive importance and a lower cytosolic electrochemical potential enhances K^+ entry into the cell even at low external K^+ concentration by voltage-gated K^+ channels. The entry of K^+ increases the cytosolic positive charge, decreases negative charge of the cytosol and finally attains equilibrium with the outer medium. Under these equilibrium conditions there is no driving force for K^+ uptake (*Mengel* and *Kirkby*, 2001).

Plasma membrane H^+ pumps permanently excrete H^+ from the cytosol into the apoplast, thus maintaining a negative charge in the cytosol and building up an electrochemical potential between the cytosol and the apoplast for K^+ uptake. Inward-rectifying K^+ channels (KIRs), such as the *Arabidopsis* AKT1 located in epidermal cells, can mediate the low-affinity K^+ uptake sufficiently to promote plant growth (*Schroeder* et al., 1994; *Lagarde* et al., 1996). However, the decreased plasma membrane H^+-ATPase pumping activity may decrease the cytosolic negative charge extruding K^+ from cytosol to apoplast via low affinity outward-rectifying channels (KORs), along the electrochemical potential gradient by facilitated diffusion (*Maathuis* and *Amtmann*, 1999). There is a lack of specific information as to how much external K^+ concentration is required to activate high or low-affinity uptake systems. Recently, however, it has been revealed that AtHAK5 is the only uptake system of no relevance to K^+ uptake at an external K^+ concentration less than 10 mM and that greater than 500 mM whereas AKT1 contributed significantly at these concentration ranges(*Rubio* et al., 2010; *Aleman* et al., 2011).

HKT1 was the first transporter involved in high-affinity Na^+ uptake in wheat (*Rubio* et al., 1995; *Schachtman* and *Schroeder*, 1994). Later on *Arabidopsis* AtHKT1 (*Uozumi* et al., 2000) and rice OsHKT1 (*Horie* et al., 2007) were found to mediate Na^+ uptake without K^+ coupling. Uptake of the Na^+ ion was demonstrated as low-affinity uptake. Subsequent molecular studies found that HKT transporters in rice mediate high-affinity Na^+ uptake under K^+-deficient conditions without any requirement for K^+ co-transport (*Garciadeblas* et al., 2003). The transcripts which encode HKT1 transporters were over-expressed in wheat, barley and rice under K^+ starved conditions whereas high affinity Na^+ uptake was enhanced (*Garciadeblas* et al., 2003; *Haro* et al., 2010). It is now largely agreed that this member of the HKT family from wheat functions as a Na^+ uniporter (*Horie* and *Schroeder*, 2004; *Kronzucker* and *Britto*, 2011). Nevertheless, it is established that the HKT family is a significant contributor to Na^+ uptake by root cells (Fig. 1).

A general consensus has also developed based on electrophysiological studies that non-selective-cation channels (NSCCs) contribute to Na^+ influx under saline conditions (*Kronzucker* and *Britto*, 2011). Based on response to change in electrical potential of plant-cell membranes, NSCCs have been categorized and subdivided into several major classes (*Demidchik* and *Maathuis*, 2007) The voltage-independent-NSCCs contribute significantly to Na^+ flux across the plasma membrane of root cells in several plant species (*White*, 1999; *Davenport* and *Tester*, 2000; *Shabala* et al., 2006). Furthermore,

a low-affinity cation transporter (LCT1) isolated from wheat may take up K^+, Na^+, Rb^+ and Ca^{2+} (*Schachtman et al.*, 1997).

4 K^+ and Na^+ dynamics in the plant

Plant tissue comprises about 1% - 10% K^+ of dry matter and is one of the most abundant mineral nutrients in the plants (*Epstein* and *Bloom*, 2005). K^+ is very mobile in plants and several transporters and channels are involved in its transport to different parts of the shoot after uptake by the root. Its mobility within the plant is also dependent on K^+ transporters and channels, especially in its loading into the xylem, K^+ efflux from the guard cells, phloem loading and unloading and sequestration into the vacuoles. About 90 - 95% of the total K^+ present in the cell is accumulated in vacuoles where it acts as an osmoticum and contributes to cell turgidity (*Subbarao* et al., 2003). Several types of channels (voltage-dependent, voltage-independent and ion-activated; *Allen* and *Sanders*, 1997; *Schonknecht* et al., 2002), and transporters are found in the tonoplast. AtKCO1, a two-pore *A. thaliana* KOR channel, has been cloned and localized to the tonoplast (*Schonknecht* et al., 2002). The rice OsHAK10 (KUP/HAK/KT family) transporter has been suggested to release K^+ from the vacuole to the cytoplasm (*Banuelos* et al., 2002). There is also evidence that NHX1 may function as K^+ transporter during low Na^+ conditions (*Blumwald*, 2000). NHX are intracellular proteins for Na^+, K^+/H^+ antiporters and are involved in K^+ homeostasis, endosomal pH regulation, and salt resistance. NHX1 and NHX2 are the isoforms of tonoplast NHX protein. Recently, it has been revealed that both these isoforms have similar expression and biochemical activities for Na^+/H^+ and K^+/H^+ antiport (*Barragán* et al., 2012). Both genes, NHX1 and NHX2, were highly expressed in guard cells with stomatal function impaired in mutant plants. Six genes encoding putative K^+/H^+ exchangers of the CPA2 family, which are actually cation/proton antiporters have been identified in *Arabidopsis* (*Mäser* et al., 2002). These K^+ exchange-antiporter genes were named KEA1 to KEA6. However, their precise functions are still unclear (*Mäser* et al., 2002). In plants, these might play an important role in K^+ homeostasis by K^+ loading into the vacuoles or other acidic compartments. Slow-activating vacuolar (SV) and fast-activation vacuolar (FV) channels are supposedly ubiquitous in the plant cell and are, activated by tonoplast potentials, permeable to K^+ as well as Na^+ (*Hedrich* and *Neher*, 1987; *Reifarth* et al., 1994).

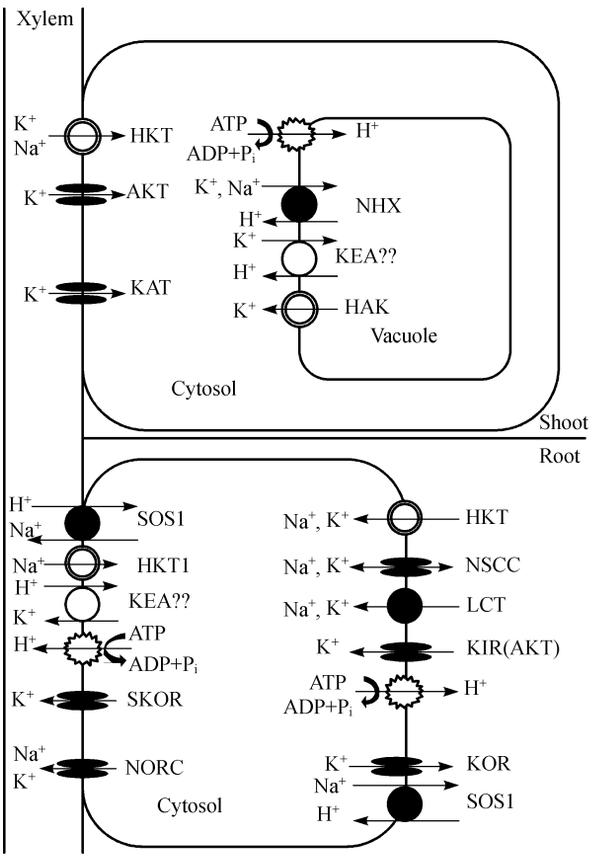

Figure 1 Scheme of important transporters and channels involved in K^+ and Na^+ absorption, translocation and intra-cell homeostasis in plants. HKT: High affinity K^+ transporter; NSCC: Non-selective cation channels; KIR: K^+ inward-rectifying channels; AKT: Arabidopsis K^+ transporter; LCT: Low affinity cation transporter; KOR: Potassium outward-rectifying channel; SOS: Salt overlay sensitive 1; KEA: K^+ exchange antiporters; SKOR: Stelar K^+ outward rectifier; NORC: Non-selective outward-rectifying channels; KAT: K^+ arabidopsis transporters; HAK: High affinity K^+-transporter; NHX: Na^+/H^+ exchanger.

The radial movement of ions from soil solution to xylem vessels involves at least two transmembrane movements: first, in epidermal or cortical cells to enter the symplasm to avoid the barrier of the casparian strip in the endodermal cells and second, in leavingthe symplasm to enter the stele. For

entry into the symplasm various HATs and LATs contribute as discussed in the previous section, whereas voltage-gated outward-rectifying channels have been shown to drive K^+ release into the upwardly flowing xylem sap (*Roberts* and *Tester*, 1995). Functional analyses of expression data support the hypothesis that KAT1, formerly identified as inward rectifying channel in *Arabidopsis* (*Anderson* et al., 1992) facilitates K^+ influx in guard cells (*Ichida* et al., 1997). KAT1 has the same family as AKT1, but in contrast it demonstrates outward-rectifying properties and its gene is expressed in pericycle and stelar parenchyma (*Gaymard* et al., 1998) and named as stelar K^+ outward-rectifier (SKOR). Membrane depolarization activates the SKOR to provide a pathway for K^+ efflux. SKOR mutants of *Arabidopsis* exhibited 50% decrease in shoot K^+ content, without affecting root K^+ contents (*Gaymard* et al., 1998). Xylem loading of K^+ by SKOR may be sensitive to NH_4^+, as its higher concentration reduced shoot content by about 90% (*Szczerba* et al., 2008). Another shaker-type channel, AKT2 was identified as mediator of K^+ loading and unloading in phloem (*Deeken* et al., 2000). Transcripts of SKOR and AKT2 increase under K^+ starvation and abscisic acid (ABA) reduces SKOR mRNA (*Deeken* et al., 2002). This is in line with the role of ABA under drought conditions of reduced K^+ transport to the shoots whereas the rate of K^+ delivery to the roots through phloem increases under water stress. The guard cell outward-rectifying K^+ (GORK) channels, members of the shaker family in *Arabidopsis*, may be responsible for K^+ efflux during stomatal closure and are activated by depolarization (*Ache* et al., 2000). Moreover, the inhibition of GORK by an acidic pH confirms the already known effect of pH on guard cell outward rectifiers (*Grabov* and *Blatt*, 1997).

Na^+ is transported across the root and into the xylem via symplastic and apoplastic pathways from root epidermal cells to the stele. Due to the effectiveness of the Casparian band, xylem loading can be restricted by the prevention of Na^+ entry into the stele. However, Na^+ transporters present in the cell membrane mediate its entry into the symplast and then to the xylem by specific transporters. Evidence that the mutant *chx*21was lower in Na^+ concentration in the xylem as well as in the shoot compared to wild type suggests that AtCHX21 present in the endodermal cells contributes to Na^+ xylem loading (*Apse* and *Blumwald*, 2007).

Under high external Na^+ concentrations, Na^+ moves into the root cell passively due to the electrochemical gradient. However, Na^+ extrusion from the cytoplasm by Na^+/H^+ antiporter is an active process energized by plasma-membrane H^+ pumps. In *Arabidopsis*, SOS1 mediates Na^+ efflux from cytoplasm to apoplast and xylem vessels (*Kronzucker* and *Britto*, 2011; Fig. 1), and SOS2 and SOS3 regulate SOS1 (*Qiu* et al., 2002). NHX transporters have attracted the attention of a large group of researchers for decades to explain and utilize their role in the development of salt-resistant plants. These are Na^+/H^+ antiporters and their up-regulation (endogenous/ transgenic) provides evidence of salt resistance in several plant species such as tomato, rice, maize, wheat, and sugar beet (*Zhang* and *Blumwald*, 2001; *Ohta* et al., 2002; *Xue* et al., 2004; *Saqib* et al., 2005; *Zörb* et al., 2005; *Liu* et al., 2008; *Pitann* et al., 2013). They tend to be up-regulated under salt stress and may use the SOS pathway (*Qiu* et al., 2004). The up-regulation of *AtNHX*1 in *A. thaliana* was positively correlated with salt stress and over-expression of *NHX* genes from other plant species and yeast in *A. thaliana* improved salt resistance (*Jha* et al., 2010). In an *Arabidopsis* mutation of SOS1 an increase in Na^+ concentration was found in all aerial organs of the plant whereas the Na^+ concentration in root was the same in both, mutant and wild type plants. This evidence together with the observation of about a 5.5 fold higher Na^+ concentration in the xylem sap of SOS1 mutant plants suggests a role for SOS1 in controlling radial transport of Na^+ from soil solution to xylem vessels(*Nublat* et al., 2001). Efficient xylem loading with high Na^+ concentrations in the xylem is a good indicator of salt resistance in plants. The Ca^{2+}- dependent SOS pathway controls long distance transport in *Arabidopsis* (*Olias* et al., 2009). Over-expression of *SbSOS*1 in tobacco suggested high salt resistance in the transgenic plants with a high degree of Na^+ loading into the xylem (*Yadav* et al., 2012).

5 K^+– Na^+ homeostasis

5.1 Na^+-induced K^+ efflux

Homeostasis of K^+ and Na^+ plays a crucial role for plant growth under saline/sodic conditions. A reduced K^+ : Na^+ ratio is a most commonly observed apprehension of Na^+ stress in glycophytic plants (*Helal* and *Mengel*, 1979). Inhibition of K^+ influx by Na^+ into the cell can be the major cause of the reduced K^+ concentration in the cell (*Kronzucker* et al., 2008). However, another potential cause may be the stimulation of K^+ efflux by Na^+ (*Lynch* and *Läuchli*, 1984; *Cramer* et al., 1985; *Kaya* et al., 2002). Variation in the electrical potential gradient across the plasma membrane, due to Na^+ movements, may be responsible for K^+ efflux from the cell. Strong electrical depolarization occurs in the plasma membrane due to influx of large amounts of Na^+ ions into the cell via depolarization-activated potassium channels (DAPCs) and/or non-selective cation channels (NSCCs) under saline/sodic conditions. Charge balancing across the cell membrane is an important function of K^+ to maintain the electrical potential of the cell across the plasma membrane and it is this role of K^+ that supposedly induces voltage-regulated outward-rectifying cation channels (NSCCs) to open, resulting in K^+ release from the cell (*Shabala* et al., 2006). ROS generated by salt stress also activate the NSCCs (*Demidchik* et al., 2003) and are responsible for K^+ leakage from the cytosol under saline conditions (Zhu, 2003). It has also been shown that osmotic stress developed by non-ionic osmolytes enhanced the K^+ efflux (*Cramer* et al., 1985). Nevertheless, different qualitative effects of ionic and non-ionic osmolytes on K^+ transport have been observed in bean leaf and barley root (*Shabala*, 2000; *Chen* et al., 2005). K^+ efflux stimulated by osmotic stress is likely to be due to membrane disintegration caused by osmotically driven water loss from the cell. In the recent studies mannitol treatment compared to NaCl was less effective in sustaining the stimulated K^+ efflux (*Britto* et al., 2010) suggesting both osmotic and ionic elements responsible for K^+ efflux (*Munns* and *Tester*, 2008).

High Na^+ concentrations upset K^+ equilibrium by increased efflux, reduced influx and decreased cytosolic K^+ pools (*Britto* et al., 2010). However all these effects can be significantly counteracted by Ca^{2+} supply accentuating the crucial role of Ca^{2+} in protecting plants from salt stress (*Cramer* et al., 1985; *Rengel* and *Elliott*, 1992; *Marschner*, 1995). The ameliorating effect of Ca^{2+} has been proposed via its channel blocking features, restricting Na^+ influx through NSCCs or K^+ efflux via DAPCs/NSCCs (*Davenport* and *Tester*, 2000; *Shabala* et al., 2006). Contradictory results have been reported that Ca^{2+} treatment had no effect on Na^+ influx and only a minor effect on the low-affinity Na^+ transport system in cotton seedlings (*Cramer* et al., 1987). Even increased Ca^{2+} was observed to increase Na^+ influx in a study on *Arabidopsis* (*Essah* et al., 2003). Furthermore, in most soils Ca^{2+} is adequately high as to make possible inhibition of Na^+ flux via NSCCs (*Zhang* et al., 2010). Increased K^+ efflux is caused by a detrimental effect of Na^+ on plasma membrane located H^+-ATPases, which reduces their pumping activity in salt-sensitive plants (*Pitann* et al., 2009) but not in salt-resistant plants (*Wakeel* et al., 2010b, 2011b). As discussed in the previous section, the decreased plasma membrane H^+-ATPase pumping activity may reduce the cytosolic negative charge extruding K^+ from cytosol to apoplast via low affinity KORs (*Maathuis* and *Amtmann*, 1999).

5.2 K^+-induced Na^+ resistance

Low cytosolic Na^+ concentration is crucial for cell metabolism and is considered to be a key component for salt resistance (*Chen* et al., 2007a). Accumulation of disproportionate amounts of Na^+ in the cytosol is toxic for enzymatic activities and should be prevented to retain the physiological concentrations of cytosolic K^+. Optimal K^+ : Na^+ ratio may be maintained by (1) restriction of Na^+ uptake via NSCC and HKT1 by root cells (*Chen* et al., 2007b; *Demidchik* and Maathuis, 2007), (2) plasma membrane Na^+/H^+ antiporter-mediated Na^+ extrusion from the cytosol to the external medium

(*Blumwald* et al., 2000), (3) tonoplast Na^+/H^+ antiporter-mediated Na^+ compartmentation in vacuoles (*Apse* et al., 1999; *Zhang* and *Blumwald*, 2001; *Pitann* et al. 2013), (4) reducing Na^+-induced K^+ efflux from the cytoplasm, and at whole plant level (5) prevention of Na^+ transport to the shoot via HKT gene family expressed in xylem parenchayma cells by extruding Na^+ from xylem sap, (*Platten* et al., 2006; *Munns* et al., 2012) (6) the recirculation of Na^+ back to the roots through the phloem (*Berthomieu* et al., 2003) appears to be fundamental for salt resistance. Reduced Na^+ influx in plant cells seems to contribute enormously to increase resistance against the toxic effects of Na^+, because increased Na^+ influx causes depolarization of the cell membrane and K^+ has to be extruded through DAPCs and NSCCs to maintain the charge across the membrane, thus disturbing the K^+ to Na^+ ratio in the cell. By first reducing entry into the root cells, several other biochemical alterations can be minimized.

Despite toxic effects, plants permit Na^+ to be taken up through certain transporters (*Mueller-Roeber* and *Dreyer*, 2007). Due to similar hydrated ionic radii, it is difficult for the transporters, HKT1 and NSCCs, to discriminate between K^+ and Na^+. At low K^+ concentration in the nutrient medium, Na^+ competes with K^+ to pass through the high-affinity K^+ channels (HKT1; *Rus* et al., 2001; *Platten* et al., 2006). Plasma membrane-located NSCCs are permeable both for Na^+ and K^+. However, they have high affinity for Na^+ (*Davenport* and *Tester*, 2000; *Yamaguchi* and *Blumwald*, 2005). Although the Na^+ concentration in shoots of salt-resistant plants was lower compared to salt-sensitive plants, the unidirectional uptake of Na^+ was not significantly different in contrasting cultivars (*Chen* et al., 2007c).

Relatively higher K^+ concentration in the root zone under saline-sodic conditions may compete more efficiently with Na^+ and reduce its uptake by plants. This will not only decrease the Na^+ concentration in the cell cytosol but will also increase the K^+ : Na^+ ratio due to increased K^+ influx and decreased K^+ efflux.

6 Alleviating Na^+ stress by K^+ application

Increased Na^+ concentration in the growth medium affects the mineral nutrient composition in the plant tissue specifically Ca^{2+} and K^+. Sodium accumulation impairs K^+ nutrition in salt-stressed plants, therefore maintenance of the K^+ : Na^+ ratio is an important guide in the assessment of salt resistance. Breeding and/or selecting crops with high K^+ : Na^+ has been suggested as a powerful strategy to minimize crop losses under salt stress (*Santa-Maria* and *Epstein*, 2001). These researchers have extensively investigated and confirmed the injurious effects of salt stress on plant growth via ionic imbalance (*Cerda* et al., 1995; *Lynch* and *Läuchli*, 1985). Plants must maintain high concentrations of K^+ and Ca^{2+} to grow successfully in saline conditions (*Greenway* and *Munns*, 1980) with K^+ deficiency at cellular level possibly contributing to salt-induced oxidative stress. Although enough information is available regarding $K^+ - Na^+$ homeostasis and application of K-fertilizers to decrease Na^+ uptake by plant roots, contradictory results have been obtained by researchers concerning the effects of K fertilization on plant growth under saline-sodic conditions. There is therefore a need to discuss the findings from these studies which have been conducted on different crop species under various growth conditions in order to consider future perspectives.

6.1 Foliar Application

Plants grown under saline-sodic conditions take up low amounts of K^+ by the roots because of cationic competition between K^+ and Na^+ which can cause K^+ deficiency. This can be avoided if potassium is provided as a foliar spray to the plants. Chlorophyll and membrane damage along with decreased biomass production induced by salt stress in tomato was minimized by foliar application of KH_2PO_4 (*Kaya* et al., 2001). Foliar application of 250 ppm KNO_3 under salt stress not only decreased toxic ion effects of salt on fruit formation of the bottle gourd (*Lagenaria siceraria*) but also increased

production by 77% (*Ahmad* and *Jabeen*, 2005). Foliar spraying of KOH on sunflower under salt stress increased leaf K^+ concentration as well as also significantly increasing growth and yield (*Akram* et al., 2009). Different K^+ sources increased growth and yield of sunflower by enhancing stomatal conductance, photosynthesis and water use efficiency under salt stress. Moreover, leaf and root K^+ concentrations were also raised. Nevertheless, KNO_3, KH_2PO_4 and K_2CO_3 were more efficient compared to KOH and KCl (*Akram* et al., 2009). Vegetative growth and fruit yield were enhanced by foliar application of K_2HPO_4 to *Solanum melongena* and Na^+ accumulation in fruits was reduced by application of 10 mM di-potassium hydrogen orthophosphate (*Elwan*, 2010).

6.2 Soil Application

Increased K^+ concentration in the root zone is antagonistic to Na^+ uptake via NSCCs and HKT1. A balanced supply of mineral nutrients is required for optimal growth and yield for all plant and crop species (*Sairam* and *Tyagi*, 2004) and high concentrations of Na^+ in the root zone disturb this nutrient balance, especially due to cationic competition. Growth enhancement has been reported by the addition of K^+ fertilizers to salt-affected soils in pepper and cucumber (*Kaya* et al., 2003), potato (*Elkhatib* et al., 2004), rice (*Bohra* and *Doerffling*, 1993), tomato and cucumber and pepper (*Kaya* et al., 2001). Application of K^+ to pearl millet under salt stress also enhanced plant growth and grain yield by decreasing the Na^+ concentration and increasing the K^+ concentration in the tissue (*Heidari* and *Jamshidi*, 2010). Similarly, a barley crop exposed to EC - 13 dS m^{-1} showed enhancement of plant growth by application of K^+ in the root zone (*Endris* and *Mohammed*, 2007). Contrarily, application of K^+ fertilizer did not increase corn growth and yield under saline conditions. Despite increased K^+ : Na^+ ratio in the plant tissue, the deleterious effects of Na^+ were not eliminated by K^+ application (*Bartal* et al., 1991). Recently we conducted a study on summer wheat which revealed that application of two-fold extra K^+ in the soil decreased Na^+ concentration and increased K^+ concentration in the plant shoots (Fig. 2; unpublished) However, a significant increase in dry matter was only attained at salinity levels of 4 and 8 dS m^{-1} and no increase in growth was observed at salinity levels of 12 and 16 dS m^{-1} compared to the control.

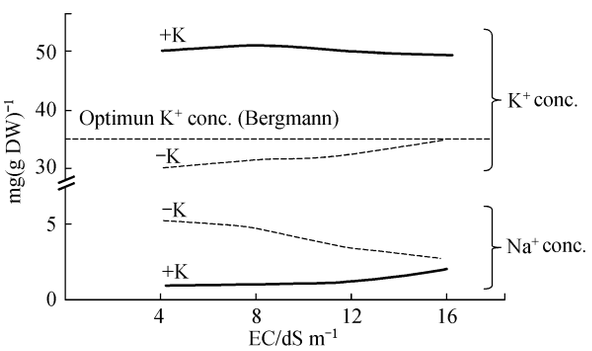

Figure 2 Shoot K^+ and Na^+ concentration of wheat grown under salinity (4, 8, 12, 16 dS m^{-1}) developed by NaCl comparing a recommended dose of K^+-fertilizer (−K) and with double dose of recommended K^+-fertilizer (+K). Wheat plants were grown in pots each containing 5 kg soil. Plants were harvested 6 weeks after sowing. Dotted line mentions minimum K^+ concentration in shoot required for optimum wheat growth (Bergmann, 1992).

6.3 Hydroponic Studies

Studies with increased K^+ fertilization in hydroponics have shown contradictory results in ameliorating effects under saline conditions. In general, however, supplemental K^+ fertilization decreased Na^+ uptake and increased K^+ uptake by plants. For example, K^+ supplied as K_2SO_4 to strawberry plants growing in saline conditions ameliorated the detrimental effect of NaCl in depressing leaf area *Khayyat* et al. (2009). The findings of these workers of increased K^+ accumulation, and decreased Na^+ and chlorine Cl^- concentrations in plant parts suggest that K^+ fertilizer can be applied under saline conditions to enhance yield. K^+ alleviated the toxic effects of Na^+ by reducing its uptake and supplemental Ca^{2+} enhanced the plant growth. Interestingly, Ca^{2+} did not improve the growth of salt-stressed plants in the absence of K^+ suggesting that Ca^{2+} did not directly reduce Na^+ but rather increased the ability of K^+ to alleviate Na^+ stress (*Kopittke*, 2012). The presence of K^+ in the nutrient solution decreased Na^+ uptake by *Jatropha curcas* seedlings exposed to salt stress. Application of K^+ decreased tissue Na^+ concentration by decreasing Na^+ influx to the xylem (*Rodrigues* et al., 2012).

These findings reveal Na^+ exclusion at root level due to increased K^+ concentration in the root zone. Sugar cane plants grown in gravel with various increasing levels of salinity over a range from 0 -160 mM decreased the concentration of K^+ in the plant tissue but application of only 3 mM K^+ raised the comparative plant K^+ concentration and enhanced plant growth (*Ashraf* et al., 2012). In a work on two cultivars of broad bean, two sources of K^+ *i. e.* KNO_3 and CH_3COOK were used in a nutrient solution to combat salinity. However, neither was growth improved nor the K^+ concentration increased in the plant tissue (*Bulut* et al., 2011).

7 Conclusion and Perspectives

Interest in K^+ and Na^+ homeostasis in soil and plant has increased considerably in the recent years and its significance recognized in understanding the mechanisms involved in salt resistance of plants. It is now established that maintenance of a high cytosolic K^+ : Na^+ ratio is an important mechanism of salt resistance in the plants. A lowered cytosolic K^+ : Na^+ ratio under salt stress is characterized by increased Na^+ influx, reduced K^+ influx and Na^+-induced K^+ efflux from plant cells. The occurrence of HKTs and NSCCs in plasma membranes permits Na^+ entry into the cell. As both of these transporters also mediate K^+ influx, Na^+ therefore competes with K^+ for these influx sites. Detrimental effects of Na^+ on plasma membrane H^+-ATPase pumping activity in salt-sensitive plants also reduce K^+ influx indirectly by decreasing the electrical gradient across the plasma membrane, a motive force for K^+ influx. Na^+-induced depolarization activates the KOR to extrude K^+ from the cell to balance the charge across the membrane. The majority of these studies have been carried out on *Arabidopsis* and only few genes have been characterized for K^+ and Na^+ transport. In recent years, however, a considerable amount of information has become available on agriculturally important crops such as wheat, rice, and barley which may be used to regulate the K^+ and Na^+ homeostasis in the cell enabling the maintenance of high cytosolic K^+ : Na^+ ratios under saline-sodic conditions. Potassium influx may increase and Na^+ influx may decrease if K^+ can be favored to compete with Na^+ for HKTs and NSCCs by application of excessive amounts of K^+ in the root zone. Foliar application of K^+ also provides another potential means of increasing K^+ influx so that an optimal cytosolic K^+ : Na^+ ratio can be maintained. As yet, however, contradictory findings have been reported. From a personal viewpoint the results are promising and inspiring, nevertheless intensive studies are still required to investigate the application of these techniques under field conditions. Genotypic variation should be considered and band application of K^+ fertilizers may give better results. Mostly researchers have conducted studies only with one foliar application. The application of potassium fertilizer in 2 - 3 installments during the growth period may be preferential to maintain the physiological cytosolic K^+ : Na^+ ratio.

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土壤盐碱度对植物和土壤中钾动态的影响

摘　要：盐胁迫指的是根区过高的可溶性盐浓度引起植物体内渗透压的变化和对离子的毒害。在这些有毒离子中，钠离子由于其在植物代谢中抑制酶活性带来的负面影响，对植物生长最为不利。合理的钾钠比对细胞质中酶促反应的激活至关重要，而这些反应对维持植物生长和产量形成必不可少。虽然大多数土壤含有足够的钾离子，然而大部分土壤因作物高产带走大量的钾，导致钾供应不足，这个问题在钠离子过量的土壤中更为严重，这是钾钠两种离子拮抗作用造成的结果。本研究发现，培养基中钠离子的存在严重影响了植物对钾离子的吸收。由于相似的理化性质，钠离子与钾离子在植物吸收上会发生竞争，尤其是通过高亲和性钾转运蛋白和非选择性阳离子通道这两种途径发生竞争。钠离子造成的膜去极化使得钾离子难以通过钾内向整流通道被植物体吸收，同时又激活了钾外向整流通道，从而增加了细胞中钾离子的渗漏。将钠离子的吸收降至最低并防止钾离子的渗漏，有助于维持盐胁迫条件下植物细胞质正常新陈代谢的最佳钾钠比。因此，我们提出了一个合理的假设：提高盐胁迫土壤钾离子浓度有助于增加钾离子的吸收并减少钠离子通过高亲和性钾转运蛋白和非选择性阳离子通道两个途径的流入。尽管从植物体内钾钠离子的平衡和拮抗方面看，这种假设是很有用的，但这方面的研究仍然缺乏，不足以在实际生产中以此推荐通过施钾减缓盐或盐碱土壤中的钠离子胁迫。尽管如此，一些关于施钾减缓钠离子胁迫的好的研究结果将会推动这方面工作的进一步开展，从而增加我们对盐或盐碱环境中钾肥作用的理解和认识。

关键词：盐胁迫；钾-钠平衡；钾肥；钾的改善作用

小麦体内钾含量变化特征及诊断叶、鞘位的研究①②

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摘　要：利用盆栽试验研究了不同供钾水平下冬小麦在拔节期、孕穗期及抽穗期各部位钾素分布特征，并进行了不同部位含钾量与植株钾含量及成熟期吸钾量的相关分析。结果表明，小麦植株钾含量随生育期的进行逐渐降低，随土壤供钾水平的升高而升高。不同时期小麦各部位钾含量变化特征存在差异性。拔节期小麦叶片与叶鞘的含钾量随叶位由上至下逐渐降低，即1叶＞2叶＞3叶＞4叶，2鞘＞3鞘＞4鞘，鞘降低幅度随供钾水平的升高而降低；孕穗期中低水平下小麦穗中含钾量最高，叶位间叶、鞘的含钾量呈由上至下逐渐降低的梯度变化，即1叶＞2叶＞3叶＞4叶，1鞘＞2鞘＞3鞘＞4鞘，而高钾水平下穗与各叶位的叶片含钾量无显著差异，2鞘的含钾量偏低；抽穗期中低钾水平小麦叶位间除1叶及1鞘含钾量明显较高，其他叶位间无明显差异。相关分析表明，3个时期植株钾素诊断在拔节期及孕穗期进行较好，1叶、2叶和3叶均可作为这两个时期植株钾素营养的诊断部位，1叶与4叶的含钾量比值可以作为植株钾素营养诊断指标。

关键词：冬小麦；供钾水平；钾含量；钾素诊断

中图分类号：S153

钾是植物必需的大量营养元素之一。已有研究表明，施用钾肥既可提高小麦产量、改善籽粒品质[1]，还可提高其抗旱性[2]，同时，钾对其他营养元素的吸收也具有显著影响[3-4]。由于农业生产中为了追求高产，施用的氮、磷肥大幅度增加，使土壤中钾素更多地被吸收，导致土壤钾素耗竭加剧[5-6]。近年来不少研究表明土壤施钾具有增产作用，且一些北方土壤上施钾也有效果，钾已成为限制作物高产的主要因子之一。苗艳芳等[7]研究了在不同钾素肥力的土壤上施钾的效果，发现不同供钾能力的土壤施钾肥对冬小麦增产效果不同。

由于我国钾素资源比较匮乏[8]，钾肥大量依靠进口，所以合理施用钾肥非常重要，而这就必须根据作物的需钾特性来实现。有关研究表明，不同作物或相同作物不同品种间及同一植株不同叶位的营养分布存在差异性[9-11]，故了解植株的吸钾特性及各叶位的含钾量规律可以有针对性地对小麦进行营养诊断，进而实现钾肥合理利用。以往对小麦需钾、吸钾特征已有部分研究[12]，但对小麦各叶位的钾含量动态变化特征研究较少，本文主要研究比较不同钾素肥力条件下小麦各部位的含钾量变化规律及其与植株钾素营养状况的关系，以期为小麦合理施钾提供理论依据。

1　材料与方法

1.1　供试材料

小麦品种：冬小麦宁麦9号，由江苏省农业科学院粮食作物研究所育成。

供试土壤：采自安徽芜湖、江苏常熟、湖北潜江3地，土壤基本理化性质（采用常规土壤农业化学分析方法分析[13]）见表1。根据土壤速效钾的含量高低，将土壤分为低、中、高3个钾素水平。

1.2　盆栽试验

将风干土壤过10目筛，装盆（22 cm × 24 cm），每盆装土5 kg，每种土壤重复3次，每千克土壤施N 0.2 g，P_2O_5 0.14 g。肥料分别为尿素、磷酸二氢钙，氮肥按2∶1的比例分别用作基肥和追肥，追肥在拔节期施入，磷肥作基肥一次施入。施肥方式为全土混施，施肥后浇去离子水1 L，养分平衡6 d后播种小麦，每盆播种40粒，15 d后每盆定苗20株，根据土壤含水量及天气浇灌去离子水。

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表 1　供试土壤基本理化性质

Table 1　Physiochemical properties of experimental soil

供钾水平	采集地	土壤类型	速效钾 (mg/kg)	缓效钾 (mg/kg)	全氮 (g/kg)	有机质 (g/kg)	pH
高	安徽芜湖	水稻土	135	275	16.4	22.8	5.42
中	江苏常熟	乌栅土	72	247	27.1	43.4	6.01
低	湖北潜江	水稻土	42	148	29.3	39.1	5.98

注：全氮量、有机质及 pH 为水稻种植前测定数据，速效钾与缓效钾为水稻收获后采样测定数据。

1.3　样品采集及分析

在小麦拔节期、孕穗期、抽穗期分别从每盆中取 5 株，单株主茎分为穗、茎、叶片和叶鞘，其中叶取上 4 片，自顶端第一片叶开始分别记作 1 叶、2 叶、3 叶、4 叶，叶片对应的叶鞘依次记为 1 鞘、2 鞘、3 鞘、4 鞘；分蘖叶片和其余叶片合并，进行烘干称重，粉碎制成样品。成熟期整盆样全取，并将籽粒与秸秆分开，分别分析。植株各部位钾含量的测定采用 H_2SO_4-H_2O_2 消煮，稀释后用 410 型火焰光度计测定。地上部含钾量＝各部位钾素累积量之和/地上部干重。

数据分析采用 Excel 2003 及 SPSS 13.0 进行。

2　结果与讨论

2.1　全生育期小麦地上部含钾量的变化特征

由图 1 可以看出，在 3 种土壤上，小麦地上部含钾量均以拔节期最高，成熟期最低。其中，从拔节期到孕穗期，小麦地上部含钾量的下降幅度最大，在高钾、中钾和低钾土壤上，小麦地上部的含钾量分别下降了 47%、45% 和 31%；但从抽穗期到成熟期，下降幅度明显降低；至成熟期，在高钾、中钾和低钾土壤上，小麦地上部的含钾量分别为拔节期的 22%、31% 和 45%。

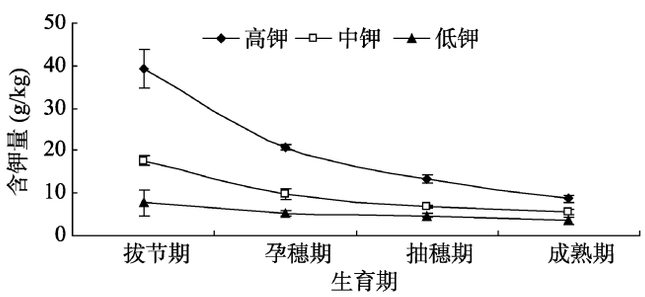


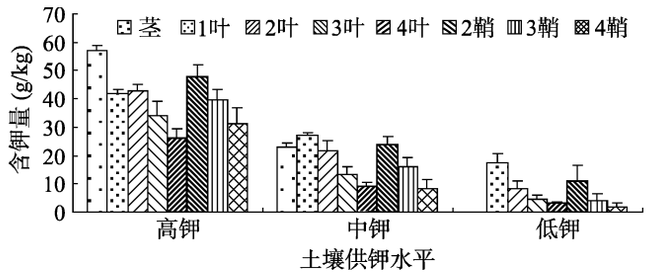
图 1　整个生育期小麦地上部含钾量变化趋势

Fig. 1　Above plant K content of wheat during whole growth period

在同一生育期，不同土壤上的小麦地上部的钾含量存在明显的差异：随土壤速效钾含量的升高而增加。分析计算表明，拔节期植株地上部的钾含量差异最大，高钾土壤上的植株地上部钾含量分别比中钾、低钾土壤植株高 1.2 倍和 4 倍，随着生育期进行，植株地上部钾含量差异减小，在孕穗期、抽穗期和成熟期，高钾土壤和低钾土壤上的植株地上部钾含量分别相差 2.94、1.86、1.52 倍。在抽穗和成熟期，中钾和低钾土壤上的植株地上部钾含量没有显著差异。对不同速效钾含量土壤上的小麦含钾量进行方差分析，结果表明，土壤钾素水平对小麦地上部的含钾量有极显著的影响（$p < 0.01$）。

2.2　拔节期小麦地上部钾素的分布特点

由图 2 可知，土壤钾素水平对拔节期小麦各部位的钾含量影响较大，植株各部位钾含量都随土壤钾素水平的升高而增加。与土壤低钾水平相比，土壤中、高供钾水平下小麦地上部各部位含钾量增长范围分别为：52.8%～356%，137%～839%。对小麦同一部位的钾含量进行方差分析，其结果表明，土壤钾素水平对各叶位的钾含量均有极显著影响（$p < 0.01$），说明小麦地上部各部位含钾量的高低与土壤供钾水平有关。如图 2 所示，在土壤低钾水平下没有茎形成，而在中、高钾素水平下茎已形成，且高钾土壤上冬小麦茎的含钾量远高于中钾土壤，这表明土壤高钾素水平可能促进小麦的生长发育。



（拔节初期，倒 1 叶与鞘尚未有明显分界，故未作区分。倒 1 叶数据为倒 1 叶与 1 鞘的测定值）

图 2　拔节期不同钾素水平下小麦各部位含钾量变化规律

Fig. 2　K content of various position of wheat planted in soil with different K contents at jointing stage

在拔节期，小麦不同叶位的叶片与叶鞘的含钾量的变化特征均呈由上至下逐渐降低的趋势，即倒 1 叶＞倒 2 叶＞倒 3 叶＞倒 4 叶，2 鞘＞3 鞘＞4 鞘。由图 2 可以看出，在不同供钾水平下，各叶位的叶鞘、叶含钾量的降低幅度不同。计算 3 个土壤钾素水平下不同叶位的叶鞘及叶的含钾量的比值发现，倒 2 叶、倒 3 叶、倒 4 叶与倒 1 叶及 3 鞘、4 鞘与 2 鞘的含钾量比值都随土壤钾素水平的升高而降低，其中，在低、中、高土壤钾素水平下，4 叶与 1 叶的含钾量比值分别为 0.63、0.34、0.18，4 鞘与 2 鞘的含钾量比值分比为 0.65、0.35、0.17。可见，在 3 个土壤钾素水平下，不同叶位间的含钾量梯度的变化规律各异，这一规律与土壤钾素水平有关。所以，不同叶位间的含钾量梯度可能是进行小麦钾素营养诊断的重要依据，有必要做进一步的研究。

2.3　孕穗期小麦地上部钾素的分布特点

孕穗期地上部小麦各部位钾含量较拔节期各部位钾含量均有不同程度的降低（新生器官穗除外，见图 3）。不同供钾水平下，小麦同一部位的含钾量间存在极显著差异（$p < 0.01$）。不同叶位的叶鞘、叶含钾量的增加幅度不同，与低钾水平相比，高供钾水平的 4 叶及对应的 4 鞘钾含量分别高 12.6 倍、11.2 倍，穗的含钾量高出 40%，其余部位高 1.4～7.3 倍。同时，高钾土壤和低钾土壤上冬小麦各叶位与鞘位间的钾含量差距自上而下呈递增趋势。在孕穗期，中钾土壤上小麦不同部位的钾含量亦明显高于低钾土壤，高出量达 0.6～1.9 倍。可见，土壤钾素水平对下位叶鞘的含钾量的影响相对较大，对穗及上位鞘、叶的含钾量影响则相对较小。

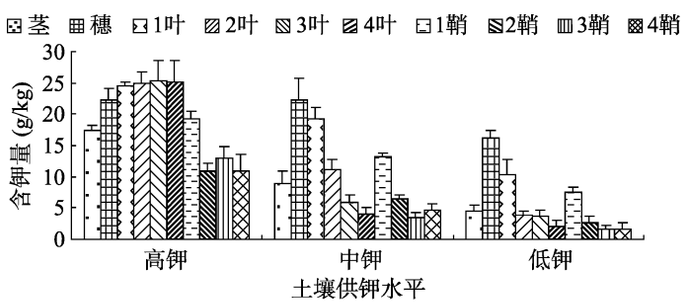


图 3　孕穗期不同钾素水平下小麦各部位含钾量变化规律

Fig. 3　K content of various position of wheat planted in soil with different K contents at booting stage

在孕穗期，3 种土壤供钾水平下小麦地上部各部位钾素的分布特点发生了变化。其中，在高钾水平下，穗的含钾量为 22.3 g/kg，低于叶片；顶 1 叶至顶 4 叶含钾量相近，平均值为 25.6 g/kg，这可能是高供钾水平下穗的钾素需求得到充足供应，多余的钾素则供应给叶和鞘，故叶位间含钾量差异减小。1 鞘与生长中心穗较近，故含钾量较高。在中、低等供钾水平下，各叶位含钾量变化趋势比较一致，均为顶 1 叶＞顶 2 叶＞顶 3 叶＞顶 4 叶，1 鞘＞2 鞘＞3 鞘＞4 鞘，且新生器官穗的含钾量较其他部位的含钾量高，分别为 22.4、16.2 g/kg。由此可见，土壤供钾水平较低时，在孕穗期钾素可能优先供应给穗这一生长中心。

2.4　抽穗期小麦地上部各部位含钾量的特征

抽穗期小麦地上部钾素的分布特点与孕穗期相似。小麦各部位钾素浓度大体呈下降趋势，但下降幅度明显低于孕穗期。随钾素水平的升高，叶位间叶的含钾量差异减小（见图 4）。在中、低钾水平下，穗的

含钾量分别为 10、9.7 g/kg，仍然高于其他部位；叶与鞘的含钾量随叶位由上至下逐渐降低，即倒 1 叶＞倒 2 叶＞倒 3 叶＞倒 4 叶，1 鞘＞2 鞘＞3 鞘＞4 鞘，但 2 鞘、3 鞘和 4 鞘含钾量相差甚小；在高钾水平下，叶位间叶的含钾量差异较小，1 叶至 4 叶钾含量相近，平均值为 18.9 g/kg。

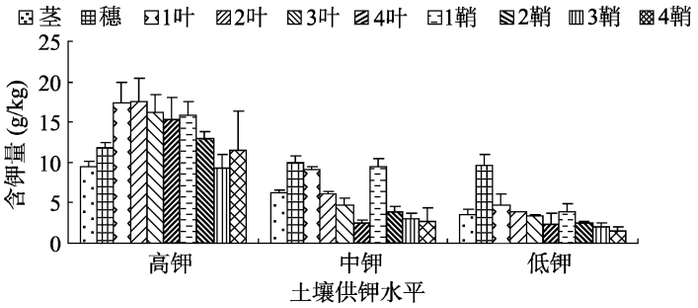


图 4　抽穗期不同钾素水平下小麦各部位含钾量规律

Fig. 4　K content law of various position of wheat planted in soil with different K contents at heading stage

由图 4 可知，小麦地上部各部位的钾含量都随土壤钾素水平的升高而增加，但各部位对钾素的响应度不同。土壤钾素水平对穗的影响较小，在高、中和低土壤供钾水平下，穗的钾含量分别为 11.7、10、9.7 g/kg；对茎的影响较大，在中和高土壤钾水平下，茎的含钾量分别是低土壤钾水平下的 1.74 倍和 2.64 倍。在 3 种供钾水平条件下，各叶位间的鞘、叶含钾量的增加幅度表现不同。其中，在中钾水平条件下，上位鞘、叶的钾含量增加幅度高于下位鞘、叶；在高钾水平条件下，变化趋势则呈现下位叶的含钾量的增加幅度高于上位叶的趋势。高钾水平下小麦 1 叶、2 叶、3 叶、4 叶的含钾量分别是低钾水平的 3.65、4.60、4.86、5.96 倍。可见，钾素可能会优先供应给小麦的上位鞘、叶。

2.5　钾素营养诊断时期及取样部位的确定

对各时期植株各部位含钾量与该期植株整株含钾量、成熟期吸钾量进行相关分析，其相关系数 r 值的大小可以反映出该指标的适合性，某部位的 r 值越大说明该部位含钾量更能反映成熟期的小麦吸钾量，即可用该部位进行营养诊断[14-15]。

2.5.1　各叶位含钾量与植株指标的相关性分析

由表 2 相关性分析表明，小麦不同时期除穗以外，各部位钾含量均与植株钾含量及成熟期吸钾量呈极显著相关。不同时期各部位与相关指标的相关系数存在不同，以拔节期叶片及叶鞘与指标相关性最好，其中以上 3 叶与植株全钾量及总吸钾量相关系数大于其余各部位；孕穗期综合来看，倒 2 叶、倒 3 叶及 3 鞘相关性最佳；抽穗期整体相关性均有所下降，这主要是随着生育期的推进，生物量增加而含钾量呈下降趋势的原因，这一时期以茎、3 叶及上位鞘相关性相对较好。

2.5.2　叶位钾素比值作为植株钾素营养诊断指标的可行性分析

小麦叶位钾素比值与植株钾含量的关系随生育期的推进而异。由图 5 可知，在拔节期和孕穗期，上位鞘、叶与下位鞘、叶的比值，可以很好地反映植株钾素状况。其中以拔节期叶位比灵活性更高，倒 1 叶、倒 2 叶与其他叶位的比值均与植株钾含量达极显著负相关；孕穗期 R^2 普遍低于抽穗期，1 叶/4 叶 R^2 最高，鞘位比相关性升高。至抽穗期叶位比与植株钾含量基本上无相关性（数据未列），难以反映不同供钾水平下植株钾素营养状况。上述分析结果表明，拔节期和孕穗期是可以预测植株钾素营养状况的最佳时间，而 1 叶/4 叶可以作为诊断植株是否缺钾的指标。

表 2　不同生育时期小麦植株各部位钾含量与植株含钾量及成熟期吸钾量的相关性

Table 2　Correlation coefficients between K content and plant indices at different growth periods

部位	拔节期		孕穗期		抽穗期	
	拔节期单株含钾量	成熟期吸钾量	孕穗期单株含钾量	成熟期吸钾量	抽穗期单株含钾量	成熟期吸钾量
茎	0.889**	0.792**	0.981**	0.841**	0.871**	0.794**
穗	—	—	0.456	0.41	0.415	0.343
1 叶	0.958**	0.945**	0.894**	0.913**	0.773**	0.741**
2 叶	0.982**	0.936**	0.957**	0.962**	0.783**	0.745**

续 表

部位	拔节期		孕穗期		抽穗期	
	拔节期单株含钾量	成熟期吸钾量	孕穗期单株含钾量	成熟期吸钾量	抽穗期单株含钾量	成熟期吸钾量
3叶	0.951**	0.943**	0.975**	0.942**	0.808**	0.777**
4叶	0.895**	0.843**	0.969**	0.890**	0.796**	0.747**
1鞘	—	—	0.829**	0.743**	0.704**	0.730**
2鞘	0.946**	0.908**	0.924**	0.908**	0.797**	0.797**
3鞘	0.912**	0.917**	0.970**	0.902**	0.831**	0.777**
4鞘	0.910**	0.947**	0.969**	0.874**	0.827**	0.771**

注：单株含钾量为植株在每个时期的整株含钾量，包括分蘖部分及单茎上的其余叶片含钾量；吸钾量为植株在成熟期的全株钾素积累量，等于秸秆含钾量×秸秆生物量＋籽粒含钾量×籽粒生物量；** 表示在 $p < 0.01$ 水平上差异显著，$r_{0.01,17} = 0.64$。

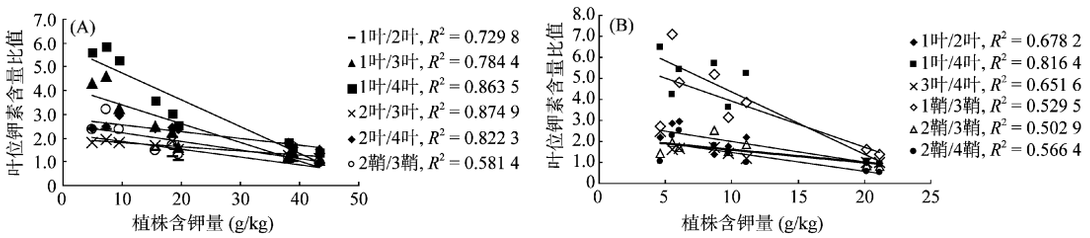


图 5 拔节期(A)与孕穗期(B)叶位间含钾量比值与植株含钾量的关系

Fig. 5 Correlation coefficients between K content ratios of different leaf positions and plant indices at booting and heading stages

3 结论与讨论

前人关于作物钾素营养的研究多侧重于不同生育阶段植株钾素变化趋势或者不同器官间的分配积累，对不同生育阶段叶位间的钾素分布特征研究相对较少。有研究表明，冬小麦叶片氮素含量在冠层垂直水平上有较清晰的层次性[10]。本研究也证明了，3 种供钾水平下拔节期不同供钾水平下小麦叶位钾素含量呈 1 叶＞ 2 叶＞ 3 叶＞4 叶的变化趋势；在孕穗期及抽穗期，中低钾水平下小麦叶位钾素含量变化特点同上；高钾水平下各叶位间叶片含钾量的差异不大，但叶鞘间呈现出不同的变化特点，孕穗期 2 鞘含量最低，抽穗期 1 鞘和 4 鞘含量高于 2 鞘和 3 鞘，这与氮素变化特点有所不同[16]。整个生育期小麦的钾素含量随生育期的推进而逐渐降低，本研究条件下，以拔节期植株含钾量最高，至成熟期植株含钾量最低。

小麦不同时期各部位含钾量分布特点因土壤供钾水平的不同而异。在 3 种供钾水平下，拔节期冬小麦各叶位间鞘、叶钾含量均呈自上而下依次降低的梯度变化趋势。植株的含钾量水平可反映土壤钾素水平，且各生育期植株钾含量与成熟期吸钾量及产量具有一定的相关性[14]，但小麦各部位钾含量并不一致，故各部位对钾素的响应度就不同。本试验结果表明，拔节期和孕穗期小麦的含钾量可以预测植株钾素营养状况的最佳时间，其中倒 1 叶、倒 2 叶和倒 3 叶的含钾量可以很好地反映植株钾素营养状况，故推测倒 1 叶、倒 2 叶和倒 3 叶可以作为小麦钾素营养的取样部位。

梁孝衍和苗青[17]用叶位差法作香蕉钾素的诊断指标，认为叶位差法具有可消除品种间的差异，在钾素营养诊断上具有比单一某一部位作为取样部位好的优点。本文将叶位差法引进到小麦钾素营养诊断上，探索了叶位间含钾量比值在小麦钾素营养诊断的效果。结果表明，不同钾素水平下不同叶位的小麦钾含量比值不同，叶位间含钾量比值与植株含钾量、吸钾量存在极显著相关性，尤其是拔节期和孕穗期 1 叶与 4 叶的含钾量比值与小麦含钾量、吸钾量存在极显著相关性。可见拔节期和孕穗期，1 叶与 4 叶的含钾量比值可以反映小麦的钾素营养状况，1 叶与 4 叶的含钾量比值可以作为植株钾素营养诊断指标，但其应用性仍需进一步验证。

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Studies on characteristic of K content of winter wheat and K nutrition diagnosis

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Abstract: Pot experiments with winter wheat were conducted to investigate potassium (K) content characteristics of main growth stages of winter wheat in soil with different K fertility, and the correlations between different part K contents and whole plant K content, K uptake of maturity stage were analyzed. The results showed that K content of wheat gradually reduced during whole growth period, and it increased with increasing soil K fertility. The characteristic of K content of wheat was different in different growth stages, jointing stage, the K content of leaf and sheath gradually reduced from upper leaf position to lower position, namely, 1st leaf > 2nd leaf > 3rd leaf > 4th leaf, 2nd sheath > 3rd sheath > 4th sheath, drop range of sheath reduced with rising soil K level, booting stage, in low and middle K level, K content of spike of wheat was highest, K contents of leaf and sheath gradually reduced from upper leaf position to lower position, namely, 1st leaf > 2nd leaf > 3rd leaf > 4th leaf, 1st sheath > 2nd sheath > 3rd sheath > 4th sheath, in high K level, there was no significant difference between K content of spike of wheat and K content of different leaf position, K content of 2nd sheath was low; heading stage, K content of different leaf position had no significant difference, but for K content of 1st was significantly higher. The correlation analysis showed that booting stage and jointing stage was the good stage for wheat K nutrition diagnosis, 1st leaf, 2nd leaf, 3rd leaf were the sampling parts of K nutrition diagnosis at booting stage and jointing stage. K content ratio of 1st leaf and 4th leaf could be used for K nutrition diagnosis of wheat.

Key words: Winter wheat, Potassium supply levels, K content, K diagnosis

基于可见/近红外反射光谱的梨树叶片钾含量的快速测定研究[①②]

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摘　要：利用可见/近红外反射光谱定量分析技术对梨树鲜叶钾素含量进行快速测定研究。对150个梨叶片样本进行光谱扫描，其中120个做建模集，30个做验证集。通过对样品的可见/近红外光谱进行多种预处理，并建立氮素预测模型，探讨了可见-近红外光谱数据预处理对预测精度的影响。结果表明，通过原始光谱与S-G(3)平滑相结合的预处理方法，用17个主成分建立的偏最小二乘法模型最好，其交叉验证集和预测集模型的决定系数(R^2)分别为0.722 7和0.679 1，交叉验证均方根误差(*RMSECV*)为1.171，预测的平均相对误差为6.81%。该方法能高效、快速地预测梨叶片钾素含量，为梨树钾素快速测定提供了新的手段。

关键词：梨；氮含量；可见/近红外反射光谱；偏最小二乘法

中图分类号：O433.1；　　**文献标识码**：A

钾是果树生长过程中必需的营养元素之一。钾与氮、磷等营养元素不同，它不参与果树体内有机物的组成，但却是果树生命活动中不可缺少的元素，它与代谢过程有着密切关系，并为多种酶的活化剂，参与糖和淀粉的合成、运输和转化[1-2]。因此，准确、快速、经济地判断植株钾素状况、确定果树钾肥需要量具有重要意义。传统的植物钾素营养诊断方法是基于叶片的实验室分析，该法要求破坏植株样本，而且需要采样、烘干、称重、研磨以及使用有潜在危害性的药品进行测试，需消耗大量的时间、人力和物力，时效性差，成本太高[3]。近年来，随着光谱技术的快速发展与不断完善，利用可见/近红外反射光谱(VIS/NIR)数据对多种植物生化组分含量进行快速与准确测定已成为现实[4-5]。

乔欣等[6]采用连续统去除法提取光谱吸收深度这一特征参数，分析波长660 nm和1 450 nm 2处敏感吸收深度和大豆钾素水平的相关关系，建立了非线性回归模型，相关系数为0.721 5，平均误差为24.37%；刘岱松等[7]对烟叶的近红外光谱和含钾量的相关关系进行了研究，建立的偏最小二乘(PLS)预测模型决定系数(R^2)为0.909，预测均方根误差为0.119。目前，有关基于光谱估测作物营养元素的研究主要集中大田作物上，对果树作物，尤其是梨树钾素的光谱诊断未见报道。

钾对叶绿素的形成具有重要作用，钾的丰缺与植物叶片结构、水分等状况密切相关，且必然会影响其可见-近红外等波段的光谱信息[8-9]。本研究以梨树鲜叶为研究对象，采用便携式地物光谱仪测定其可见/近红外反射光谱，建立梨树鲜叶全钾含量与可见/近红外光谱之间的关系模型，以期为梨树叶片钾素快速诊断和合理施用钾肥提供依据。

1　材料与方法

1.1　试验材料

样品于2011年7月19日采自江苏省宜兴市新街镇紫云山梨园，共采集150个新鲜叶片样本，包括翠冠和黄花梨两个品种。随机多点取样。每棵树按东、南、西、北4个方位，采集冠层外围当年生枝条中部叶片。将样品迅速装入保鲜袋、封口，放入冰盒内带回实验室测定。

1.2　光谱采集

利用美国ASD公司生产的FieldSpec 3便携式地物光谱仪测定叶片光谱。波段值为350～2 500 nm，其中350～1 000 nm光谱采样间隔为1.4 nm，光谱分辨率为3 nm；1 000～2 500 nm光谱采样间隔为2 nm，光谱分辨率为10 nm，输出波段数为2 151个(重采样间隔为1 nm)。利用植被探头和参考白板测定

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叶片光谱。为使测定的光谱能涵盖整个叶片，每个叶片采集中部叶脉对称的 2 个点，每点记录 10 条光谱，以其平均值作为该样品的光谱反射率。

1.3 光谱预处理与模型构建

利用光谱仪自带处理软件 ViewSpec 对原始光谱数据导出和转换，再将原始光谱(OS)、一阶微分光谱(FDS)、二阶微分光谱(SDS)、倒数光谱(1/R)、对数光谱(Log R)和倒数的对数光谱(Log(1/R))等数据导入 Unscrambler 9.7 中处理。利用该软件对光谱数据进行移动平均平滑(MAS)、Savitzky-golay 平滑(S-G)、多元散射校正(MSC)、归一化(Normalize)、消噪(Noise)、基线校正(Baseline)、变量标准化(SNV)等预处理，以减少光程变化、样品粒度和粗糙度、光谱平移和旋转对光谱产生的影响。同时，运用 Unscrambler 9.7 中偏最小二乘法(PLS)功能构建模型，默认最大主成分数为 20，该软件能自动输出最优主成分下的 PLS 模型，因此不会出现模型过拟合或拟合不足的情况。模型采用内部验证对其性能进行评价，由模型校正相关系数(*Rc*)、交互验证相关系数(*Rcv*)、校正均方根误差(*RMSEC*)和交互验证均方根误差(*RMSECV*)进行评价。模型的相关系数越高，*RMSEC* 和 *RMSECV* 越小，且越接近，则模型的预测能力越强。*RMSECV* 可按下式计算：

$$RMSECV=\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(y_i-\hat{y}_i)^2}$$

其中，y_i 和 $\hat{y}_i$ 为交互验证集第 i 个样本氮含量的预测值和实测值；n 为交互验证集中样本数。

1.4 钾素含量测定

叶片测定完光谱后，于 105℃恒温杀青 30 min，70℃下烘至恒重，用研钵磨碎装入自封袋备用。采用 H_2SO_4-H_2O_2 法消煮，火焰光度计测定含钾量。

2 结果与讨论

2.1 梨树叶片钾素可见/近红外光谱特征

图 1 是部分梨树叶片样本原始光谱曲线图。在整个光谱区域内，光谱的趋势都是大致相同的，这是由梨树叶片的物质组成基本相同决定的，但是在某一波长处各样本的反射率大小存在差异；此外，各样本的波峰和波谷也不全在同一波长处，说明叶片内部组成存在差异。在可见光区域(350～680 nm)，由于色素(叶绿素、类胡萝卜素等)对光的强烈吸收，透射光和反射光很少，所以反射率很低。尤其在是 460 nm 的蓝光区域和 680 nm 的红光区域形成两个吸收谷；叶绿素对绿光的吸收较弱，所以在 560 nm 处形成一个中等反射峰，反射率一般在 0.1～0.3 之间；而在 680～750 nm 区域内，反射率急剧上升，曲线陡而接近于直线的形状，其间有一个拐点，即反射率对波长的二次微分等于零，该拐点所对应的波长被称为“红边”，红边的变动只与叶片组成密切相关。750～1 300 nm 区域是近红外高反射平台，光曲线高且略有波动，吸收很少，反射率较高，一般在 0.6 以上。1 360～1 510 nm 和 1 850～2 100 nm 波段是水和二氧化碳的强吸收带，由于梨树新鲜叶片存有大量水分和二氧化碳，因此在 1 430 nm 和 1 920 nm 附近出现明显的低谷，导致在这两个吸收谷之间出现两个反射峰，分别位于 1 650 nm 和 2 220 nm 附近。

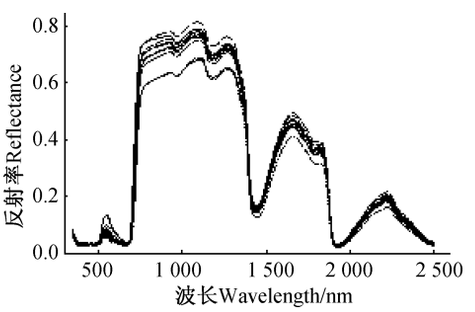

图 1 梨树叶片样本原始光谱曲线图

Fig. 1 Visible and near infrared spectra of pear leaves

2.2 梨树叶片钾素状况

据 K-S 算法将 150 个样品随机分为建模集(n=120)和验证集(n=30)两组。梨树叶片中钾含量的统计值如表 1 所示，建模和验证样本的钾含量均包含了较大的变异，并且验证样本的范围在建模样本的范围内，这有益于所建模型的预测能力。

表 1 7 月份梨树叶片钾素状况

Table 1 Statistics for Potassium content of pear leaves in July (g/kg)

	样本数 No. of samples	最小值 Min./(g/kg)	最大值 Max./(g/kg)	平均值 Mean/(g/kg)
全部 All	150	6.13	17.25	11.77±2.22
建模集 Calibration	120	6.13	17.25	11.66±2.22
预测集 Validation	30	7.76	17.11	12.21±2.20

2.3 梨树叶片钾含量预测模型的建立

2.3.1 不同光谱波段对模型精度的影响

图 2 是不同波段处梨树叶片钾含量与光谱反射率的相关系数曲线图。从图上可以看出，梨树正叶片的钾含量与光谱反射率在全波段(350～2 500 nm)光谱区域内主要成正相关，在少部分波段成负相关。正相关表明，在此波段内光谱反射率随钾含量的增加而增大；负相关表明，光谱反射率随钾含量的增加而减小。根据梨鲜叶钾含量和反射光谱的相关性分析，选择相关系数达极显著水平下的 3 个波段建立 PLS 模型，波段 1：513～623 nm；波段 2：692～713 nm；ALL：350～2 500 nm。

表 2 是不同光谱波段的偏最小二乘法模型结果，可以看出全波段的建模效果最好，波段 513～623 nm 的建模效果最差，因此本文选用全波段建模。

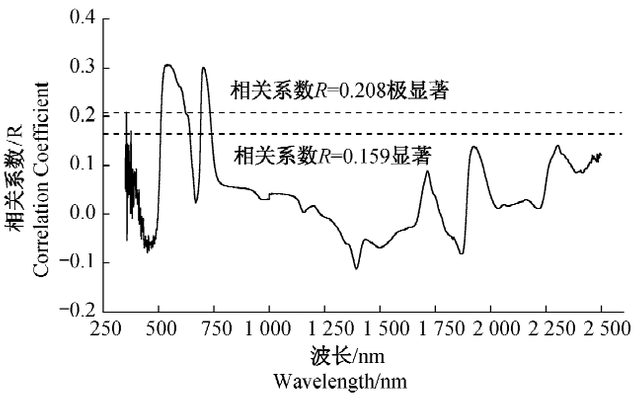

图 2 不同波段处梨叶片钾含量与光谱反射率的相关系数曲线

Fig. 2 Correlation between potassium content and spectral reflectance under different wave bands in pear leaves

表 2 不同光谱波段的 PLS 模型结果

Table 2 Modeling results of PLS with different spectrum wave bands

波段 Spectrum	主成分数 Factor number	建模集 Calibration		内部交叉验证 Internal cross-validation	
		R^2c	*RMSEC*	R^2cv	*RMSECV*
1	5	0.391 6	1.722 7	0.163 5	1.832 3
2	7	0.434 9	1.660 3	0.300 2	1.859 5
1＋2	8	0.414 6	1.689 7	0.29	1.870 3
ALL	15	0.852 8	1.270 7	0.679 3	1.257 5

2.3.2 不同光谱形式对模型精度的影响

不同的光谱形式建立的模型精度也不同，从而改变光谱的建模效果。从表 3 可以看出，原始光谱形式建立的 PLS 预测模型精度最高，因此下文中只采用原始光谱形式进行预处理。

表 3 不同光谱形式的 PLS 模型结果

Table 3 Modeling results of PLS with different spectrum style methods

光谱形式 Spectrum style	主成分数 Factor number	建模集 Calibration		内部交叉验证 Internal cross-validation	
		R^2c	*RMSEC*	R^2cv	*RMSECV*
ALL_FDS 3	4	0.530 9	1.512	0.345 9	1.807
ALL_FDS 9	12	0.840 5	0.882	0.552 0	1.493
ALL_FDS 3＋LOG R-1	4	0.484 9	1.585	0.295 3	1.862
ALL_LOG R-1	7	0.572 3	1.444	0.405 0	1.718
ALL_R	15	0.852 8	1.271	0.679 3	1.257
ALL_SDS 3	4	0.380 6	1.738	0.213 3	1.972
ALL_SDS 9	8	0.747 9	1.109	0.484 4	1.601

2.3.3　不同光谱预处理对模型精度的影响

表 4 为不同光谱预处理类型的 PLS 建模结果。不同预处理光谱的校正和交互验证的相关系数绝大多数在 0.67～0.89 之间，达到了极显著相关水平（$N=120$，$r_{0.01}=0.232$），从 *RMSEC* 和 *RMSECV* 值尽量小且大小接近的原则考虑，原始光谱经 S-G 平滑（窗口大小为 3）后建立的模型最佳，PLS 模型交叉验证结果如图 3。此时，R^2c 和 R^2cv 分别为 0.873 和 0.723 3，*RMSEC* 和 *RMSECV* 分别为 0.039 和 0.137。

表 4　不同光谱预处理的 PLS 模型结果

Table 4　Modeling results of PLS with different spectrum pretreatment methods

光谱预处理 Spectrum style	主成分数 Factor number	建模集 Calibration		内部交叉验证 Internal cross-validation		预测 prediction	
		R^2c	*RMSEC*	R^2cv	*RMSECV*	R^2p	*RMSEP*
OS	15	0.852 8	1.270	0.679 3	1.257	0.580 6	1.406
MAS(3)	13	0.808 7	0.966	0.686 6	1.251	0.639 4	1.304
SGS(3)	17	0.872 7	0.787 9	0.722 7	1.171	0.679 1	0.825
Normalize	14	0.853 1	0.846 5	0.706 6	1.208	0.616 3	1.345
MSC	13	0.848 4	0.859 8	0.696 3	2.230	0.593 0	1.385
Noise	4	0.897 7	0.706 3	0.272 2	1.899	0.220 3	1.918
Baseline	14	0.850 7	0.853 3	0.700 2	1.219	0.573 2	1.419
SNV	13	0.850 9	0.852 7	0.700 0	1.220	0.608 7	1.358

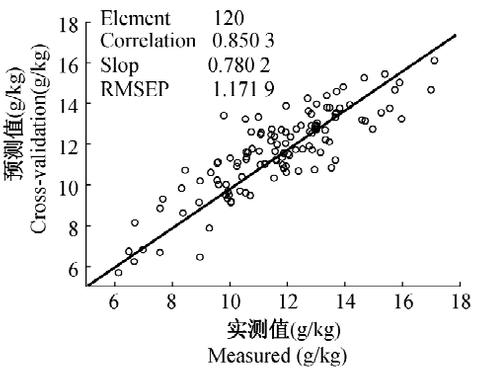

图 3　梨树叶片钾含量交叉验证结果

Fig. 3　Plotting of K content of pear leaves between predicted results and experimental results

2.4　PLS 回归模型验证的结果

用此模型对已测定全钾含量的 30 个样品进行预测，剔除两个异常样本后，所得预测结果如图 4 所示。模型预测决定系数（R_p^2）和预测均方根误差（*RMSEP*）分别为 0.679 和 0.826，预测值的平均相对误差为 6.81%，表明该模型性能可以满足实际应用。因此，可以用经 S-G(3)校正方法预处理的原始光谱构建梨树叶片钾含量的预测模型。

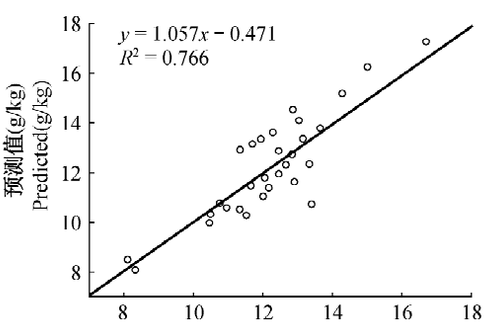

图 4　30 个未知样本的预测结果

Fig. 4　Prediction of 30 samples in validation set by PLS model

3　讨论

在植物体中，钾主要以离子状态存在，具有很强的移动性，并且钾在果树生长发育、开花结实的生命过程中具有多种生理作用和功能。钾素虽然不能直接影响光谱的吸收反射，但其可以通过影响叶片中的化合物间接地影响光谱的吸收反射[10]，如图 5 所示。从上文图 2 可以看出，钾含量与 420～500 nm 波段反射率成负相关，表明在此波段光谱反射率随着钾含量的增多有相反的趋势。钾含量的增多，不仅有利于提高叶绿素合成酶活性和叶绿素合成，同时也有利于叶绿体基粒的形成[11]，提高 420～500 nm 波段光的吸收和光合效率，这与王珂等[12]对水稻冠

层不同钾营养水平下的反射光谱特征研究结果一致。研究表明，钾素有利于提高植物叶片中蔗糖和淀粉的含量[13-14]，而蔗糖和淀粉在1 230～1 670 nm波段中具有多处吸收峰[15]，因此钾素含量与1 230～1 670 nm波段的反射率成负相关。另外，由于钾素含量影响了叶片含水量和气孔开放，而水分和二氧化碳在1 390 nm具有强烈的吸收，因此钾素含量与光谱反射率在1 390 nm处有较强的负相关性[16]。

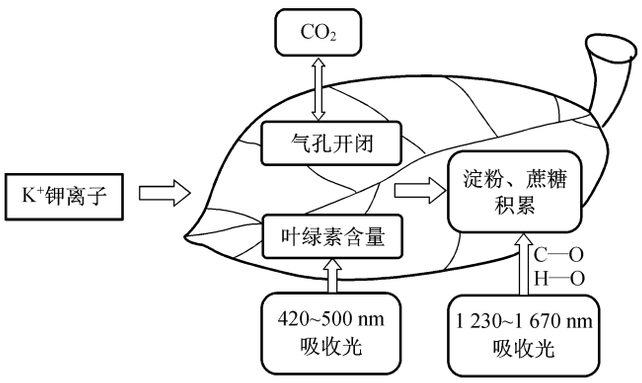

图5　钾离子对叶片可见/近红外光吸收的影响

Fig. 5　Effect of potassium on leaf which has a absorption for visible/near infrared spectra

由于光谱仪本身的性能、采集光谱的环境条件、基线漂移和光散射等不利因素的影响，需对原始光谱进行预处理。易时来[17]采用二阶微分光谱和多元散射校正相结合的光谱预处理方式得到了最佳柑橘钾素PLS预测模型。邢东兴[19]通过在苹果上的研究发现，波长间隔为5 nm时一阶微分光谱的PLS预测模型最佳。由于钾素不能直接对光谱做出反应，只能通过影响其他化合物进而间接地影响光谱，所以同一样本中钾素预测模型一般不如氮素预测模型的精确度高。Alastair[20]通过在草坪上的研究发现，氮和钾预测模型的决定系数R^2均为0.77，但两个模型的RER分别为9.32和6.56（RER，一种评价模型精度的指标，其值越大，模型的精度越高）。Liu[18]记录了油菜叶片的氮和钾预测模型决定系数R^2分别为0.95和0.86，RMSEP分别为0.145和0.179。

本文采用Unscrambler 9.7处理实验数据，通过对150个样品进行分析。在利用偏最小二乘法（PLS）及完全交互验证建立模型时，选择软件默认的最大主成分数20进行模型拟合，该软件能自动输出最优主成分下的PLS模型，因此不会出现模型过拟合和拟合不足的情况。通过对其6种光谱形式的7种预处理方式分析发现，原始光谱经S-G(3)校正方法预处理后，主成分17时，模型最佳。利用该模型对验证集的中的30个样本进行预测，预测的平均相对误差为6.81%，实测值与预测值的相关系数r为0.875，研究结果为田间开展梨树氮素营养无损诊断奠定了基础。

在光谱采集中，本文利用植被探头和叶片夹持器共同完成，内置光源，这样能为叶片光谱采集提供稳定的工作环境。本文采集的梨树品种只包括翠冠和黄花梨，因此本文的模型不一定很好地适用于其他品种的梨树。为了完善模型，后期的工作将会增加不同年龄以及不同品种的梨树叶片进行分析，以提高模型的适用性。

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Fast determination of potassium content in fresh pear leaves using visible-near infrared spectroscopy technique

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Abstract: The objective of this present research was to study the potential of visible-near infrared reflectance spectroscopy (Vis/NIR) for non-destructive determination of potassium (K) content in fresh pear leaves with an ASD FieldSpec 3 spectrometer. All the samples were divided randomly into two groups, one with 120 samples as the calibration set, and the other with 30 samples as the validation set. Different spectra wave bands, spectra preprocessing in different way and different spectra styles were used in the prediction model of K content. The results showed that, after the preprocessing of original spectral with the whole wave band plus S-G(3) smoothing, the prediction model, calibrated with 17 principal component factors, has the best performance by the partial least squares (PLS) regression, in which the determination coefficient (R^2) of calibration and cross-validation is 0.7227 and 0.6791, respectively, and the root mean square error of cross-validation (RMSECV) is 1.171. Testing of the best PLS model with 30 samples in the validation set showed that the predicted average relative error is 6.81%. Therefore, it can be concluded that Vis/NIR has a huge potential for the determination of total K content in fresh pear leaves in a rapid and nondestructive way.

Key words: Nitrogen content, pear leaves, visible-near infrared spectroscopy, partial least squares

不同基因型甘蔗钾吸收动力学研究[①②]

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摘　要：采用水培方法研究了4个不同基因型甘蔗（YT60、YT55、ROC22、BC2-32）根系钾离子的吸收动力学参数，结果表明YT55最低养分浓度临界值最低（C_{min}值最小），对钾离子的亲和力最高（K_m值最小），而BC2-32的C_{min}值最大，对钾离子的亲和力最低（K_m值最大）。I_{max}在各基因型甘蔗之间差异不显著。

关键词：甘蔗；钾；吸收动力学；基因型；养分高效

中图分类号：Q945.12

甘蔗是我国最重要的糖料作物。甘蔗是喜钾作物，钾能促进甘蔗的光合作用及体内碳水化合物、蛋白质和纤维素的合成，参与水分利用、碳水化合物运输等过程。最初人们认为根对养分吸收的动力学过程可以用描述酶促动力反应的米氏方程模拟，这开创了植物营养吸收动力学的先河[1]。1974年Claassen和Barbe根据植物根系的养分吸收特性对米氏方程进行了修正，建立了根系养分吸收动力学方程[2]。其中有3个参数用来定量表征植物对养分吸收的特征。I_{max}为最大吸收速率；K_m为米氏常数，表示根系对养分离子的亲和力；C_{min}为根系能够吸收的介质最低养分浓度。植物养分离子的吸收动力学参数可以表示根系吸收离子的效率[3]，通过测定动力学参数可以了解根系对养分离子的吸收特性。高I_{max}表示在高浓度环境中迅速吸收营养，低K_m表示亲和力高，吸收效率增加[4-6]。

已有的研究表明，同一作物不同基因型或者品种在对钾离子吸收利用等方面存在显著差异，比如烟草[7]、香蕉[8]、小麦[9]、水稻[10]和棉花[11]等。因此，可以筛选利用吸钾能力强及对土壤和肥料中钾利用效率高的作物品种，以适应低钾的土壤。这不仅可以节省钾肥，以缓解钾肥的短缺，降低生产成本，还可为耐低钾品种的遗传育种提供种质资源和理论基础。在甘蔗这种作物上只有万美亮等做过磷的吸收动力学研究[12]，钾的研究还未见报道。本研究选取不同基因型甘蔗苗期材料在低钾情况下（0.3 mmol/L）对其钾离子吸收动力学进行初步探索。

1　材料与方法

1.1　试验材料

以粤糖60（YT60）、粤糖55（YT55）、新台糖22（ROC22）、斑茅甘蔗杂交后代（BC2-32）的苗期材料为试材。先将各个基因型组培苗从培养基中取出洗净，在沙中假植成活后，再转入1/2霍格兰营养液，培养3周左右待组培苗适应液体培养环境后，挑选生长一致的甘蔗苗进行试验。

1.2　试验方法

将液培3周的甘蔗苗从营养液中取出，在无钾霍格兰营养液中饥饿48 h后，各基因型分别取6株用纯水洗净后再用0.2 mmol/L硫酸钙溶液浸洗3次，吸干水分后转入2 L广口黑色试剂瓶中，每瓶1株，瓶中装有吸收液，其组分为0.3 mmol/L氯化钾＋0.2 mmol/L硫酸钙[13]，用海绵将幼苗固定在瓶口，放置在恒温光照培养箱中进行试验，试验条件为白天14 h，夜晚10 h，培养温度25℃，在0、0.5、1、2、3、4、5、6、7、8、9、10、11、12 h后分别取2 mL营养液，每次取样后用纯水补充至原来的体积，使吸收液的体积保持不变。并且每次取样加水后对试剂瓶称重，用来扣除蒸发减少的水分。营养液中钾离子含量用火焰光度计测定。

1.3　数据处理

将试验收集样品的时间值及该时间测得的样品K^+浓度的成对数据输入计算机，拟合出一元二次方

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程 $y=ax^2+bx+c$（x 代表时间，y 为该时间溶液中的 K^+ 浓度），得离子消耗曲线方程，将不同时间值 x 代入其导数方程 $y=b+2ax$，求得的负导数（$-y$）即为该时间的 K^+ 消耗速率。I_{max} 用每小时每克鲜重根吸收 K^+ 的微摩尔钾离子数表示。公式如下：

$$I_{max}=b\times V/\ RFW(RDW)$$

$$K_m=b^2/16a-b^2/4a+c$$

$$C_{min}=b^2/4a-b^2/2a+c$$

式中：$RFW(RDW)$ 是根鲜（干）重（g）；I_{max} 是钾离子最大吸收速率[μmol/(g·h)]；K_m 是当钾离子吸收速率达到最大吸收速率一半时溶液中的 K^+ 浓度（μmol/L）；C_{min} 是植株根系吸收培养液中 K^+ 的最低临界浓度值。

2 结果与分析

2.1 不同基因型甘蔗钾离子吸收动力学特征分析

植物养分离子的吸收动力学参数可以表示根系吸收离子的效率，通过测定动力学参数可以了解根系对养分离子的吸收特性。吸收液中的 K^+ 浓度与时间的关系可以用一元二次回归方程拟合，通过回归方程计算 4 个基因型甘蔗吸收钾离子的动力学特征参数。表 1 列出了各基因型甘蔗钾离子吸收的动力学方程，从相关系数可以看出，拟合的程度都比较高，能够反映出溶液中钾离子实际消耗的变化情况。

表 1 不同基因型甘蔗钾离子吸收动力学方程

Table 1 Kinetic equations of potassium absorption of different sugarcane genotypes

基因型	拟合吸收动力学方程	相关系数
YT60	$y=2.664x^2-55.014x+287.50$	0.994 3
YT55	$y=2.146x^2-48.612x+289.61$	0.996 2
ROC22	$y=2.306x^2-49.891x+278.13$	0.990 5
BC2-32	$y=2.228x^2-49.639x+283.94$	0.994 3

2.2 不同基因型甘蔗钾离子吸收动力学参数分析

根据钾离子消耗曲线拟合的方程，我们用根系的鲜重和干重两种量纲分别计算出各动力学参数（见表 2、表 3）。首先以鲜重计算，从表 2 可以看出，各个基因型甘蔗的不同参数都有一定差异，只是不同参数的差异大小不同。各基因型甘蔗对钾离子的最大吸收速率（I_{max}）的差异很小，都很相近；K_m 值的高低排序依次为：BC2-32＞YT60＞ROC22＞YT55，K_m 值越高，亲和力越小，因此 YT55 对钾离子的亲和力高于其他基因型。4 个基因型甘蔗的 C_{min} 值差异比较大，高低排序为 BC2-32＞ROC22＞YT60＞YT55，其中 BC2-32 的 C_{min} 最高，是最低的 YT55 的 7.5 倍，由此也说明 YT55 更耐低钾胁迫。由 α 值可知，YT55 的吸收能力要稍高于 BC2-32，4 个基因型相差并不大，说明 4 个基因型甘蔗的根系实际吸收能力相差不很大。

表 2 不同基因型甘蔗钾离子吸收动力学参数（用根鲜重计算）

Table 2 Kinetic parameters of potassium absorption of different sugarcane genotypes (calculated by the root fresh weight)

基因型	I_{max}(RFW)[μmol/(g·h), FW]	K_m(μmol/L)	C_{min}(μmol/L)	$\alpha=I_{max}/K_m$	$\beta=(K_m\times C_{min})^{1/2}$
YT60	25.87	77.16	3.31	0.32	15.99
ROC22	25.64	76.20	8.26	0.32	25.09
BC2-32	24.00	84.29	15.71	0.28	36.39
YT55	25.13	73.63	2.61	0.34	13.86

注：RFW，root fresh weight，根系鲜重。

表 3 不同基因型甘蔗根系钾离子吸收动力学参数（用根干重计算）

Table 3 Kinetic parameters of potassium absorption of different sugarcane genotypes (calculated by the root dry weight)

基因型	I_{max}(RDW)[μmol/(g·h), FW]	K_m(μmol/L)	C_{min}(μmol/L)	$\alpha=I_{max}/K_m$	$\beta=(K_m\times C_{min})^{1/2}$
YT60	120.90	77.16	3.31	1.57	15.99
ROC22	112.73	76.20	8.26	1.48	25.09
BC2-32	108.97	84.29	15.71	1.29	36.39
YT55	118.10	73.63	2.61	1.60	13.86

注：RDW，root dry weight，根系干重。

表 3 是根据根系干重计算得出的参数，相比而言，只有 I_{max} 和 α 值的大小与鲜重计算的结果不一样，因为另外两个参数不涉及根系重量。不难看出，利用干重计算出的参数，能更好地把 4 个基因型的 I_{max} 和 α 值区分开来。

以往将离子吸收动力学参数 I_{max}、K_m、C_{min} 作为耐土壤养分贫瘠能力的评价参考指标。然而也有一些营养贫瘠耐受性研究表明，这些指标反映的情况有时候会与实际不一致。为了克服这种矛盾，蒋廷惠提出了 β 值[14]的概念，定义 $\beta=(K_m\times C_{min})^{1/2}$，由 β 值的大小可对植物耐低养分能力进行排序，β 值越低，植物耐低养分能力越高。根据此公式可以计算出 4 个基因型的 β 值，如表 2、表 3 所示。可以看出，β 值在 4 个基因型中差异比较明显，大小排序依次为：BC2-32＞ROC22＞YT60＞YT55，与 C_{min} 排序一致。最高的 BC2-32 与最低的 YT55 相比，两者相差 2.6 倍。因此说明 YT55 和 YT60 的耐低钾能力相对较高。

综合以上各个参数指标可以得知，YT55 号对钾离子的亲和力最高，耐低钾能力最高，所以该基因型在 4 种基因型中属于相对钾高效（耐低钾）基因型。

3 讨论与结论

从 Epstein 开创植物根系养分吸收动力学的先河以来，关于植物对养分吸收动力学的研究就一直不断，动力学方程以及相关参数也不断得到修正。在实验取材的方法上，以往采用离体根用不同浓度的养分系列进行短期的吸收试验求出吸收动力学参数。虽然这种方法也能取得有一定参考价值的结果，但也存在许多不足之处，如离体根与整株植物的吸收特性是有差别的，测定时要用很多植株样品，必然存在较大的取样差异，增大试验误差。为了克服这些缺陷，Claassen 和 Barbe 提出了利用完整植株进行离子吸收动力学研究的耗竭法[2]，即采用含有不同离子的营养液让植株进行长时间的吸收消耗，根据养分随着时间的浓度变化，求出离子变化的曲线方程，从而计算出吸收动力学的各个参数。由于甘蔗是高生物量植物，从苗期开始个体差异就开始显现出来，如果采用浓度梯度法进行动力学研究，必需消耗大量的材料，从而增加了试验误差，降低了结果的准确性。本研究采用耗竭法对不同基因型甘蔗苗期材料进行钾离子吸收动力学研究，长期对营养液中钾离子浓度进行测定，根据监测结果，发现在 10 h 以后，营养液中的钾离子浓度就降低到非常低的水平，在 24 h 后，溶液中的钾离子浓度几乎不能检测出来。这一方面说明甘蔗对钾的需求量很大，所以能将溶液中钾耗竭尽，另一方面也说明即使在较低的钾离子浓度下，甘蔗也能吸收利用溶液中的钾离子，而且速率很快。

植物根系对外界养分的吸收有高亲和、低亲和两种机制。根据外界环境的钾离子浓度，在低浓度情况下一般为高亲和机制起主导作用，而在高浓度条件下则为低亲和机制起主导作用。高亲和力吸收为主动机制，因为吸收是逆 K^+ 电化学势梯度，可能与 K^+：H^+ 或 K^+：Na^+ 的协同运输相关。低亲和力吸收为经由 K^+ 选择性通道的被动运输。后来的研究表明[15]，无论外界 K^+ 浓度为何，两个系统要开始工作都必须要先由 H^+ 外排系统建立的 ΔpH 达到一定值。只有当 ΔpH 达到一定值时，才会激发高亲和系统先开始运作，并且不依赖外界钾离子浓度，当高亲和系统达到饱和吸收而且外界 K^+ 浓度饱满（一般认为 1 mmol/L 以上），和 ΔpH 能够激励低亲和系统运作时，吸收是双相可饱和模式。本研究采用的钾离子浓度为 0.3 mmol/L，是根据甘蔗苗期对钾的需求而设定的。在水培实验中，0.1 mmol/L 的钾离子浓度仍然过低，导致甘蔗苗出现缺钾症状，另外在钾浓度过低的情况下，溶液中钾离子会被甘蔗迅速吸收掉，不利于长时间观察溶液中钾离子浓度的变化，加上甘蔗对钾素的需求量大，因此我们适当地提高了钾离子的浓度。

植物对养分的吸收受到多方面因素的影响，如光照、水分、pH、通气和肥料种类等，以及本身基因型的影响，而作物不同基因型对养分吸收和利用效率之间的差异则主要是受作物本身基因型特性如根系形态、钾离子通道基因等影响[13]。由于众多因素都影响着吸收动力学参数，因此我们很难全面考虑所有因素，探索不同条件下的吸收动力学参数的变化，因此，选取一定时期的材料，在一定的环境条件下进行试验，得到的结果也具有一定参考意义。若要对甘蔗钾营养效率做出比较客观的判断，还需与土壤试验结合才行，土壤中的钾有不同形态，作物对其利用也存在差异[16]。本研究主要是从根系吸收动力学方面来研究不同基因型甘蔗苗期材料对钾养分吸收效率的差异，在 4 个基因型中 YT55 属于相对钾吸收高效型，而 BC2-32 属于相对钾吸收低效型。本试验结果对于甘蔗苗期大田钾肥施用也具有一定的参考价值。

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Preliminary study on potassium ion uptake kinetics by different genotype sugarcane seedling

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Abstract: We used a hydroponic experiment to research the kinetic parameters of potassium of four genotypes of sugarcane(YT60, YT55, ROC22, BC2-32). The kinetic parameters were different among the four genotypes. YT55 proved to be the most K efficient with the lowest K_m and C_{min}, while BC2-32 was the least efficient. There was no difference in I_{max} among these four genotypes.

Key words: Sugarcane, potassium, kinetic parameters, genotype, nutrient efficient

不同钾素水平对水稻不同部位含钾量的影响①②

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摘　要：通过盆栽试验研究了不同供钾水平下水稻各叶位的含钾量变化。结果表明，水稻含钾量随生育期的推进逐渐下降，下降幅度达 69%～75%。水稻含钾量与生育期和土壤供钾水平有关：分蘖期不同叶位的鞘、叶含钾量由上至下大幅下降，鞘与叶的含量钾比值均大于 1，且比值随叶片含钾量的增加而上升。拔节期钾素水平由低至高，叶位间鞘、叶含钾量由上至下降低的趋势减弱；鞘与叶含钾量比值为 0.26～1.49，且随叶片含钾量的增加而增加。齐穗期，低钾水平下，叶位间鞘、叶含钾量由上至下降低，高钾水平则相反；鞘叶含钾量比值为 0.36～1.33。成熟期，秸秆的含钾量范围为 2.8～22.9 g/kg，随钾素水平增加而增加；籽粒的含钾量约为5.0 g/kg。综合不同时期含钾量变化规律可以看出：水稻分蘖期，上部叶是钾素优先积累的部位，而叶鞘更是钾奢侈吸收储存的部位；齐穗期以后，钾奢侈吸收主要是积累到了中下部叶和叶鞘中。由于水稻植株钾含量因不同生育期、不同部位而变化很大，根据植株钾含量来进行营养诊断需要考虑取样时期、取样部位，而鞘、叶钾含量比值可能有较好的指示作用。

关键词：水稻；钾素水平；含钾量；鞘叶比

中图分类号：S153

钾是植物生长过程中必需的大量营养元素之一。植物吸钾量较高，一般高于吸磷量，低于吸氮量，有时植株吸钾量也会高于吸氮量[1-3]。我国农田土壤复种指数较高，随农作物产量的增加，氮、磷肥用量也大幅度增加，多数土壤中作物带走的钾量也在增加。在秸秆还田率不高、有机肥用量不足，以及化肥钾用量也不高的情况下，土壤钾素入不敷出，耗竭加剧[4-5]。不少研究表明钾不足已成为限制作物高产的主要因子之一，施钾对多种作物具有增产作用[10-12]。水稻是我国的主要粮食作物，需钾量较大，而且主产水稻的我国南方主要土壤供钾潜力低，这也导致水稻缺钾容易发生[6-9]。因而了解水稻钾素营养特性、合理施用钾肥对水稻高产稳产意义重大。

以往的研究表明，各种植物的含钾量常因作物生育期及土壤供钾水平不同而异[13-18]。水稻植物钾含量也同样受多种因素的影响。有研究表明水稻各叶位的含钾量由上至下逐渐降低[2]，供钾水平较低时，钾素在植株体内的含量存在明显的梯度，而在钾素供应充足时，叶位间含钾量差异减小[19-20]。已有的关于水稻植株钾含量方面的研究，主要针对某一时期或主要部位，较为系统和详细的水稻植株钾含量变化规律目前尚未见报道。本研究拟通过室内盆栽试验，研究我国不同种类土壤上，钾供应水平对水稻植株不同器官钾含量动态变化的影响，以期深入了解水稻植株钾含量的变化特征，为水稻植株钾素诊断及钾营养调控提供依据。

1　材料与方法

1.1　供试材料

供试土壤分别采自安徽芜湖、湖南望城、江苏常熟、湖南怀化、重庆潼南、湖北潜江、湖北蕲春、安徽怀宁、福建漳州和广西北流，土壤样品经自然风干、过筛，土壤基本理化性质见表 1。供试水稻品种为汕优 63。

表 1　土壤基本理化性质

Table 1　Physiochemical properties of soil tested

采集地	速效钾(mg/kg)	缓效钾(mg/kg)	四苯硼钠钾(mg/kg)	有机质(g/kg)	pH	CEC(cmol/kg)
安徽芜湖	61.3	401	226	22.8	5.42	16.41
湖南望城	77.8	247	211	33.8	5.58	12.39

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续 表

采集地	速效钾(mg/kg)	缓效钾(mg/kg)	四苯硼钠钾(mg/kg)	有机质(g/kg)	pH	CEC(cmol/kg)
江苏常熟	66.7	422	259	43.4	6.01	14.15
湖南怀化	95.3	321	279	34.1	7.64	13.21
重庆潼南	95.3	571	435	13.9	7.55	19.52
湖北潜江	121.9	288	259	39.1	5.98	8.16
湖北蕲春	103.8	304	283	28.5	5.82	10.58
安徽怀宁	132.0	325	311	30.2	5.64	20.44
福建漳州	156.4	440	405	29.6	5.89	13.37
广西北流	347.6	476	573	27.7	6.13	22.31

1.2 试验方法

1.2.1 盆栽试验设计

将采集的土样自然风干、过筛，每盆(直径为 23 cm，高为 25 cm)装土 5 kg，插秧 7 穴，每穴 3 棵苗。每个土样设施钾(+K)及不施钾(CK)两个处理，每个处理设 3 个重复。施钾处理的钾肥用量根据原始土壤速效钾含量的高低来定，速效钾含量低于 100 mg/kg 的 5 个土壤(安徽芜湖、湖南望城、江苏常熟、湖南怀化、重庆潼南)施钾(K_2O)量为 0.15 g/kg，速效钾含量高于 100 mg/kg 的 5 个土壤(湖北潜江、湖北蕲春、安徽怀宁、福建漳州、广西北流)施钾(K_2O)量为0.1 g/kg。每 kg 土施 0.15 g N、0.1 g P_2O_5，氮肥按 4∶3∶3 做基肥、分蘖肥、穗肥 3 次施用，磷、钾肥一次性基施。水稻生长期间根据天气情况及时补充蒸馏水。

1.2.2 样品采集与测定

分别在分蘖期(移栽后 21 d)、拔节期(移栽后 45 d)、齐穗期(移栽后 78 d) 3 次采集水稻植株样品，每盆采集一穴水稻植株。各时期样品采集后根据部位分样，分为茎、穗、1 叶、2 叶、3 叶、4 叶、1 鞘、2 鞘、3 鞘、4 鞘，其中 1 叶、2 叶、3 叶、4 叶、1 鞘、2 鞘、3 鞘、4 鞘表示由上至下数第 1、2、3、4 片叶及第 1、2、3、4 片叶对应的叶鞘。成熟期(移栽后 112 d)整盆样全取，并将籽粒与秸秆分开。分好的样品分别风干、称重，磨细供分析用。植株钾素测定用 H_2SO_4-H_2O_2 消煮，稀释后用火焰光度计测定。

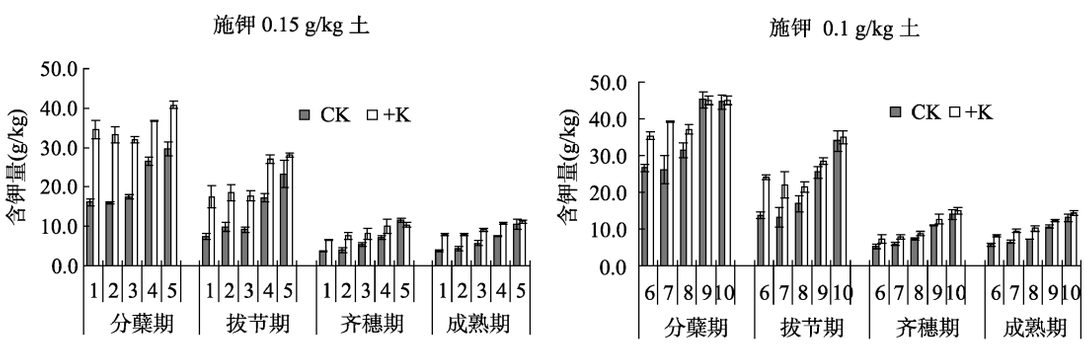
1.3 数据分析与统计

有关数据分析与统计采用 Excel、SPSS 17.0 软件。

2 结果与分析

2.1 钾素水平对各生育期水稻含钾量的影响

由于不同土壤的供钾能力不同，不同土壤上水稻植株的含钾量具有差异。由图 1 可知，在不施钾处理中，各土壤上水稻的含钾量基本随土壤速效钾含量的增加而增加。施钾后土壤上的水稻含钾量都有所升高，但各土壤的升高幅度不同。由图 1 可知，同一施钾水平，不同土壤上水稻植株的含钾量升高幅度不同，如施钾(K_2O)量为 0.15 g/kg 的土壤上，钾素水平低的芜湖、望城、常熟的水稻含钾量升高幅度较高，而潼南、怀化土壤的含钾量升高幅度较低；施钾(K_2O)量为 0.1 g/kg 的土壤上，钾素水平相对较低的潜江、蕲



(1、2、3、4、5、6、7、8、9、10 分别表示安徽芜湖、湖南望城、江苏常熟、湖南怀化、重庆潼南、湖北潜江、湖北蕲春、安徽怀宁、福建漳州、广西北流 10 个土样)

图 1 各种土壤上水稻钾素效应

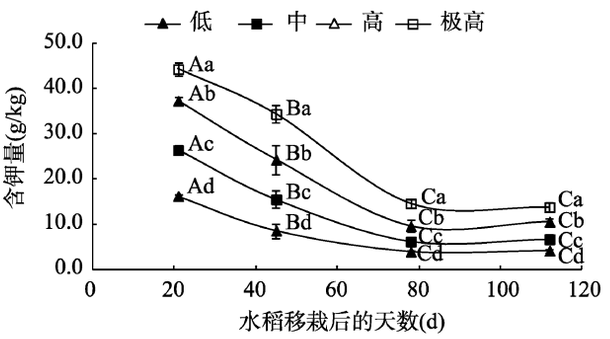
Fig. 1 Effet of potassium application on rice K content with different soils

春土壤施钾后水稻含钾量升高幅度较大，钾素水平相对较高的怀宁、漳州、北流土壤上施钾后水稻含钾量的升高幅度较低。根据图 1 中各生育期土壤施钾处理与不施钾处理时水稻含钾量的差异大小可知，施钾对分蘖期、拔节期的水稻含钾量影响较大，而对齐穗期、成熟期的含钾量影响相对较小。可见钾肥使用在钾素水平较低的土壤以及在生育前期效用更大。

2.2 水稻整株含钾量动态变化

根据这 10 种土壤上、20 个处理的土壤钾素水平及水稻植株含钾量的高低，将土壤钾素水平分为 4 种情况，用低、中、高、极高表示。低钾为望城、芜湖土壤不施钾处理；中钾为怀化、潜江不施钾处理；高钾为怀宁、怀化施钾处理；极高钾为北流施钾及不施钾处理。以下的分析都将按该方法进行分析，以确定不同钾素水平对水稻含钾量的影响。

植株的含钾量与植株所处的生育期有关（见图 2）。移栽后，随水稻生育期的推进，植株含钾量逐渐下降，由分蘖期的 16.2～44.3 g/kg 下降到成熟期的 4.1～13.8 g/kg。对各生育期水稻含钾量的方差分析表明：各钾素水平条件下，生育期对植株含钾量均有极显著影响，即随着生育期的推进，水稻植株的含钾量呈极显著的降低趋势；多重比较显示，只有成熟期和齐穗期植株含钾量无显著差异，其他各时期之间均存在极显著差异。



（图中大写字母不同表示同一钾素水平不同生育期的水稻植株含钾量的差异达 $p<0.01$ 显著水平，小写字母不同表示同一生育期不同钾素水平的水稻植株含钾量的差异达 $p<0.01$ 显著水平）

图 2 整个生育期水稻整株含钾量的变化

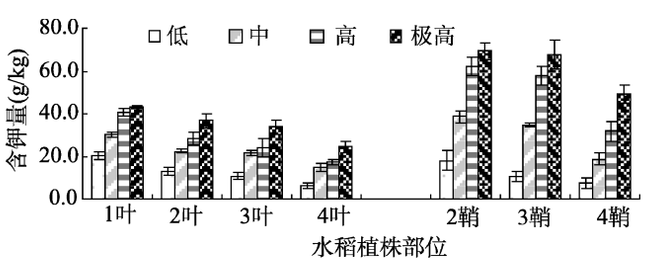
Fig. 2 K content changes of whole rice during whole growth period

分析图 2 中各生育阶段的含钾量降低速率可知，低、中、高钾水平下，植株含钾量在分蘖期至拔节期的下降速率较拔节期至齐穗期的下降速率大。而极高钾水平相反，分蘖期至拔节期的含钾量降低速率[3.83 mg/(kg·d)]小于拔节期至齐穗期含钾量降低速率[5.81 mg/(kg·d)]。这一差异可能是因为在钾素水平高的情况下，前期土壤钾素供应充足，分蘖期至拔节期的下降速率较低，而拔节期至齐穗期土壤钾素供应能力减弱，所以降低速率较大。

2.3 水稻不同部位含钾量变化

2.3.1 分蘖期各部位含钾量变化

分蘖期水稻各部位钾含量随土壤供钾水平上升迅速增加（见图 3）。极高钾水平植株叶的含钾量是低钾水平的 2.03～3.64 倍，含钾量倍数呈 1 叶<2 叶<3 叶<4 叶趋势；极高钾水平植株鞘的含钾量是低钾水平的 3.18～6.54 倍，鞘的含钾量倍数呈 2 鞘<3 鞘<4 鞘趋势。这表明钾素水平对下位叶、鞘的影响更大。



（第一片叶分蘖期不能区分鞘、叶，所以将 1 叶与 1 鞘合并表示为 1 叶（下同））

图 3 不同钾素水平下分蘖期水稻鞘、叶含钾量变化

Fig. 3 K content changes of rice sheath and leaf in different soil K levels at tillering stage

由图 3 可见，分蘖期，水稻叶片钾含量随叶位由上至下显著下降，即 1 叶>2 叶>3 叶>4 叶，且随着钾素肥力的升高，叶位间含钾量差异相对减小。低钾水平下，4 叶的含钾量为 2 叶的 47%，极高钾水平下，4 叶的含钾量为 2 叶的 67%，可见高钾水平下，叶位间叶的含钾量差异较小。鞘的含钾量也呈类似规律，但鞘的含钾量由上至下的下降幅度更大，低钾水平下，4 鞘的含钾量仅为 2 鞘的 30%，极高钾水平下，4 鞘的含钾量仅为 2 鞘的 62%。

分蘖期水稻鞘的含钾量都高于对应叶的含钾量。由表 2 可知，随着钾素水平的升高，鞘叶含钾量比值增大，鞘叶含钾量比值表现为低钾＜中钾＜高钾≈极高钾。在低钾时，鞘与叶的含钾量相当，各叶位鞘叶比为 1.07～1.67；中钾时，鞘叶比为 1.28～1.75，鞘叶比大于极缺钾的鞘叶比；在高钾及极高钾时，鞘的含钾量远高于对应叶，鞘叶比值较大，约为 2。

表 2　分蘖期水稻各部位含钾量比值

Table 2　K content ratios of various parts of rice at tillering stage

钾素水平	各叶位鞘叶含钾量比值			叶位含钾量比值	
	2 鞘/2 叶	3 鞘/3 叶	4 鞘/4 叶	4 叶/2 叶	4 鞘/2 鞘
低	1.67	1.16	1.07	0.47	0.30
中	1.75	1.61	1.28	0.64	0.47
高	2.17	2.35	1.83	0.61	0.51
极高	2.10	2.14	1.92	0.67	0.62

2.3.2　拔节期各部位含钾量

拔节期，各种钾素水平条件下各器官的含钾量见表 3。水稻各部位的含钾量都以茎最高，而鞘与叶的含钾量与钾素水平有关，在低、中钾水平下，叶＞鞘，在高、极高钾水平下，鞘＞叶。随着钾素水平的提高，各器官的含钾量有所升高，以鞘增加幅度更大，增加幅度呈鞘＞叶＞茎趋势。说明鞘含钾量弹性变化范围大，钾素对鞘的影响最大。

表 3　拔节期水稻各器官的含钾量(g/kg)

Table 3　K contents of various organs of rice at jointing stage

钾素水平	茎	叶	鞘
低	13.3±2.0	7.9±1.6	4.6±1.4
中	19.0±2.4	14.3±1.7	13.1±3.9
高	29.6±5.7	20.6±1.6	27.6±6.0
极高	42.0±4.2	28.8±0.3	40.8±3.5

拔节期，水稻各叶位鞘、叶的钾含量随土壤供钾水平上升而增加(见图 4)，其中鞘的增加幅度大于叶，即 2 鞘＞2 叶，3 鞘＞3 叶，4 鞘＞4 叶；叶的增加幅度为 4 叶＞3 叶＞2 叶＞1 叶；鞘的增加幅度以 4 鞘最大，4 鞘＞3 鞘＞2 鞘，可见钾素水平对下位叶、鞘影响更大。

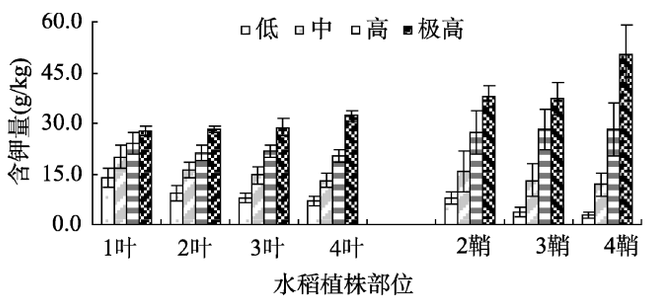


图 4　不同钾素水平下拔节期水稻鞘、叶含钾量变化

Fig. 4　K content changes of rice sheath and leaf in different soil K levels at jointing stage

拔节期，不同叶位钾含量变化与分蘖期类似，但随着钾素水平的上升，水稻叶片钾含量随叶位由上向下呈现下降的趋势减弱，叶位间的含钾量差异减小。在低、中钾水平下，叶的含钾量由上至下逐渐降低；高钾水平下，叶位间叶含钾量无明显的梯度变化；极高钾水平下含钾量由上至下逐渐增加。鞘的含钾量规律与叶相似。可见随着钾素水平的上升，叶位间鞘及叶的含钾量的差异逐渐减小。含钾量梯度变化可以反映拔节期植株、土壤钾素水平的高低，在判断植株是否缺钾上具有潜力。

拔节期，鞘与叶的含钾量比值范围为 0.26～1.49，小于分蘖期鞘与叶含钾量比值1.07～2.35；鞘与叶的含钾量比值仍然随钾素水平的升高而增加。由表 4 可知，在低、中钾水平下，鞘叶含钾量比值小于 1，且低钾＜中钾；在高、极高钾水平下，鞘叶比大于 1，且高钾＜极高钾；鞘叶含钾量比值总体呈低钾＜中钾＜

高钾＜极高钾趋势。

表 4　拔节期水稻各部位含钾量比值

Table 4　K content ratios of various parts of rice at jointing stage

钾素水平	各叶位鞘叶含钾量比值			叶位间含钾量比	
	2 鞘/2 叶	3 鞘/3 叶	4 鞘/4 叶	4 叶/2 叶	4 鞘/2 鞘
低	0.91	0.42	0.26	0.65	0.20
中	0.96	0.88	0.89	0.82	0.79
高	1.27	1.31	1.39	0.96	1.05
极高	1.34	1.22	1.49	1.14	1.27

2.3.3　齐穗期钾素水平对水稻各部位含钾量规律的影响

齐穗期，不同钾素水平下各器官的含钾量高低不同，其结果见表 5。在低钾时，穗的含钾量(4.7 g/kg)高于秸秆的含钾量(4.3 g/kg)，其他 3 种钾素水平都是秸秆的含钾量高于穗的，且随钾素水平的升高，秸秆与穗的含钾量差异逐渐增大。在不同钾素水平下，水稻穗、茎、鞘、叶的含钾量大小有差异，在低钾水平下，茎＞穗＞叶＞鞘；在中钾水平下，茎＞叶＞鞘＞穗；在高、极高钾水平下，叶＞鞘＞茎＞穗。可见随钾素水平的升高，各器官的含钾量都有所增加，秸秆的增加幅度远大于穗；各器官中以鞘的含钾量增加幅度最大，其次是叶、茎、穗。这表明，齐穗期各器官对钾素的响应程度不同，鞘的含钾量变化幅度最大，鞘对钾素反应较灵敏。

表 5　齐穗期各器官含钾量(g/kg)

Table 5　K contents of various organs of rice at full heading stage

钾素水平	穗	茎	叶	鞘	秸秆
低	4.7±0.7	7.8±1.4	4.1±1.7	2.3±1.0	4.3±1.3
中	4.6±1.1	11.2±3.4	11.0±1.8	5.4±0.2	8.5±0.7
高	6.1±0.6	12.9±1.9	16.6±1.2	14.3±2.0	14.2±0.9
极高	6.1±0.5	12.5±2.5	20.7±1.2	17.6±2.1	17.6±1.4

齐穗期，水稻各叶位鞘、叶钾含量随土壤钾素水平上升而增加。极高钾水平叶的含钾量是低钾水平的 2.57～9.01 倍，其中，3 叶(9.01 倍)＞4 叶(8.84 倍)＞2 叶(6.43 倍)＞1 叶(2.57 倍)；鞘的含钾量增加幅度以 4 鞘最大，其极高钾的含钾量是低钾的 15.87 倍，其次是 3 鞘、2 鞘、1 鞘。

齐穗期含钾量规律见图 5。随钾素水平的升高，水稻各部位含钾量由上至下逐渐降低的趋势减弱，叶位间的含钾量差异减小，这与拔节期相似。在低、中钾水平下，鞘、叶的含钾量由上至下逐渐降低。高、极高钾水平下，叶位间含钾量的差异较小。极高钾水平下，鞘、叶的含钾甚至出现由上至下逐渐增加的趋势。齐穗期，鞘与叶含钾量比值为 0.36～1.33，较前两个时期小。水稻鞘与叶含钾量比值因钾素水平的不同而异，随着钾素水平的上升，比值基本呈增加的趋势，但规律不如分蘖期、拔节期明显。

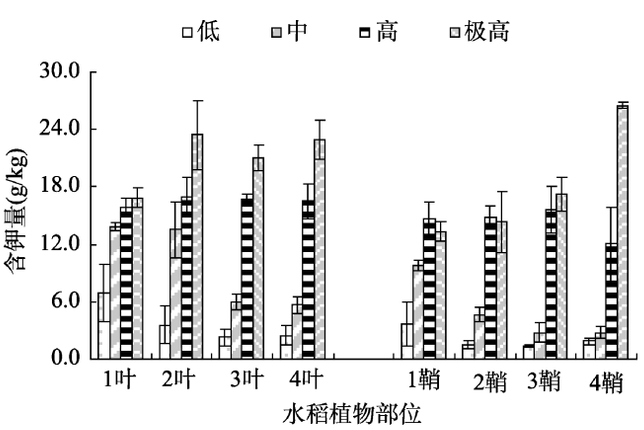
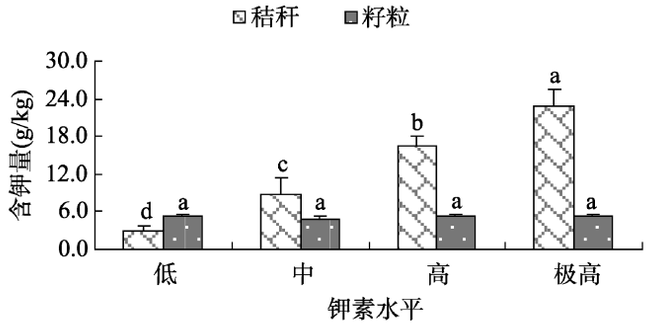


图 5　不同钾素水平下齐穗期水稻鞘、叶含钾量变化

Fig. 5　K content changes of rice sheath and leaf in different soil K levels at full heading stage

2.3.4　成熟期钾素水平对水稻秸秆、籽粒含钾量的影响

由图 6 可知，成熟期水稻秸秆的含钾量差异较大，含钾量范围为 2.8～22.9 g/kg，最高含钾量是最低含钾量的 8 倍。方差分析的结果表明，各钾素水平之间的秸秆含钾量存在极显著差异；不同水平之间籽粒的含钾量无显著差异，都在 5.0 g/kg 左右。可见秸秆对钾素较敏感，而籽粒对钾素反映较迟钝。



（图中小写字母不同表示在不同钾素水平土壤间水稻同一部位含钾量达到 $p<0.01$ 显著水平）

图 6　成熟期籽粒、秸秆含钾量

Fig. 6　K contents of rice stalk and kernel at maturity stage

3　讨论与结论

3.1　整个生育期不同钾素水平条件下水稻含钾量变化趋势

植株含钾量随水稻生育期推进逐渐降低，由分蘖期的 16.2～44.3 g/kg 下降到成熟期的 4.1～13.8 g/kg，下降速率以分蘖期至拔节期的最大，这与王亚艺[16]、裴又良[17]、李玉鹏[21]和贾彦博等[22]的研究结果较一致。这主要是由于随着生育期的推进，水稻生物量逐渐增加，对含钾量有稀释作用，以及土壤钾素供应能力的下降使水稻含钾量降低；土壤钾素水平对整个生育期植株含钾量均有影响，影响最大的时期为拔节期，所以水稻前期钾素供应非常重要。

3.2　钾素水平对水稻各生育期各器官含钾量变化的影响

分蘖期，各种钾素水平条件下，都呈现鞘的含钾量高于叶，这与朱维和等[20]的研究结果不一致：随着钾素水平的升高，都以鞘的含钾量增加更显著。拔节期，随着钾素水平的增加鞘的含钾量增加最大；各钾素水平条件下，各器官的含钾量顺序不同，低、中钾水平下，各器官含钾量顺序为茎＞叶＞鞘，高、极高钾水平下，顺序为茎＞鞘＞叶，钾素水平对鞘的含钾量影响最大，这与朱维和等[20]的研究结果不一致（叶鞘＞叶＞茎）。齐穗期，钾素水平对各器官的含钾量大小有影响，随着钾素水平的升高，叶的含钾量绝对增加量最大，而鞘的相对增加量最大；低钾水平下，各器官含钾量顺序为茎＞穗＞叶＞鞘，中钾水平下，茎＞叶＞鞘＞穗，高、极高钾水平下，叶＞鞘＞茎＞穗。这与朱维和等[20]的研究结果具有一定的差异，一方面是由于该研究是针对不同钾素水平的水稻含钾量进行，而钾素水平对各器官的含钾量影响大小不同；另一个原因可能是由于采样时间的差异。

3.3　钾素水平对水稻各叶位鞘叶含钾量的影响

分蘖期，不同钾素水平下，各部位的含钾量都呈由上至下逐渐降低的趋势；各叶位鞘、叶钾含量比值均大于 1，且该比值随土壤钾素水平的增加而显著上升。拔节期，钾素水平由低至高，叶位间含钾量由上至下呈现降低的趋势减弱，钾素水平对各叶位鞘的含钾量影响更大，以鞘的增加幅度更大；鞘与叶含钾量比值为 0.26～1.49，且随钾素水平的增加而增加。齐穗期，钾素水平由低至高，叶位间由上至下含钾量下降的趋势减弱，含钾量较高时，出现下位含钾量高于上位；鞘叶含钾量比值为 0.36～1.33。

综合 3 时期分析，随生育期的推进水稻各叶位鞘、叶的含钾量逐渐降低，水稻鞘与叶含钾量比值逐渐降低；各叶位含钾量随钾素水平的升高而增加，以鞘的增加幅度较大；不同时期含钾量变化规律可以看出，水稻分蘖期上部叶是钾素优先积累的部位，而叶鞘更是钾奢侈吸收储存的部位；齐穗期以后，钾奢侈吸收主要是积累到了中下部叶和叶鞘中。上面的结果表明，不同叶位间，各叶位的含钾量并不相同，且不同钾素水平条件下，各叶位鞘与对应叶的含钾量也有差异，所以根据植株钾含量来进行营养诊断需要考虑取样时期、取样部位，而鞘、叶钾含量比值以及叶位间含钾量比值可能有较好的指示作用。分蘖期及拔节期，水稻鞘与对应叶的含钾量比值随钾素水平的升高而增加，表明鞘叶含钾量比值可以反映土壤钾素水平的高低，根据水稻鞘叶的含钾量比值高低来判断钾素是否充足。拔节期及齐穗期，不同施钾水平条件下，各叶位的叶片含钾量变化梯度不同，低钾水平下各叶位含钾量由上至下逐渐降低，而随着钾素水平的增加这一趋势减弱，高钾水平还出现相反的趋势。这表明，叶位间叶片含钾量的梯度变化能反映土壤、植株钾素水平，这可能在植株钾素营养诊断上具有重要作用。

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Dynamic changes of rice K content influenced by different soil K levels

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Abstract：A pot culture experiment was carried out to investigate the effect of soil K level on K contents in various parts of rice plants. The results showed that K content of rice plant reduced gradually during whole growth period. Compared with tillering stage，K content of rice plant decreased by about 69%-75% at maturity stage. Both growing stage and soil K level were the key factors affecting K content of rice plant. At tillering stage，K content of leaf and sheath reduced significantly from top leaf to lower leaves. The ratios of the sheath K content to the corresponding leaf K content were all higher than 1，and the ratios increased accordingly as leaf K content increased. At jointing stage，the similar trend of K content among leaves was also observed as compared with that of tillering stage，but the decrement of K content from top leaf to lower leaves became smaller，and K content ratios of sheath to leaf also reduced，which ranged from 0.26 to 1.49. At full heading stage，K content of upper leave and sheaths was higher than that of lower leave or

sheaths when K supply in soil was lower, but K content of lower leave was higher that that of upper leaves when soil K supply was higher. At maturity stage, K content of rice stalk ranged from 2.8 to 22.9 g/kg as the soil K supply increased, while K content of rice seeds remained about 5.0 g/kg. The above results indicated that rice K was preferentially accumulated in upper leaves at tillering stage, and the sheath is the reserve for luxury K uptake, while the lower leave and sheaths were the reserve for luxury K uptake after full heading stage. As rice K content varied greatly among different growing stages and different organs, it's important to choose the right stage and right organ for rice K status diagnoses. The ratios of sheath K content to corresponding leaf K content is possibly a good index for rice K status diagnoses.

Key words: Rice, soil K level, K content, ratio of sheath to leaf

柱花草属不同种钾含量研究①②

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摘　要：本文对柱花草属 8 个种 153 份种质的钾素含量进行测定，结果表明，圭亚那柱花草钾平均含量为 1.19%，其中品 129 显著（$p<0.01$）高于其他种质；西卡柱花草钾平均含量为 0.95%，品 121 和品 122 显著（$p<0.01$）高于其他种质；灌木状柱花草钾平均含量为 0.87%，品 153 显著（$p<0.01$）高于其他种质；头状柱花草钾平均含量为 1.16%；有钩柱花草钾平均含量为 0.90%；马弓形柱花草钾平均含量为 1.14%；大头柱花草钾含量为 1.22%；矮柱花草钾含量为 1.03%。各不同种柱花草之间存在显著差异（$p<0.01$），大头柱花草，圭亚那柱花草，头状柱花草，马弓形柱花草钾含量显著（$p<0.01$）高于矮柱花草，西卡柱花草，有钩柱花草，灌木状柱花草；矮柱花草钾含量显著（$p<0.01$）高于灌木柱花草和有钩柱花草，西卡柱花草与有钩柱花草和灌木状柱花草之间差异不显著（$p>0.05$）。

关键词：柱花草属；钾；含量；差异

柱花草（Stylosanthes SW.），又被称作热带苜蓿、巴西苜蓿，原产于美洲，我国自 20 世纪 60 年代起开始引进，并在广东、广西、云南等地栽培。柱花草属（Stylosanthes Sw.）资源丰富，约有 50 个种，主要有：圭亚那柱花草（S. guianensis Sw.）、西卡柱花草（S. scabra Vog.）、灌木柱花草（S. seabrana）、有钩柱花草（S. hamata（L.）Taub.）、大头柱花草（S. macrocephala Ferr.）、矮柱花草（S. humilis Kunth）和头状柱花草（S. capitata Vog.）等[1]。其中以圭亚那柱花草在世界上栽培面积最大[2]，同时也是柱花草属中分支最多、起源最早、分布最广和遗传多样性最丰富的一个物种[3]。目前，柱花草已经成为南方地区大面积推广种植的重要热带豆科牧草与绿肥。因我国南方地区气候具有高温多雨、雨量分布不均匀且多暴雨的特点，很容易引起水土流失，土壤有机质分解快，养分淋溶流失剧烈等问题。数据显示海南岛年平均降雨量为 1 549 mm，其中淋溶雨量为 845 mm，造成胶园等土壤钾素损高达 63.0 kg/hm^2[4-5]。再者，由于有机肥价格和劳动力成本的不断升高，南方地区的胶园或果园有机肥使用量大幅下降，土壤肥力也持续降低。柱花草的氮含量比较高，耐干旱、耐贫瘠、耐酸性瘦土，是用作绿肥和幼龄胶园、果园等的理想覆盖水保作物[6-7]。然而由于柱花草多年来一直作为牧草研究，很少对其肥用价值进行系统研究评价，目前还没对其含钾量的研究报道，本文对农业部热带牧草种质资源圃收集保存的 153 份、8 个种的柱花草种质进行钾元素的测定，以期明晰不同种质柱花草的含钾量，为柱花草绿肥的肥用价值评价提供研究依据，从而为优质柱花草绿肥的遗传育种研究提供依据。

1　材料与方法

1.1　材料

柱花草来自于农业部热带牧草种质资源圃所收集和保存的 153 份柱花草种质（见表 1）。于营养期刈割地上部分，105℃杀青后于 75℃烘 48 h，粉碎，过 1 mm 筛，用密封袋将样品保存，备用。

表 1　供试柱花草种质材料拉丁名表

Table 1　The latin name of the Stylosanthes

品系号	种名	拉　丁　名
品 3	圭亚那柱花草	*Stylosanthes guianensis* cv. CPI18750A
品 4	圭亚那柱花草	*Stylosanthes guianensis* TPRC90139

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续 表

品系号	种名	拉 丁 名
品 5	圭亚那柱花草	*Stylosanthes guianensis*
品 6	圭亚那柱花草	*Stylosanthes guianensis* USF873017
品 7	圭亚那柱花草	*Stylosanthes guianensis* TPRC90144
品 8	圭亚那柱花草	*Stylosanthes guianensis* TPRC90072
品 9	圭亚那柱花草	*Stylosanthes guianensis* TPRC E4
品 10	圭亚那柱花草	*Stylosanthes guianensis* CV. Graham
品 11	圭亚那柱花草	*Stylosanthes guianensis* USF873015
品 12	圭亚那柱花草	*Stylosanthes guianensis* TPRC90075
品 13	圭亚那柱花草	*Stylosanthes guianensis* cv. Endeavour
品 14	圭亚那柱花草	*Stylosanthes guianensis* CIAT11364
品 15	圭亚那柱花草	*Stylosanthes guianensis* TPRC90030-1
品 16	圭亚那柱花草	*Stylosanthes guianensis* cv. Reyan No. 5
品 17	圭亚那柱花草	*Stylosanthes guianensis* TPRC R292
品 18	圭亚那柱花草	*Stylosanthes guianensis* USF873016
品 19	圭亚那柱花草	*Stylosanthes guianensis* USF873015
品 20	圭亚那柱花草	*Stylosanthes guianensis* TPRC90069
品 21	圭亚那柱花草	*Stylosanthes guianensis* USF873014
品 22	圭亚那柱花草	*Stylosanthes guianensis* TPRC90067
品 23	圭亚那柱花草	*Stylosanthes guianensis* TPRC90015
品 24	圭亚那柱花草	*Stylosanthes guianensis* TPRC90089
品 25	圭亚那柱花草	*Stylosanthes guianensis* TPRC R291
品 26	圭亚那柱花草	*Stylosanthes guianensis* CIAT1044(2)
品 27	圭亚那柱花草	*Stylosanthes guianensis* TPRC90105
品 28	圭亚那柱花草	*Stylosanthes guianensis* USF873016
品 29	圭亚那柱花草	*Stylosanthes guianensis* cv. Reyan No. 10
品 30	圭亚那柱花草	*Stylosanthes guianensis* CIAT11371
品 31	圭亚那柱花草	*Stylosanthes guianensis* TPRC90006
品 32	圭亚那柱花草	*Stylosanthes guianensis* TPRC90033
品 33	圭亚那柱花草	*Stylosanthes guianensis* TPRC90107，90120
品 34	圭亚那柱花草	*Stylosanthes guianensis* TPRC90005(2)
品 35	圭亚那柱花草	*Stylosanthes guianensis* TPRC90074(3)
品 36	圭亚那柱花草	*Stylosanthes guianensis* TPRC90003
品 37	圭亚那柱花草	*Stylosanthes guianensis* CIAT1281
品 38	圭亚那柱花草	*Stylosanthes guianensis* cv. COOK
品 39	圭亚那柱花草	*Stylosanthes guianensis* TPRC90050，90049
品 40	圭亚那柱花草	*Stylosanthes guianensis* TPRC90058
品 41	圭亚那柱花草	*Stylosanthes guianensis* TPRC90074(1)
品 42	圭亚那柱花草	*Stylosanthes guianensis* TPRC90093
品 43	圭亚那柱花草	*Stylosanthes guianensis* TPRC90028
品 44	圭亚那柱花草	*Stylosanthes guianensis* TPRC90037(3)
品 45	圭亚那柱花草	*Stylosanthes guianensis* TPRC R273
品 46	圭亚那柱花草	*Stylosanthes guianensis* TPRC90085
品 47	圭亚那柱花草	*Stylosanthes guianensis* CIAT11376
品 48	圭亚那柱花草	*Stylosanthes guianensis* TPRC90005
品 49	圭亚那柱花草	*Stylosanthes guianensis* TPRC90005(4)
品 50	圭亚那柱花草	*Stylosanthes guianensis*
品 51	圭亚那柱花草	*Stylosanthes guianensis* TPRC90047
品 52	圭亚那柱花草	*Stylosanthes guianensis* cv. Reyan No. 7
品 53	圭亚那柱花草	*Stylosanthes guianensis* TPRC90037(2)

续 表

品系号	种名	拉 丁 名
品 54	圭亚那柱花草	*Stylosanthes guianensis* TPRC90095(2)
品 55	圭亚那柱花草	*Stylosanthes guianensis*
品 56	圭亚那柱花草	*Stylosanthes guianensis* TPRC90108，90048
品 57	圭亚那柱花草	*Stylosanthes guianensis*CIAT1283，TPRC90045
品 58	圭亚那柱花草	*Stylosanthes guianensis* TPRC 98
品 59	圭亚那柱花草	*Stylosanthes guianensis* TPRC 87
品 60	圭亚那柱花草	*Stylosanthes guianensis* TPRC90134(2)
品 61	圭亚那柱花草	*Stylosanthes guianensis* FM9405
品 62	圭亚那柱花草	*Stylosanthes guianensis* GC1578
品 65	圭亚那柱花草	*Stylosanthes guianensis* FM05-1(FM05-2)
品 66	圭亚那柱花草	*Stylosanthes guianensis* FM05-3
品 67	圭亚那柱花草	*Stylosanthes guianensis* FM03-2
品 69	圭亚那柱花草	*Stylosanthes guianensis* 58719
品 70	圭亚那柱花草	*Stylosanthes guianensis* 87830，TPRC252
品 71	圭亚那柱花草	*Stylosanthes guianensis* 67652，TPRC254
品 72	圭亚那柱花草	*Stylosanthes guianensis* TPRC L8
品 73	圭亚那柱花草	*Stylosanthes guianensis* TPRC E3
品 74	圭亚那柱花草	*Stylosanthes guianensis* TPRC L1
品 75	圭亚那柱花草	*Stylosanthes guianensis* TPRC L2
品 76	圭亚那柱花草	*Stylosanthes guianensis* TPRC90034
品 77	圭亚那柱花草	*Stylosanthes guianensis* TPRC90119
品 78	圭亚那柱花草	*Stylosanthes guianensis* TPRC E1
品 79	圭亚那柱花草	*Stylosanthes guianensis* TPRC E7
品 80	圭亚那柱花草	*Stylosanthes guianensis* TPRC E9
品 81	圭亚那柱花草	*Stylosanthes guianensis* TPRC R93
品 82	圭亚那柱花草	*Stylosanthes guianensis* GC1480(IRRI)
品 83	圭亚那柱花草	*Stylosanthes guianensis* GC1576(IRRI)
品 84	圭亚那柱花草	*Stylosanthes guianensis* GC1528(IRRI)
品 85	圭亚那柱花草	*Stylosanthes guianensis* GC1463
品 86	圭亚那柱花草	*Stylosanthes guianensis* GC1576(EMBRAPA)
品 87	圭亚那柱花草	*Stylosanthes guianensis* GC1524(IRRI)
品 88	圭亚那柱花草	*Stylosanthes guianensis* FM07-3(IRRI)
品 89	圭亚那柱花草	*Stylosanthes guianensis* GC1579(EMBRAPA)
品 90	圭亚那柱花草	*Stylosanthes guianensis* GC348 (EMBRAPA)
品 91	圭亚那柱花草	*Stylosanthes guianensis* FM07-2(IRRI)
品 92	圭亚那柱花草	*Stylosanthes guianensis* GC1557(IRRI)
品 93	圭亚那柱花草	*Stylosanthes guianensis* GC1517(EMBRAPA)
品 94	圭亚那柱花草	*Stylosanthes guianensis* GC1517
品 95	圭亚那柱花草	*Stylosanthes guianensis* GC1524(EMBRAPA)
品 96	圭亚那柱花草	*Stylosanthes guianensis* cv. Reyan No：2
品 97	圭亚那柱花草	*Stylosanthes guianensis* cv. Graham
品 98	圭亚那柱花草	*Stylosanthes guianensis*
品 99	圭亚那柱花草	*Stylosanthes guianensis* cv. Graham
品 100	圭亚那柱花草	*Stylosanthes guianensis*
品 101	圭亚那柱花草	*Stylosanthes guianensis*
品 102	圭亚那柱花草	*Stylosanthes guianensis* CIATearly flowering species
品 103	圭亚那柱花草	*Stylosanthes guianensis* ATF3309
品 104	圭亚那柱花草	*Stylosanthes guianensis* ATF3308
品 105	圭亚那柱花草	*Stylosanthes guianensis*

续 表

品系号	种名	拉 丁 名
品 106	圭亚那柱花草	*Stylosanthes guianensis* GC1581
品 107	圭亚那柱花草	*Stylosanthes guianensis* FM9405
品 108	圭亚那柱花草	*Stylosanthes guianensis* FM9405
品 109	圭亚那柱花草	*Stylosanthes guianensis*
品 111	圭亚那柱花草	*Stylosanthes guianensis* cv. Graham
品 112	圭亚那柱花草	*Stylosanthes guianensis* cv. Endeavour
品 114	圭亚那柱花草	*Stylosanthes guianensis* cv. Cook
品 120	圭亚那柱花草	*Stylosanthes guianensis*
品 125	圭亚那柱花草	*Stylosanthes guianensis* 907
品 126	圭亚那柱花草	*Stylosanthes guianensis* 90005
品 127	圭亚那柱花草	*Stylosanthes guianensis*
品 128	圭亚那柱花草	*Stylosanthes guianensis*
品 129	圭亚那柱花草	*Stylosanthes guianensis*
品 131	圭亚那柱花草	*Stylosanthes guianensis*
品 132	圭亚那柱花草	*Stylosanthes guianensis*
品 133	圭亚那柱花草	*Stylosanthes guianensis*
品 134	圭亚那柱花草	*Stylosanthes guianensis*
品 135	圭亚那柱花草	*Stylosanthes guianensis*
品 136	圭亚那柱花草	*Stylosanthes guianensis*
品 137	圭亚那柱花草	*Stylosanthes guianensis*
品 138	圭亚那柱花草	*Stylosanthes guianensis*
品 139	圭亚那柱花草	*Stylosanthes guianensis*
品 140	圭亚那柱花草	*Stylosanthes guianensis*
品 141	圭亚那柱花草	*Stylosanthes guianensis*
品 142	圭亚那柱花草	*Stylosanthes guianensis*
品 143	圭亚那柱花草	*Stylosanthes guianensis*
品 144	圭亚那柱花草	*Stylosanthes guianensis*
品 145	圭亚那柱花草	*Stylosanthes guianensis*
品 146	圭亚那柱花草	*Stylosanthes guianensis*
品 147	圭亚那柱花草	*Stylosanthes guianensis*
品 149	圭亚那柱花草	*Stylosanthes guianensis*
品 150	圭亚那柱花草	*Stylosanthes guianensis*
品 154	圭亚那柱花草	*Stylosanthes guianensis*
品 155	圭亚那柱花草	*Stylosanthes guianensis*
品 2	西卡柱花草	*Stylosanthes scabra* cv. Seca
品 121	西卡柱花草	*Stylosanthes scabra* Fitzroy 40205
品 115	西卡柱花草	*Stylosanthes scabra*. *Seca* 33260
品 122	西卡柱花草	*Stylosanthes scabra*. *Seca* 40292
品 117	西卡柱花草	*Stylosanthes scabra*. *Seca* 93116
品 116	西卡柱花草	*Stylosanthes scabra*. *Seca* Q10042
品 68	西卡柱花草	*Stylosanthes scabra*. *Seca* TPRC250
品 118	灌木柱花草	*Stylosanthes seabrana*
品 119	灌木柱花草	*Stylosanthes seabrana*
品 152	灌木柱花草	*Stylosanthes seabrana*
品 153	灌木柱花草	*Stylosanthes seabrana*
品 64	头状柱花草	*Stylosanthes capitata*
品 148	头状柱花草	*Stylosanthes capitata*
品 1	有钩柱花草	*Stylosanthes hamata* cv. Verano
品 124	有钩柱花草	*Stylosanthes hamata*
品 113	马弓形柱花草	*Stylosanthes hippocampoides*
品 151	马弓形柱花草	*Stylosanthes hippocampoides*
品 63	大头柱花草	*Stylosanthes macrocephala*
品 130	矮柱花草	*Stylosanthes humilis*

1.2 方法

烘干样品，用 $H_2SO_4-H_2O_2$ 消煮后，消煮液中的钾采用火焰光度计法测定[8]。

钾含量（质量分数）以烘干样的重量（质量）为基数。

1.3 数据统计与分析

用 MS-Excel 进行数据的计算、处理和表格的绘制，用 SAS9.0 统计软件中的方差分析程序对处理后的数据进行统计分析。

2 结果分析

2.1 圭亚那柱花草钾含量

表 2 圭亚那柱花草钾元素含量（单位 w：%）

Table 2 The K element content of S. guianensis SW（unit w：%）

品系号	K 含量	差异显著性	品系号	K 含量	差异显著性
品 3	1.24±0.03	IJKLMNOPQRSTUVWXYZA	品 73	1.39±0.10	CDEFGHIJ
品 4	1.26±0.19	HIJKLMNOPQRSTUVWXYZ	品 74	1.14±0.05	WXYZABCDEFGHIJKMNO
品 5	1.18±0.09	PQRSTUVWXYZABCDEFGHIJ	品 75	1.22±0.07	LMNOPQRSTUVWXYZABC
品 6	1.34±0.10	EFGHIJKLMN	品 76	1.15±0.15	STUVWXYZABCDEFGHIJKMN
品 7	1.02±0.05	KMNOPQRSTUVW	品 77	1.22±0.07	LMNOPQRSTUVWXYZABC
品 8	1.28±0.09	GHIJKLMNOPQRSTUVW	品 78	1.15±0.06	STUVWXYZABCDEFGHIJKMN
品 9	0.81±0.05	Y	品 79	1.19±0.05	NOPQRSTUVWXYZABCDEFG
品 10	1.30±0.09	EFGHIJKLMNOPQRST	品 80	1.02±0.11	KMNOPQRSTUV
品 11	0.88±0.10	WXY	品 81	1.16±0.12	QRSTUVWXYZABCDEFGHIJKL
品 12	0.97±0.10	RSTUVWX	品 82	0.89±0.08	VWXY
品 13	1.16±0.10	RSTUVWXYZABCDEFGHIJKM	品 83	1.38±0.16	CDEFGHIJ
品 14	1.15±0.09	STUVWXYZABCDEFGHIJKMN	品 84	1.28±0.06	FGHIJKLMNOPQRSTUVW
品 15	1.30±0.07	EFGHIJKLMNOPQRST	品 85	1.18±0.11	PQRSTUVWXYZABCDEFGHIJ
品 16	1.17±0.11	PQRSTUVWXYZABCDEFGHIJ	品 86	1.10±0.07	ABCDEFGHIJKMNOPQR
品 17	1.29±0.06	EFGHIJKLMNOPQRSTUV	品 87	1.43±0.10	BCDEF
品 18	1.24±0.07	JKLMNOPQRSTUVWXYZAB	品 88	1.39±0.07	BCDEFGH
品 19	1.04±0.08	IJKMNOPQRSTU	品 89	1.12±0.06	YZABCDEFGHIJKMNOPQ
品 20	1.17±0.13	QRSTUVWXYZABCDEFGHIJK	品 90	1.31±0.13	EFGHIJKLMNOPQ
品 21	1.29±0.12	EFGHIJKLMNOPQRSTUV	品 91	1.03±0.04	JKMNOPQRSTUV
品 22	1.07±0.05	FGHIJKMNOPQRST	品 92	1.08±0.11	CDEFGHIJKMNOPQRS
品 23	0.99±0.09	PQRSTUVWX	品 93	1.23±0.15	KLMNOPQRSTUVWXYZABC
品 24	1.20±0.07	NOPQRSTUVWXYZABCDEFG	品 94	1.09±0.07	BCDEFGHIJKMNOPQR
品 25	1.07±0.12	EFGHIJKMNOPQRST	品 95	1.24±0.13	JKLMNOPQRSTUVWXYZA
品 26	1.27±0.13	GHIJKLMNOPQRSTUVWX	品 96	1.18±0.09	PQRSTUVWXYZABCDEFGHIJ
品 27	1.07±0.12	DEFGHIJKMNOPQRST	品 97	1.50±0.09	BC
品 28	1.49±0.10	BCD	品 98	1.23±0.08	KLMNOPQRSTUVWXYZABC
品 29	1.37±0.06	CDEFGHIJK	品 99	1.50±0.13	BC
品 30	1.30±0.07	EFGHIJKLMNOPQR	品 100	1.25±0.13	HIJKLMNOPQRSTUVWXYZA
品 31	1.20±0.07	NOPQRSTUVWXYZABCDEFG	品 101	1.36±0.15	DEFGHIJKLM
品 32	1.13±0.12	XYZABCDEFGHIJKMNOP	品 102	1.12±0.04	YZABCDEFGHIJKMNOPQ
品 33	1.31±0.11	EFGHIJKLMNOPQ	品 103	1.32±0.09	EFGHIJKLMNO
品 34	1.38±0.12	CDEFGHIJ	品 104	1.13±0.06	WXYZABCDEFGHIJKMNO
品 35	1.37±0.13	CDEFGHIJKL	品 105	0.94±0.09	STUVWX
品 36	1.22±0.07	LMNOPQRSTUVWXYZABC	品 106	0.88±0.16	XY
品 37	1.30±0.06	EFGHIJKLMNOPQRST	品 107	0.93±0.08	TUVWXY
品 38	1.42±0.07	BCDEFG	品 108	1.10±0.08	ABCDEFGHIJKMNOPQR
品 39	1.28±0.12	GHIJKLMNOPQRSTUVW	品 109	1.21±0.12	MNOPQRSTUVWXYZABCDEF
品 40	1.39±0.09	BCDEFGHI	品 111	1.19±0.12	OPQRSTUVWXYZABCDEFGHI
品 41	1.31±0.25	EFGHIJKLMNOPQ	品 112	1.01±0.06	MNOPQRSTUVWX
品 42	1.22±0.05	LMNOPQRSTUVWXYZABC	品 114	1.28±0.06	GHIJKLMNOPQRSTUVW
品 43	1.03±0.04	JKMNOPQRSTUV	品 120	1.29±0.08	EFGHIJKLMNOPQRSTU
品 44	1.28±0.20	GHIJKLMNOPQRSTUVW	品 125	1.19±0.03	OPQRSTUVWXYZABCDEFGH
品 45	1.22±0.11	LMNOPQRSTUVWXYZABCD	品 126	1.06±0.06	GHIJKMNOPQRSTU

续 表

品系号	K 含量	差异显著性	品系号	K 含量	差异显著性
品 46	1.52±0.07	B	品 127	1.24±0.08	JKLMNOPQRSTUVWXYZA
品 47	1.15±0.09	TUVWXYZABCDEFGHIJKMN	品 128	1.17±0.09	QRSTUVWXYZABCDEFGHIJK
品 48	1.20±0.08	NOPQRSTUVWXYZABCDEFG	品 129	1.91±0.09	A
品 49	0.92±0.07	UVWXY	品 131	0.98±0.10	QRSTUVWX
品 50	1.12±0.10	YZABCDEFGHIJKMNOPQ	品 132	1.16±0.07	RSTUVWXYZABCDEFGHIJKM
品 51	1.01±0.12	NOPQRSTUVWX	品 133	0.92±0.15	UVWXY
品 52	1.00±0.07	OPQRSTUVWX	品 134	1.14±0.12	VWXYZABCDEFGHIJKMNO
品 53	1.27±0.07	GHIJKLMNOPQRSTUVWX	品 135	1.37±0.05	CDEFGHIJK
品 54	1.05±0.09	HIJKMNOPQRSTU	品 136	1.20±0.04	NOPQRSTUVWXYZABCDEFG
品 55	1.07±0.10	FGHIJKMNOPQRST	品 137	1.10±0.11	ABCDEFGHIJKMNOPQR
品 56	1.17±0.07	PQRSTUVWXYZABCDEFGHIJ	品 138	1.02±0.09	MNOPQRSTUVWX
品 57	1.15±0.12	STUVWXYZABCDEFGHIJKMN	品 139	1.15±0.05	STUVWXYZABCDEFGHIJKMN
品 58	1.02±0.11	MNOPQRSTUVWX	品 140	1.30±0.14	EFGHIJKLMNOPQRS
品 59	1.18±0.15	OPQRSTUVWXYZABCDEFGHI	品 141	0.94±0.11	STUVWX
品 60	1.32±0.09	EFGHIJKLMNOP	品 142	1.44±0.04	BCDE
品 61	1.19±0.11	NOPQRSTUVWXYZABCDEFGH	品 143	1.16±0.05	RSTUVWXYZABCDEFGHIJKMN
品 62	1.11±0.08	ZABCDEFGHIJKMNOPQR	品 144	0.92±0.14	UVWXY
品 65	1.02±0.19	MNOPQRSTUVWX	品 145	1.14±0.05	UVWXYZABCDEFGHIJKMNO
品 66	1.26±0.07	HIJKLMNOPQRSTUVWXY	品 146	1.50±0.11	BC
品 67	1.19±0.06	OPQRSTUVWXYZABCDEFGH	品 147	1.32±0.10	EFGHIJKLMNO
品 69	1.19±0.08	OPQRSTUVWXYZABCDEFGHI	品 149	1.22±0.08	MNOPQRSTUVWXYZABCDE
品 70	1.35±0.10	DEFGHIJKLM	品 150	1.28±0.10	GHIJKLMNOPQRSTUVW
品 71	1.29±0.14	EFGHIJKLMNOPQRST	品 154	1.12±0.05	YZABCDEFGHIJKMNOPQ
品 72	1.20±0.11	NOPQRSTUVWXYZABCDEFG	品 155	1.13±0.10	WXYZABCDEFGHIJKMNO

注:同一列具有相同字母的量,种质含钾量不存在显著差异($p>0.01$),具有不同字母的,两种质的含量具有显著差异($p<0.01$)。

由表 2 可知,参试的圭亚那柱花草总共有 134 份种质,占了全部参试种质的 87.58%。圭亚那柱花草 K 含量在 0.81%～1.91%之间,平均含量为 1.19%。其中,以品 9 的钾素含量最低,为 0.81%,以品 129 钾素含量最高,为 1.91%。钾含量在 0.5%～1.00%范围的有 13 份种质,占全部种质的 9.70%;钾含量在 1.00%～1.50%范围的有 117 份种质,占全部种质的 87.31%;钾含量在 1.50%～2.00%范围的有 4 份种质,占全部种质的 2.99%,由此可以看出供试的圭亚那柱花草种质含钾量主要集中在 1.00%～1.50%之间。

将所得数据经 SAS 统计分析可知,各种质间的 $F=14.91$, $p<0.0001$,说明各参试种质间均数差异显著($p<0.01$)。各均数间多重比较结果显示,在 0.01 水平下,品 129 的钾含量显著($p<0.01$)高于其他种质。

2.2 西卡柱花草钾含量

表 3 西卡柱花草钾元素含量表(单位 w:%)

Table 3 The K element content of S. scabra (unit w:%)

品系号	K 含量	差异显著性
品 2	0.90±0.09	B
品 68	0.88±0.09	B
品 115	0.97±0.09	B
品 116	0.75±0.11	C
品 117	0.89±0.08	B
品 121	1.10±0.06	A
品 122	1.18±0.11	A

由表 3 可知,参试的西卡柱花草总共有 7 份种质,占了全部参试种质的 4.51%。西卡柱花草 K 含量在 0.75%～1.18%之间,平均含量为 0.95%。其中,以品 116 的钾素含量最低,为 0.75%,以品 122 钾素

含量最高，为 1.18%。钾含量在 0.5%～1.00%范围的有 5 份种质，占全部种质的 71.43%；钾含量在 1.00%～1.50%范围的有 2 份种质，为品 121 和品 122。将所得数据经 SAS 统计分析可知，各种质间的 $F=14.74$，$p<0.0001$，说明各参试种质间均数差异达极显著。各均数间多重比较结果显示，在 0.01 水平下，品 121 和品 122 的钾含量显著（$p<0.01$）高于其他四份种质，品 2、品 68、品 117 的钾含量显著（$p<0.01$）高于品 116。

2.3 灌木状柱花草钾含量

由表 4 可知，参试的灌木状柱花草总共有 4 份种质，占了全部参试种质的 2.58%。灌木状柱花草 K 含量在 0.79%～1.00%之间，平均含量为 0.87%。其中，以品 118 的钾素含量最低，为 0.79%，以品 153 钾素含量最高，为 1.00%。钾含量在 0.5%～1.00%范围的有 3 份种质。该种钾含量在达到 1.00%的只有品 153 一份种质。将所得数据经 SAS 统计分析可知，各种质间的 $F=8.61$，$p=0.0007$（<0.01），说明各参试种质间均数差异达极显著。各均数间多重比较结果显示，在 0.01 水平下，品 153 的钾含量显著（$p<0.01$）高于品 118、品 119 和品 152。

表 4 灌木柱花草钾元素含量表(单位 w:%)

Table 4 The K element content of S. seabrana (unit w:%)

品系号	K 含量	差异显著性
品 118	0.79±0.07	B
品 119	0.86±0.11	B
品 152	0.84±0.03	B
品 153	1.00±0.06	A

2.4 其他参试种的钾含量

表 5 参试样品中其他柱花草的钾元素含量(单位 w:%)

Table 5 The K element content of other species (unit w:%)

种名	品系号	K 含量
头状柱花草	品 64	1.13±0.12
	品 148	1.18±0.09
	平均值	1.16±0.11
有钩柱花草	品 1	1.02±0.09
	品 124	0.78±0.12
	平均值	0.90±0.15
马弓形柱花草	品 113	1.09±0.06
	品 151	1.18±0.07
	平均值	1.14±0.08
大头柱花草	品 63	1.22±0.12
矮柱花草	品 130	1.03±0.09

由表 5 可知，参试的 153 份种质中，除圭亚那柱花草、西卡柱花草、灌木柱花草外，还有占全部种质少量的头状柱花草、有钩柱花草、马弓形柱花草、大头柱花草、矮柱花草。参试的头状柱花草总共有 2 份种质，分别为品 64 和品 148。其中，品 64 钾含量为 1.13%，品 148 钾含量为 1.18%，平均含量为 1.16%。参试的有钩柱花草总共有 2 份种质，分别为品 1 和品 124。其中品 1 钾含量为 1.02%，品 124 钾含量为 0.78%，平均含量为 0.90%。参试的马弓形柱花草有 2 份种质，分别为品 113 和品 151。其中品 113 钾含量为 1.09%，品 151 钾含量为 1.18%，平均含量为 1.14%。参试的大头柱花草有 1 份种质，为品 63，其钾含量为 1.22%。参试的矮柱花草有 1 份种质，为品 130，其钾含量为 1.03%。

2.5 各品种间钾含量比较

由表 6 可知，参试的柱花草属共有 8 个品种，取各不同种所参试的种质的平均值比较。其中圭亚那柱花草的钾含量为 1.19%，西卡柱花草钾含量为 0.95%，灌木状柱花草钾含量为 0.87%（为供试的不同种柱花草中钾含量最低值），有钩柱花草钾含量为 0.90%，头状柱花草钾含量为 1.16%，马弓形柱花草钾含

量为 1.14%，大头柱花草钾含量为 1.22%（为供试的不同种之间钾含量最高值），矮柱花草钾含量为 1.03%。将所得数据经 SAS 统计分析可知，各品种间的 $F=22.86$，$p<0.0001$，说明各参试的不同种之间钾含量差异达极显著。经多重比较结果显示，在 0.01 水平下，圭亚那柱花草、头状柱花草、马弓形柱花草、大头柱花草钾含量极显著高于西卡柱花草、灌木状柱花草、有钩柱花草、矮柱花草；矮柱花草钾含量极显著高于灌木柱花草和有钩柱花草，西卡柱花草与有钩柱花草和灌木状柱花草之间差异不显著。

表 6　参试的柱花草属不同种钾元素含量（单位 w：%）

Table 6　The K element content of different species of the Stylosanthes (unit w：%)

种　名	K 含量	差异显著性
大头柱花草	1.22±0.12	A
圭亚那柱花草	1.19±0.18	A
头状柱花草	1.16±0.11	A
马弓形柱花草	1.14±0.08	A
矮柱花草	1.03±0.09	B
西卡柱花草	0.95±0.16	BC
有钩柱花草	0.90±0.15	C
灌木状柱花草	0.87±0.11	C

3　讨论

钾是植物生长过程中具重要作用的大量营养元素之一，钾能显著促进作物的高产优质[9-17]，因此享有品质元素之称[18]。近些年来，我国土壤钾素，尤其是可供作物吸收的耕作层土壤的速效钾严重亏缺，且我国钾肥资源比较短缺，因此引起了人们的广泛关注[19]。为缓解土壤钾素肥力下降的压力，有人提出适量地增加钾肥进口[20]，但这无疑进一步增加了劳作成本，而比较科学绿色的解决办法就是增施能给土壤提供很好钾素来源的有机肥。加强钾的循环再利用，尤其是选用含钾量高的绿肥在果园间作或压青，对于提高主作物的产量和品质各方面都具有重要的意义。土壤覆盖绿肥后，在提供有机质的同时，因土壤微生物的作用有机质腐殖质化，产生大量具有粘着性的胶体物质，同时配合绿肥根系较强的穿插力，有效促进了土壤水稳性团粒结构的形成，最终大大改善了土壤的物理性状[21]。潘福霞等通过研究发现绿肥翻压后不仅能够改变土壤 pH，还有效提高土壤硝态氮和速效钾含量[22]。线琳等对砖红壤施用 8 种野百合属绿肥后，在不同的时间内都能不同程度地提高土壤速效钾的含量，施用绿肥后的土壤速效钾含量显著高于不施用绿肥的土壤[23]。柱花草作为我国南方地区重要和广泛栽培的热带牧草，在园区间作后，不仅可以作为牧草刈割或直接放牧饲喂家畜，同时作为绿肥，由于其固氮作用不仅可以将土壤的氮素有效地固定，渐少施氮量，节约成本，另一方面其自身含氮量也较高，压青施入土壤后又给土壤提供了一份氮素来源，同时还提供了其他营养元素来源，符合生态农业的发展需求。因此，应在热区大力推广营养元素丰富、干物质产量高、抗病性强的柱花草品种。

4　结论

（1）圭亚那柱花草钾含量在 0.81%～1.91%之间，平均含量为 1.19%，主要集中在 1.00%～1.50%之间。各均数间多重比较结果显示，在 0.01 水平下，品 129 的钾含量显著（$p<0.01$）高于其他种质。

西卡柱花草钾含量在 0.75%～1.18%之间，平均含量为 0.95%，各均数间多重比较结果显示，在 0.01 水平下，品 121 和品 122 的钾含量显著（$p<0.01$）高于其他 4 份种质，品 2、品 68、品 117 的钾含量显著（$p<0.01$）高于品 116。

灌木状柱花草钾含量在 0.79%～1.00%之间，平均含量为 0.87%，各均数间多重比较结果显示，在 0.01 水平下，品 153 的钾含量显著（$p<0.01$）高于品 118、品 119 和品 152。

参试的头状柱花草钾平均含量为 1.16%；有钩柱花草平均含量为 0.90%；马弓形柱花草钾平均含量为 1.14%；大头柱花草钾含量为 1.22%；矮柱花草钾含量为 1.03%。

（2）对参试的柱花草属不同种之间钾含量比较分析可知，大头柱花草钾含量最高，为 1.22%；灌木状

柱花草钾含量最低，为0.87%。经多重比较结果显示，在0.01水平下，大头柱花草、圭亚那柱花草、头状柱花草、马弓形柱花草钾含量显著（$p<0.01$）高于矮柱花草、西卡柱花草、有钩柱花草、灌木状柱花草；矮柱花草钾含量显著（$p<0.01$））高于灌木柱花草和有钩柱花草，西卡柱花草与有钩柱花草和灌木状柱花草之间差异不显著（$p>0.05$）。

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Research on the potassium contents of different species of *Stylosanthes*

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Abstract: The content of potassium(K) in 153 Germplasms 8 species of Stylosanthes guianensias was evaluated in this paper . The results showed that the K content of S. guianensis Sw potassium (K) was 1.19%, and Number 129 was higher significantly ($p<0.01$) than the other germplasms; the K content of S. scabra Vog wss 0.95%, Number 121 and 122 was higher significantly ($p<0.01$) than the other germplasms; the K content of S. seabrana is 0.87%, number 153 was

higher significantly ($p < 0.01$) than the other germplasms; the K content of S. capitata was 1.16%; the K content of S. hamata was 0.90%; the K content of S. hippocampoides was 1.14%; th K content of S. macrocephala was 1.22%; the K content of S. humilis was 1.22%. Analysis of the significance of difference among the different species showed that S. macrocephala, S. guianensis Sw, S. capitata, S. hippocampoides was significantly higher ($p < 0.01$) than the other species; S. humilis was significantly higher ($p < 0.01$) than S. seabrana and S. hamata; the difference of S. scabra with S. seabrana and S. hamata was not significant.

Key words: Stylosanthes, potassium, contents, difference

Long-term effect of fertilizer and rice straw on mineral composition and potassium adsorption in a reddish paddy soil①

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Abstract: Increasing potassium (K^+) adsorption can be an effective alternative in building an available K pool in soils to optimize crop recovery and minimize losses into the environment. We hypothesized that long-term fertilization might change K^+ adsorption because of changes in the chemical and mineralogical properties of rice (*Oryza sativa* L.). The aims of this study were: (i) to determine clay minerals in paddy soil clay size fractions using X-ray diffraction methods and a numerical diagram-decomposition method; (ii) to measure K^+ adsorption isotherms before and after H_2O_2 oxidation of organic matter; and (iii) to investigate whether K^+ adsorption is correlated with changes in soil chemical and mineral properties. The 30-year long-term fertilization treatments caused little change in soil organic C (SOC) but a large variation in soil mineral composition. The whole-clay fraction (<5 μm) corresponded more to the fertilization treatment than the fine-clay fraction (<1 μm) did in terms of percentage of illite peak area. The total percentage of vermiculite - chlorite peak area was significantly negatively correlated with the total percentage of illite peak area in the <5 μm soil particles ($R = -0.946$, $p = 0.000\ 6$). Different fertilization treatments gave significantly different results in K^+ adsorption. The SOC oxidation test showed positive effects of SOC on K^+ adsorption at lower K^+ concentration (≤120 mg·L^{-1}) and negative effects at higher K^+ concentration (240 mg·L^{-1}). The K^+ adsorption by soil clay minerals after SOC oxidization accounted for 60-158% of that by unoxidized soils, suggesting a more important role for soil minerals than SOC on K^+ adsorption. The K^+ adsorption potential was significantly correlated to the amount of poorly crystallized illite present ($R = 0.879$, $p = 0.012$). The availability of adsorbed K^+ for plant growth needs further study.

Keywords: Long-term experiment, mineral composition, potassium adsorption, reddish paddy soil

1 Introduction

K^+ ions may undergo fixation or adsorption on soil materials immediately following fertilization, when K^+ levels in solution and exchangeable form are high (*Selim* et al., 1976). An increase in the K^+ concentration can be expected in groundwater within infiltration areas with agricultural land use, as a consequence of K^+ leaching (*Jalali* and *Rowell*, 2003). Apart from the clay type and content, organic matter content, the amount of applied K^+ (*Johnston* et al., 1993), and drainage (*Shepherd* and *Bennett*, 1998), the leaching of K^+ is also dependent on the concentration of other cations, especially Ca^{2+}, in the soil solution (*Jalali* and *Rowell*, 2003). The movement of K^+ in soil is markedly affected by the extent of sorption by the soil. Chemical processes can influence sorption reaction, control the concentration of K^+ in solution and its movement through the soil profile. A thorough understanding of

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the effects of long-term application of fertilizer and organic amendment on K^+ adsorption is an important element in establishing sustainable agricultural systems.

Soil organic carbon (SOC) concentration was influenced by fertilization (*Shen* et al., 2007; *Majumder* et al., 2008); in turn, the SOC can influence K^+ adsorption. The effects of SOC on K^+ adsorption are proved contradictorily, as by *Li* et al. (2000) and *Lin* et al. (2007). Removal of SOC with hydrogen peroxide (H_2O_2) decreases K^+ adsorption in flood-irrigated paddy soils (*Liao*, 2010). Potassium adsorption can be inhibited in soils because organic molecules may hinder the diffusion and the adsorption of K^+ ions into the interlayer sites of clay minerals (*Evangelou* et al., 1986). It may open some of the smectite layers by the insertion of hydrated exchange cations (*Velde* and *Peck*, 2002). Potassium adsorption can also be stimulated by flooding in paddy soils because SOC enhances the decline in redox potential (*Schneiders* and *Scherer*, 1998), which induces a reduction of octahedral iron (Fe) in 2∶1 clay minerals and an increase in the negative charge of soil minerals, which in turn can induce a higher affinity for K^+ (*Scherer* and *Zhang*, 1999, 2002).

Results from a long-term fertilization experiment show that fertilization can significantly change the kinetics of K release in the soil, and increase the release of exchangeable K and non-exchangeable K (*Conti* et al., 1995). Long-term application of N and NP fertilizer increased soil K adsorption in specific sites (Kx) (*Sharma* et al., 1994). Both the above results indicate that fertilization can improve K^+ adsorption capacity of soil, thereby enhancing the availability of soil potassium. Long-term application of fertilizer containing SO_4^{2-} could increase the K supplying intensity and enhance the K buffering capacity in the soil. But under long-term application of fertilizer containing Cl^-, K supplying intensity and K buffering capacity in the soil was decreased. In addition, soil pH value (*Ioanoon* and *Dimirkou*, 1994; *Ardalan* and *Doroudic*, 1997), soil temperature (*Doula*, 1995), soil moisture, soil mineral composition, soil layers (*Rao* et al., 1998) and the background electrolyte during extraction, have an impact both on the soil K^+ adsorption and desorption processes (*Zeng* and *Liu*, 2000).

Fertilization can change soil chemistry, which impacts K^+ adsorption. Usually, interactions between K^+ and NH_4^+ are observed in both field studies and laboratory studies. Both K^+ ion and NH_4^+ ion have low hydration energies, similar ionic radii and the same mechanism for fixation by 2∶1 phyllosilicates (*Fanning* et al., 1989). Typically, soils have only a limited number of fixation sites for ions because of the relatively stable proportion of soil clay minerals; as a result, K^+ and NH_4^+ ions compete for these sites (*Liu* et al., 1997). It was observed in a long-term experiment that application of K increased the K^+ adsorption potential in upland soils (*Shaviv* et al., 1985; *Olk* et al., 1995). Application of K in combination with N in these experiments resulted in an increase in K^+ fixation in soils containing 2∶1 minerals such as illite, vermiculite, and mica (*Kovar* and *Barber*, 1990; *Chen* and *Mackenzie*, 1992). Application of K then reduced NH_4^+ availability to nitrifiers because of enhanced NH_4^+ fixation (*Chappell* and *Evangelou*, 2000). Application of N, P and K in combination in flooded paddy soil also increased K^+ in the total soil K pool (*Liao* et al., 2010). The amount of K^+ adsorbed increased either linearly or nonlinearly as the initial K^+ concentration increased (*Matthew* et al., 1990; *Stehouwer* et al., 1993). Potassium ions adsorbed in soil can move into the interlayer of clay minerals as newly fixed K^+ (*Shaviv* et al., 1985), but cannot be immediately available for plant uptake. When the K^+ concentration in the soil solution falls below a certain level, they can be gradually released and become available for uptake by plants.

In recent studies, *Pernes-Debuyser* et al. (2003) and *Liu* et al. (2008) showed that long-term application of organic and inorganic fertilizers could alter the clay mineralogy because of changes in the chemistry of the soil solution. Other researchers showed that application of K or animal manure for several decades increased the illite content or the illite layer content of illite – smectite in soil (*Poonia*, 1996; *Velde* and *Peck*, 2002). *Mcgahan* et al. (2003) reported that the application of NH_4^+ based fertilizers tended to increase short range order pools of hydroxy-Al in the soils and caused interlayering

of 2∶1 minerals because of intense acidification. The amount of K^+ adsorption (fixation) generally depended on the characteristics of the 2∶1 clay minerals present and therefore varied from one soil to another (*Shaviv* et al., 1985). The K^+ adsorption, or fixation capacity, was also influenced by particle size and chemical composition (*Murashkina* et al., 2007). The selectivity coefficient of K^+ is often larger for the sand fraction at lower K^+ concentrations than for the clay fraction at higher K^+ concentrations (*Shen* et al., 1997).

In China, the effects of fertilization on K^+ adsorption have been reported mostly for upland soils (*Li* et al., 2000; *Lin* et al., 2007). Few studies have been made on paddy soils, and the underlying mechanisms for K^+ exchange are far less understood. A long-term experiment established in 1981 to determine the effects of different combinations of N, P and K fertilizer and rice straw on rice crop yield offered an opportunity to investigate K^+ relations in flooded paddy soils. We hypothesized that long-term fertilization might change K^+ adsorption because of the change in soil chemical and mineralogical properties. The objectives of this study were: (i) to determine clay minerals in two clay fractions using classical X-ray diffraction methods and numerical diagram decomposition methods; and (ii) to measure the K^+ adsorption isotherms before and after H_2O_2 oxidation of the organic matter. This information will help to establish whether K^+ adsorption is correlated to changes in soil mineralogical properties because of long-term fertilization.

2 Materials and methods

2.1 Site description, soil and treatment

Soils were collected from the long-term soil fertility experiment established in 1981 at the Key Field Monitoring Experimental Station for Reddish Paddy Soil Eco-environment in Wangcheng County of the Ministry of Agriculture of China. The station is located in Huangjin Village Town (112° 80′ E, 28° 37′ N, 100 m altitude), in the central region of Xiangjiang River (a branch of Dongting Lake), China. The local climate of this area is sub-tropical monsoonal. Average annual precipitation is approximately 1,370 mm and annual mean temperature is 17 ℃, with the lowest monthly temperature of 4.4 ℃ in January and the highest of 30 ℃ in July. The annual frost-free period is approximately 300 days (d). The paddy field had been used for double rice cropping for 150 years before the experiment. The paddy soil was derived from Quaternary red clay and was classified as a Fe-accumuli-Stagnic Anthrosols according to the Chinese soil classification (*Shi* et al., 2004). It had a typical soil profile of A-P-W-G, where P is a plow pan. The depths of the A horizon and the P horizon were 5-7 cm and 15-17 cm, respectively. On the basis of the analysis of soil samples taken from the experimental site before the experiment was established in October 1980, the selected characteristics of the A horizon (0-15 cm) were: pH 6.9; soil organic carbon (SOC) 19.91 g·kg^{-1}, total N 2.05 g·kg^{-1}, alkali-hydrolyzable N 151.0 mg·kg^{-1}, available P 10.2 mg·kg^{-1} and exchangeable K 62.3 mg·kg^{-1}.

The field experiment was conducted in a randomized complete block design, including nine treatments with three replications. Seven treatments were selected for this study. Treatments included different combinations of N, K (NK), N, P (NP), P, K (PK), N, P, K (NPK) fertilizers, an unfertilized control (CK), NP plus rice straw (NP+RS) and NPK plus rice straw (NPK+RS). Each plot area was 66.7 m^2 and all were separated by cement dividers to avoid mixing of irrigation water and cross-contamination of treatments. The annual cropping system was rice - rice - fallow (winter). During the experiment, the early rice was transplanted in late April and harvested in mid-July, while the late rice was transplanted in mid-July and harvested in late October. Four to five seedlings were transplanted in late April and mid-July with a spacing of 16 cm×23 cm, 25-30 days old in the early planting season and 30-35 days old in the late planting season. All the aboveground biomass for both crops (early rice and late rice) was harvested manually by a sickle and removed from the field for

mechanical threshing by a paddy thresher, leaving 4-6 cm short stalks on a whole-plot basis. Grain and straw yield for both crops on a whole-plot basis were measured and expressed in kg • ha^{-1}. After harvest, the straw was removed from every plot. Natural weeds were allowed to grow during the winter fallow period, and weed biomass was incorporated into the soil by plowing during land preparation for the next year's early rice planting. Weed biomass was not recorded. Nitrogen fertilizer was applied at 150 N • kg • ha^{-1} for early rice and 180 N • kg • ha^{-1} for late rice during 1981-2010. Nitrogen was applied as urea in two splits: 50% of the total N amount was applied as basal dressing on the day immediately before transplanting of rice seedlings, and 50% was applied at the active tillering stage. Phosphate fertilizer was applied at 75 P_2O_5 kg ha^{-1} for both early rice and late rice during 1981-2010. Potassium fertilizer was applied at 120 K_2O kg • ha^{-1} for both early rice and late rice during 1981-2010. Phosphorus and K fertilizer was applied as superphosphate and potassium chloride (KCl) respectively, during final land preparation and prior to transplanting. Rice straw was applied at 2.1 t ha^{-1} for both early rice and late rice during 1981-2010. This was collected from a nearby rice field and applied as straw bedding. Rice straw was applied on a dry basis and mixed well with the soil, by manual digging, about one week before transplanting of rice in both seasons each year. Nutrient concentrations in rice straw were determined from 1981 to 2010. Rice straw contained 10.19 g kg^{-1} total N, 1.33 g kg^{-1} total P, and 25.99 g kg^{-1} total K.

2.2 Soil sampling and sample analysis

The soils in the surface layer (0-15 cm) were sampled randomly at five points across each plot after the late rice harvest in 2010. The samples were mixed thoroughly, air-dried, crushed to pass through a 1 mm sieve and a 0.25 mm sieve, and then stored in sealed glass jars for subsequent analysis. The 1 mm soil samples were used to determine the soil chemical properties, including the total K, exchangeable K and non-exchangeable K content. The 0.25 mm soil samples were used to determine pH, SOC and cation exchange capacity (CEC). Soil organic C and CEC were measured before and after the samples were oxidized with H_2O_2(*Lu*, 2000). The H_2O_2 - treated soils were then dried in air and ground to pass through a 0.25 mm sieve for analyzing SOC and CEC. Soil organic C was determined by the Walkley - Black method (*Nelson* and *Sommers*, 1982). Cation exchange capacity was determined by extracting soils with 1 mol L^{-1} NH_4OAc and measuring retained total N by distillation (*Bremner* and *Mulvaney*, 1982); Soil pH, total K, non-exchangeable K and exchangeable K were measured using *Lu*'s (2000) methods.

Clay mineral compositions were determined using classical X-ray diffraction methods of oriented clay preparations (*Moore* and *Reynolds*, 1997) and numerical decomposition methods (*Lanson*, 1997). This allows a quantitative estimation of mineral change with field treatments. The above method is comparative and not used as an absolute measure of relative clay mineral abundance and therefore no measurements were done with the field treatment replications. The whole soil (<0.15 mm) and two soil clay fractions (<5 and <1 μm) were investigated for the field fertilization treatments. The whole clays (<5 μm) from the sampled soils were used for the K saturation test. In the K saturation treatment, the samples were prepared by adding 1 mol L^{-1} KCL solution, then shaking and centrifuging for 5 min. These procedures were repeated five times and then the samples were rinsed five times with deionized water to remove excess KCL (*Poonia*, 1996; *Velde* and *Peck*, 2002).

During the process of X-ray diffraction analysis, random powders of soil samples (<0.15 mm) were firstly prepared by filling holders for step scanning from 2° to 65° with a Bruker D8 advance diffractometer (Bruker, Aks, Gmbh) with the goniometer PW3050/60 (theta/theta) and the X-ray tube PW3373/00. The diffractometer has a step-scanning program and CuK_α as the radiation source, in order to have an overview of possible minerals in the soils and to optimize the analysis conditions. The <5 μm and <1 μm clay fractions before and after the K saturation treatment were mounted as oriented aggregates on glass slides. The slides were step scanned from 2° 2θ to 15° 2θ, with step intervals of

0.02° 2θ at 3s. After the initial diffraction analysis, the following treatments were performed in sequence on untreated samples: ethylene glycol treatment and K^+ saturation, heating for 2 h at 550℃.

The X-ray spectra were decomposed after smoothing the patterns on a seven-point interval, having subtracted the background (*Lanson*, 1997). Convergence of the fitting routine to 98% concordance was used as a reasonable criterion for identifying the peak position and intensity. Relative peak surface areas of each clay mineral fraction were calculated by multiplying the peak intensity and full width at half maximum intensity. The mineral layer percentage of peak area in mixed-layer minerals was calculated by using the NEWMOD program (*Reynolds*, 1985).

2.3 Potassium adsorption isotherms

Potassium adsorption isotherms were measured and fitted to the first order (Langmuir) adsorption equation (*Hundal* and *Pasricha*, 1998). The measurements were performed before ([$-H_2O_2$]) and after ([$+H_2O_2$]) H_2O_2 oxidation to isolate the SOC effect from the mineral effect. Aliquots of 5.00 g of soil (<2 mm) were weighed into 50 mL centrifuge tubes in triplicate for each K solution. A series of 50 mL solutions of 0, 40, 80, 120, 160 and 200 K mg L^{-1} were transferred into the centrifuge tubes. The mixture of soil and K solution was equilibrated for 7 d at 25±0.5 ℃ and then was centrifuged at 3000 rpm for 3 min. The supernatant was used to measure the K concentration by flame atomic absorption spectroscopy (AAS). The adsorption of K by the soil was calculated by subtracting the K concentration in the suspension from the initial K concentration.

The measured K isotherms were fitted to the Langmuir adsorption equation:

$$\frac{1}{Y}=\frac{1}{M}+\frac{1}{MKC} \tag{1}$$

where Y is the amount of K (mg kg^{-1}), C is the K concentration at equilibrium (mg L^{-1}), M is the K adsorption potential (mg kg^{-1}), and K is the adsorption coefficient, which is used to calculate the adsorption free energy, ΔG, according to (*Graham*, 1953):

$$\Delta G=-RT\ln K=-5.7\ln K-25.6 \tag{2}$$

where R is the gas constant (0.008314 kJ mol^{-1} K^{-1}) and T is the temperature(25℃)

2.4 Statistical analysis

A completely randomized block design was applied to the variance, for multiple comparisons of the effects of fertilization treatments on rice yield and soil chemical properties. Duncan's least significant difference (LSD at $p=0.05$) test was adopted to assess the differences among the means of the three replication fertilization treatments. The paired-sample t-test was used to compare the significant differences among the K^+ adsorption isotherms at $p=0.05$ (*Liu* et al., 2008). Linear correlation among the parameters of the first order (Langmuir) equation, soil chemical properties, and the peak area percentages of clay mineral fractions was determined for the soils without H_2O_2 oxidation. All statistical analysis was performed with SPSS 11.5 software.

3 Result

3.1 Rice yield

Rice yield, on average, was higher for both early rice and late rice with NP and NPK plus RS than with only NP and NPK or unfertilized CK treatments (Table 1). In the treatments with unfertilized, NP-omitted-K, there was a declining trend in rice yields during the 30-yr period of the system. This declining trend was even more pronounced with the CK treatment for both early rice and late rice. Of those seven treatments, annual rice yields were highest with NPK+RS, with other treatments following in this sequence: NPK+RS>NPK>NP+RS>NP>NK>PK>CK. Sustainable yield index values were also highest with the NPK+RS in all treatments.

Table 1 Summary of rice yield and yield sustainability indexes in long - term fertilizer and rice straw application experiment in Wangcheng, Hunan Province, China

Treatment	Early rice				Late rice			
	Average yield# (t ha^{-1})	$Y^{\$}_{max}$ (t ha^{-1})	SD$^{\&}$	SYI*	Average yield# (t ha^{-1})	$Y^{\$}_{max}$ (t ha^{-1})	SD$^{\&}$	SYI*
CK	2.80 g	4.54	0.85	0.29	3.42e	4.48	0.70	0.39
PK	3.92e	6.20	0.76	0.47	4.22 d	5.65	0.60	0.48
NP	4.78 d	6.32	0.92	0.57	4.82c	6.00	1.01	0.56
NK	3.41f	6.76	1.67	0.26	4.73c	6.89	0.92	0.51
NPK	5.50b	7.04	0.91	0.68	5.62b	7.28	1.18	0.65
NP+RS	5.27c	6.34	1.03	0.63	5.47b	6.86	1.19	0.62
NPK+RS	5.91a	6.74	1.10	0.72	5.96a	7.50	1.27	0.69

Note: #: The value within each column followed by the different letter differ significantly ($p < 0.05$) by Duncan's multiple range test. $: stands for maximum yield observed over 30-yr-period in the experiments. &: stands for standard deviation of yield over 30-yr-period in the experiments. *: stands for sustainable yield for a given treatment.

3.2 Soil chemical properties

Soil chemical characteristics changed dramatically over the 30 years (Table 2). In 2010, the pH values in all treatment plots decreased, compared with the initial value in 1980 (pH = 6.9). More precisely, in the unfertilized CK plot, the pH value decrease was ~1.3 units. In the plots amended with rice straw, the pH values were 5.1 and 5.2, respectively. The SOC content changed considerably. It was 19.91 g kg^{-1} in the initial soil (IS) in 1980. But in 2010, the SOC in the surface soil in the plots under fertilizer application alone did not change or increased slightly, whereas the SOC content in the plots with NP+RS and NPK+RS treatments increased by 20.4% and 20.3%, respectively, over the initial level. After H_2O_2 treatment, carbon oxidization was not complete. Oxidization with H_2O_2 diminished SOC by 80.0 to 83.2% compared with the un-oxidized samples, resulting in a less significant difference in SOC content. Soil cation exchange capacity (CEC) was similar, except in the initial soil and unfertilized plot. Difference in soil CEC was found after 30 rice crop cycles for the fertilization plots. In the plots under unbalanced fertilization (PK, NP, NK), CEC decreased from 12.3 cmol kg^{-1} (IS) to the range of 11.6~11.9 cmol kg^{-1}, while the NPK+RS—treated plot had the highest CEC value (12.9 cmol kg^{-1}). But there was little difference in the CEC values among the NPK-, NP+RS— and NPK+RS—treated plots.

The non-exchangeable (Non-ExK^+) and exchangeable K^+ (ExK^+) in the plots with no K fertilizer application decreased compared with the initial level. The Non-ExK^+ content and the ExK^+ content in the surface soil in fertilized K treatments (PK, NK, NPK and NPK+RS) were higher than those in unfertilized K treatments (Table 2). There was a further increase in the exchangeable K^+ under the NPK+RS-treated plot compared to the NPK-treated plot.

Table 2 Selected chemical properties in different treatments in 2010

Treat-ment	pH (H_2O)	SOC† (g kg^{-1})	TN†† (g kg^{-1})	CEC# (cmol kg^{-1})	Non-Ex K& (mg kg^{-1})	Ex K§ (mg kg^{-1})	SOC [+H_2O_2]* (mg kg^{-1})	CEC [+H_2O_2] ** (cmol kg^{-1})
IS	6.9	19.91	2.05	12.3	174.0	62.30	3.34	9.2
CK	5.6	19.29	2.21	11.2	165.0	49.03	3.65	9.3
PK	5.4	19.61	2.28	11.9	191.0	178.7	3.93	9.2
NP	5.2	19.79	2.44	11.7	162.0	49.20	3.48	9.4
NK	5.2	20.86	2.55	11.6	199.0	193.70	3.86	9.3
NPK	5.1	22.10	2.52	12.8	194.0	80.70	4.18	9.5
NP+RS	5.1	23.98	2.53	12.7	165.0	62.20	4.21	10.4
NPK+RS	5.2	23.95	2.45	12.9	175.0	123.70	4.21	10.3

Note: †: Soil organic C; ††: Total N; #: Cation exchange capacity; &: Non-exchangeable K; §: Exchangeable K; *: Soil organic C after H_2O_2 treatment; **: Cation exchange capacity after H_2O_2 treatment.

3.3 Soil mineral properties

The x-ray diffraction (XRD) analysis on the whole-clay (<5 μm) fraction showed that all soil had

the same mineral assemblage (Fig. 1). Larger peaks were present near 1.42 nm, 1.00 nm and 0.72 nm among all test treatments. Those peaks did not shift after the glycol saturation treatment, which indicates an absence of swelling clay minerals. After the K saturation treatment, there was a decrease in the vermiculite-chlorite (V/CH) intensity at 1.42 nm, indicating the presence of exchangeable hydroxyl interlayer ions in V/CH minerals. After the K saturation treatment, 300 ℃ heating treatments showed the appearance of peak at 1.42 nm and the disappearance of peak at 0.72 nm, indicating the presence of chlorite and kaolinite, respectively (*Liu* et al, 2008).

Figure 1 shows the XRD pattern of the $<5\mu$m sample run in the air-dried and glycol-saturated state. It shows that the clay mineral assemblage was dominated by a mixed-layer (ML), indicating a wide peak among 0.75～1.25 nm. The decomposition peaks derived from them (Fig. 2) show that this ML was composed of two peaks, a wider brand peak near 1.03 nm (poorly crystallized illite, PCI) and a sharp brand peak at 1.00 nm (well crystallized illite, WCI) (*Li* et al., 2003, *Liu* et al., 2008). According to model fitting (*Li* et al., 2003), the ML components were likely to be illite and chlorite or perhaps vermiculite.

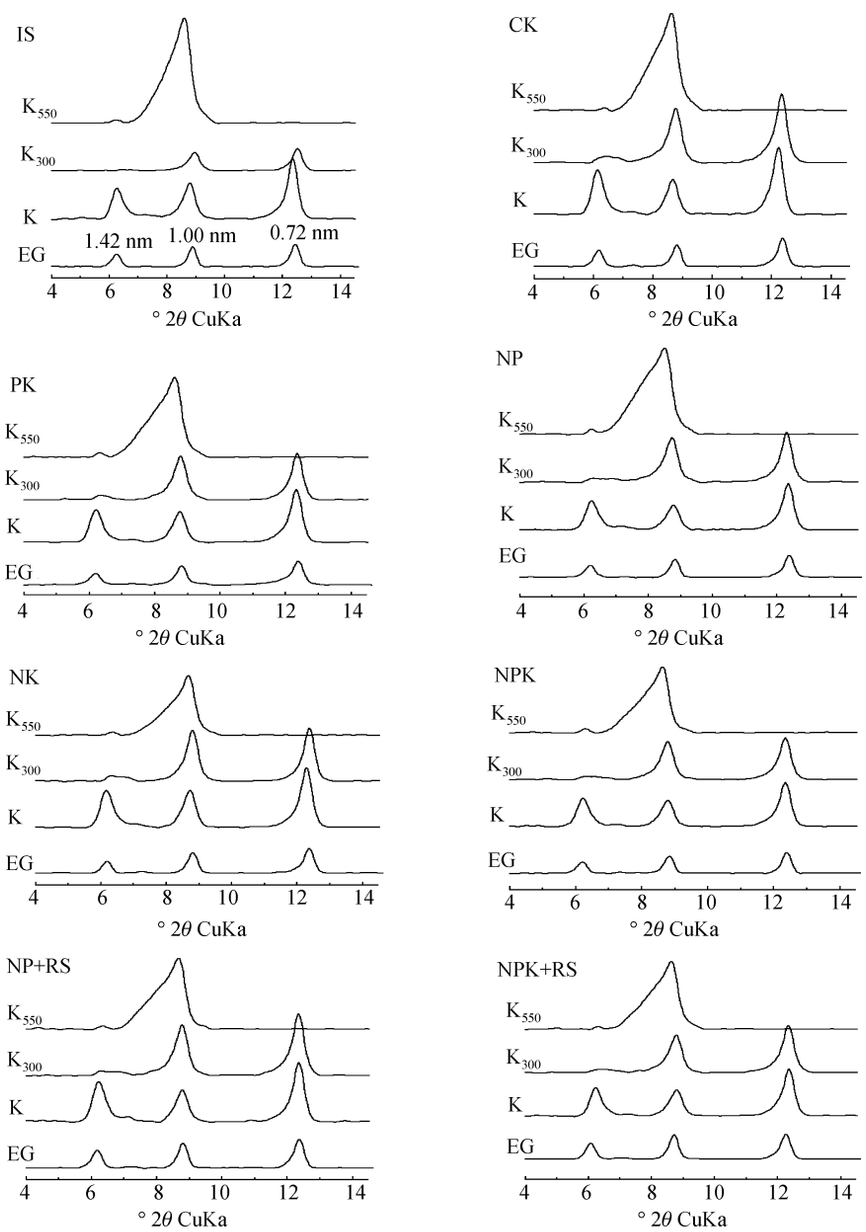

Figure 1 The X-ray diffraction patterns for the whole-clay fraction (<5 μm) in different fertilization treatments detected following ethylene glycol treatment, K^+ saturation, and K^+ saturation followed by 300 ℃ and 550 ℃ heat treatments.

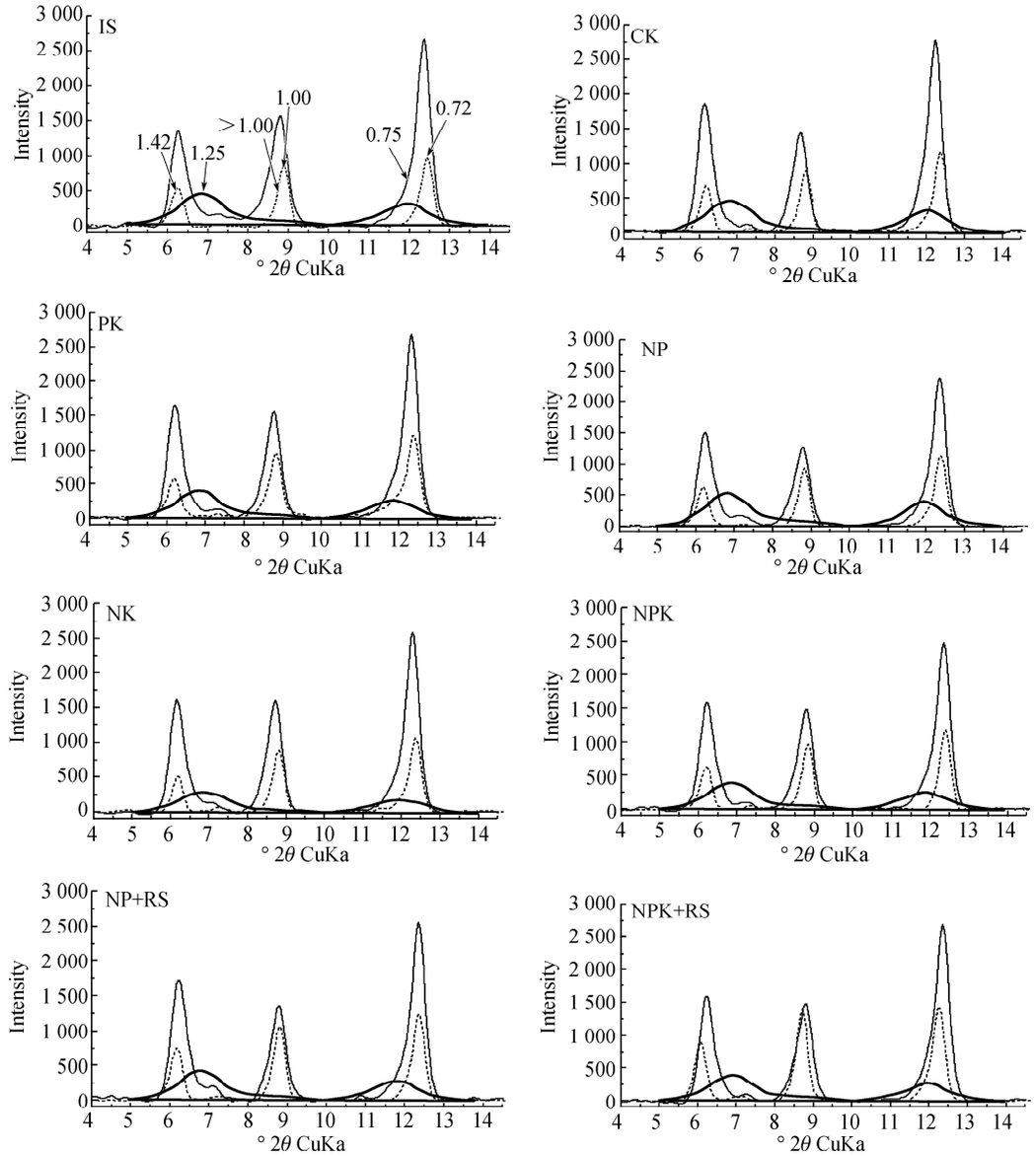

Figure 2 The X-ray diffraction patterns with the background subtracted (dotted line) and decomposed (solid line) for the different fertilization treatments sampled in 2010. The decomposed spectra, e. g., for the check treatment, showed the three narrow peaks at the positions of 1. 42 nm, 1. 00 nm and 0. 72 nm, indicating vermiculite-chlorite, well crystallized illite and kaolinite, respectively, one wide peak at >1. 00 nm indicating poorly crystallized illite, and two broad peaks at 1. 25 nm and 0. 75 nm indicating a mixed layer mineral.

The calculated relative peak areas of the clay minerals in fertilization treatments showed that relative peak areas were more in the whole-clay fractions than in the fine-clay fractions (Fig. 3). The clay mineral proportions appeared to be rather constant in the fine clays, with V/CH and ML dominating at approximately 48% of total peak area. The total percentage of illite (PCI plus WCI) ranged from 18% to 32% of the total peak area. In the whole-clay fraction, the dominant minerals were sequential V/CH (33-42% of the total peak area) and illite (18-33%), followed by kaolinite (15-28%) and ML (12-18%). The fertilized K treatments (PK, NK, NPK and NPK+RS) had lower ML percentages (12-18% of the total peak area) and greater illite percentages (18-33% of the total peak area) than the other treatments. The unfertilized K treatments (NP and NP+RS) had greater ML peak areas than those with K application. The NPK+RS treatment had the greatest percentage of ML peak area and a lower percentage of illite peak area among the P application treatments. The CK treatment had a higher percentage of V/CH peak area and a lower percentage of ML peak area in the soil sampled in 2010 than in the initial soil of 1981. The PK−, NK−, NPK− and NPK+RS −treated soils sampled in 2010

showed an increased percentage of V/CH and illite peak area and a decreased percentage of kaolinite and ML peak area, compared with the initial soil in 1980 (Fig. 3).

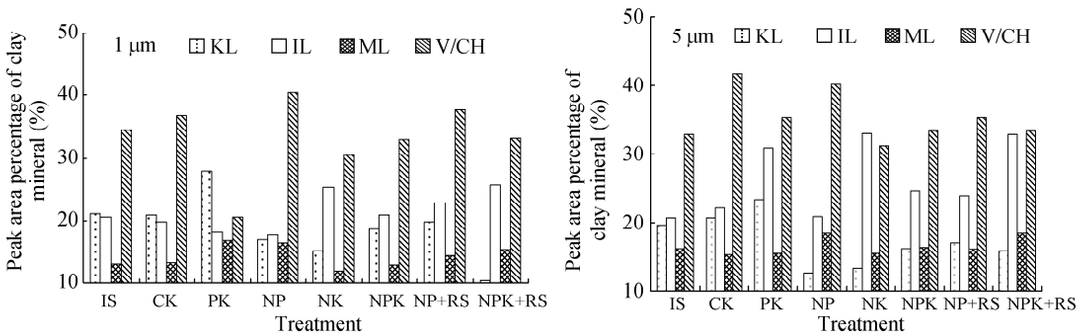

Figure 3 Peak area percentage of vermiculite-chlorite (V/CH), mixed-layer vermiculite-chlorite/illite mineral (ML), kaolinite (KL), and illite (IL) in the <5 μm-clay fraction (the whole-clay fractions) and <1 μm-clay fraction (the fine-clay fractions) of the different fertilization treatments.

Overall, the percentages of PCI and WCI peak area in free illite in the whole-clay fraction (<1 μm) and the fine-clay fraction (<5 μm) under all fertilized treatments were higher than those the initial soil and unfertilized treatments (CK). After 30 rice crop cycles, the effects of fertilizer treatment on the percentage of PCI and WCI peak area in free illite in the <1 μm clay fraction and the <5 μm clay fraction were significant. On average, the percentages of PCI and WCI peak area in free illite in the <1 μm clay fraction, and the <5 μm clay fraction under the K fertilizer treatments, were 15.5% and 8.0%, and 19.8% and 7.2% higher than in the initial soil, respectively. The <1 μm clay and the <5 μm clay fraction under the fertilized K treatments (PK, NK, NPK, and NPK+RS) increased the percentage of PCI and WCI peak area in free illite by 19.1-50.4% and 2.7-33.6%, respectively, over those under fertilizer treatments without K (NP and NP+RS).

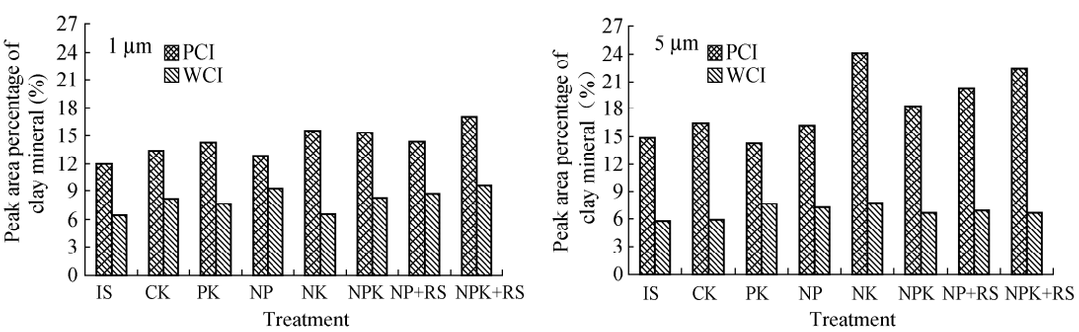

Figure 4 Peak area percentage of poorly crystallized illite (PCI) and well-crystallized illite (WCI) in < 1 μm and <5 μm clay fraction of the initial soil (IS) and different fertilization treatments in 2010.

The laboratory K saturation treatment of the soil clays increased the peak area of free illite for all samples (Fig. 5A). Also the percentage of peak area of illite layers in the chlorite-illite ML mineral increased under all the fertilization treatments except that under CK and NP (Fig. 5B). This resulted in an increase in the total percentage of illite layer peak area (free illite percentage plus illite layer percentage in the ML), except that under NP and NP+RS (Fig. 5C). The magnitudes of the increases were larger in the NPK treatment and the NPK+RS treatment than in other treatments. As a corollary to the change in the percentage of illite peak area, total V/CH (the percentage of free V/CH plus the percentage of V/CH layer in the ML) decreased in all the soils except that in the NK and the NPK treatment after the K saturation treatment (Fig. 5D). The total percentage of illite peak area was inversely related to the total percentage of V/CH peak area on the data sets with and without the K saturation treatment ($R=-0.946$, $p<0.0006$).

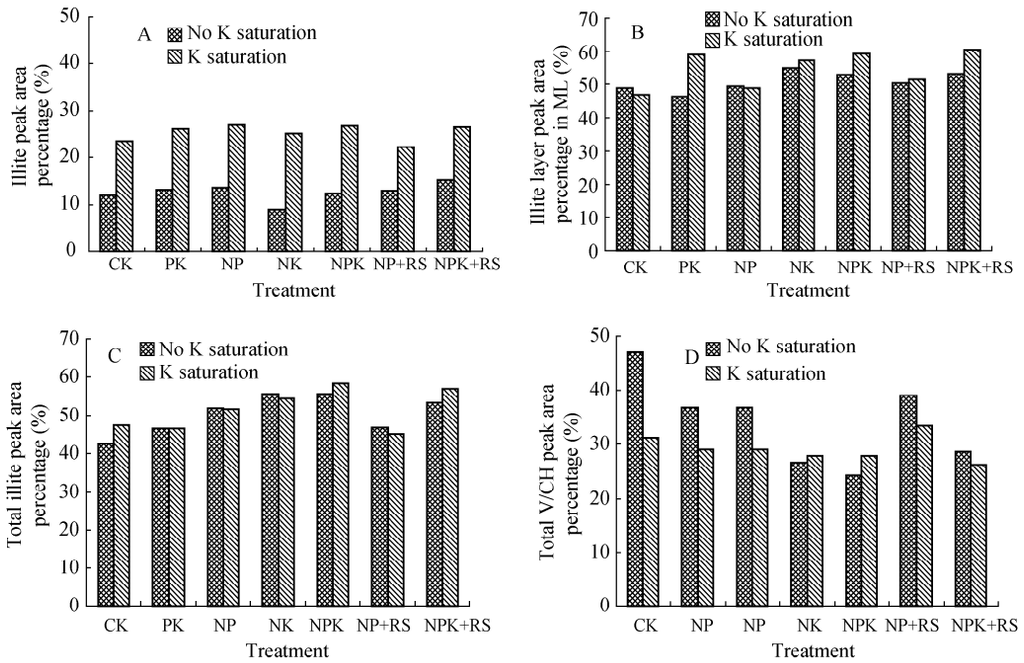

Figure 5 (A) Free illite peak area percentage in the<5 μm clay fraction, (B) illite peak area percentage in the mixed-layer vermiculite-chlorite/illite minerals(ML), (C) total peak area percentage of free illite and layer illite in ML minerals in the <5 μm clay fraction, (D) total peak area percentage of free vermiculite-chlorite (V/CH) and layer V/CH in ML minerals in the<5 μm clay fraction for the different fertilization sampled in 2010, with and without K saturation treatments.

3.4 Potassium adsorption isotherms

The percentage of K^+ adsorption on H_2O_2-oxidized samples generally decreased with increased K^+ concentration at the range of 20-240 mg L^{-1}(Fig. 6). At 120 mg $L^{-1}$of added K^+, the percentage of K^+ adsorption ranged from 18-27% on the untreated samples [$-H_2O_2$] and from 24-28% on the treated samples [$+H_2O_2$]. At 240 mg L^{-1} of added K^+, the percentage of K^+ adsorption was only about 10%, irrespective of H_2O_2 treatment. In general, the amount of K^+ adsorbed increased with increasing K^+ concentration irrespective of oxidization, although the slopes of the isotherms were steeper in the oxidized samples than the unoxidized ones. The paired t-test showed that the K^+ adsorption isotherms were significantly different among most of the fertilization treatments and were less differentiated among the fertilization treatments after the oxidization treatment (Fig. 6, Table 3).

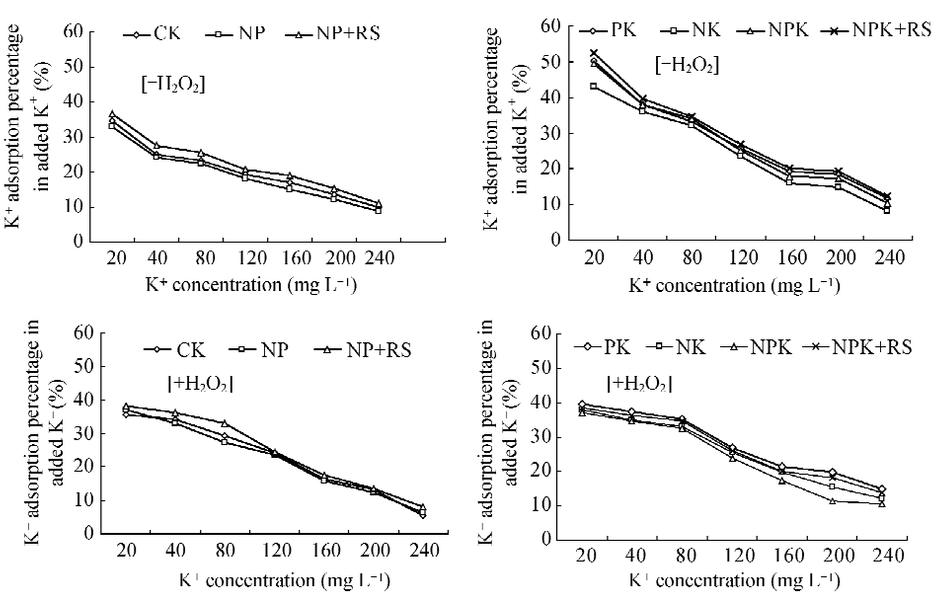

Figure 6 Potassium adsorption percentage of added K^+ for different fertilization treatments sampled in 2010 before organic matter removed ([$+H_2O_2$]) or not ([$-H_2O_2$]) from soil samples

Table 3 Difference in average K^+ adsorption between the different treatments (row subtracted by column) before no removed organic matter [$-H_2O_2$] and after removed organic matter [$+H_2O_2$] of soil sample

Treatment	Difference in average K^+ adsorption											
	[$-H_2O_2$]						[$+H_2O_2$]					
	PK	NP	NK	NPK	NP+RS	NPK+RS	PK	NP	NK	NPK	NP+RS	NPK+RS
CK	−73.8**	18.0**	−67.7**	−76.0**	−21.5**	−51.6**	0.9	4.0	24.4**	−32.8**	21.7**	−8.4*
PK		91.8**	6.0*	−2.32	52.2**	22.1**		3.1	−40.0**	−33.6**	20.9**	−9.2*
NP			−85.8**	−94.1**	−39.5**	−69.6**			−36.9**	−94.1**	−39.5**	−69.6**
NK				−8.3*	46.3**	16.2**				−57.2**	−63.2**	−32.7**
NPK					54.6**	24.5**					−6.0*	−42.1**
NP+RS						−30.1**						−36.1**

* Significant difference between treatments at $p < 0.05$.

** Significant difference between treatments at $p < 0.01$.

The relative K^+ adsorption capacity, defined as the difference in K^+ adsorption between [$-H_2O_2$] and [$+H_2O_2$] divided by the [$-H_2O_2$] treatment, showed a positive effect of SOC at low K^+ concentrations from 40 mg L^{-1} to 120 mg L^{-1} in all soils (Fig. 7). The SOC effect became negative at high K^+ concentrations from 160 mg L^{-1} to 240 mg L^{-1} under all treatments except the CK one and NP one at 160 mg L^{-1}, and became even more negative at K^+ concentrations of 240 mg L^{-1} under the PK, NK, NPK and NPK+RS treatments. The NPK+RS treatment had the largest negative SOC effect at the high range of tested K^+ concentrations. The relative K^+ adsorption showed that the K^+ adsorption of the [$+H_2O_2$] treatment divided by that of the [$-H_2O_2$] treatment, showed that the K^+ adsorption capacity in the oxidized soils accounted for from 40-144% of that in the unoxidized soils. The average amount of K^+ adsorption in the soils in the oxidized treatment in all treatments was 5.0% higher than in the unoxidized treatment, and was 2.9% higher in the combined application of rice straw treatments (NP+RS and NPK+RS) than in the NP treatment and the NPK treatment (Table 2).

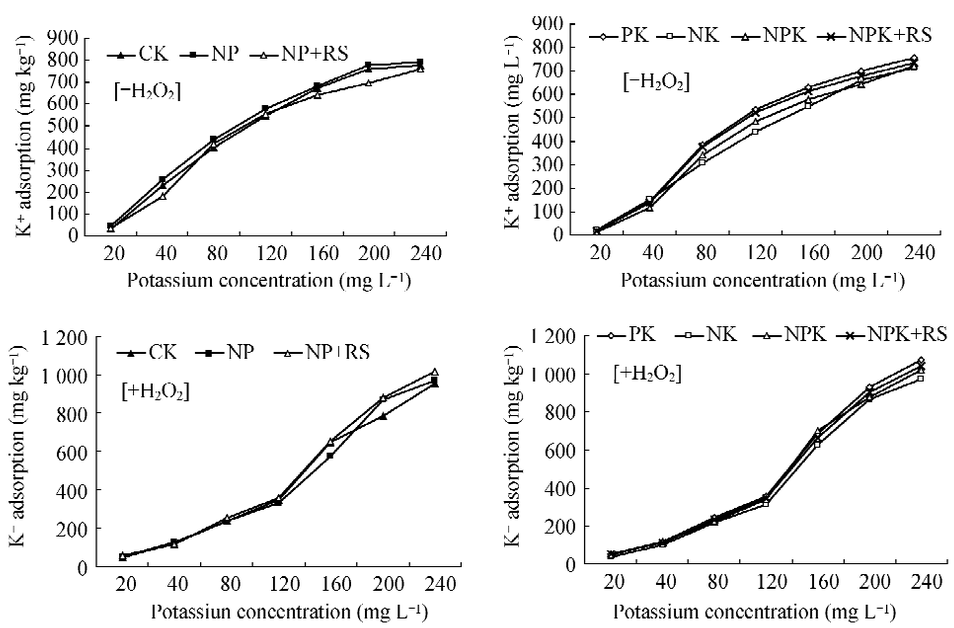

Figure 7 Potassium adsorption isotherms of different fertilization treatments sampled in 2010 before no removed organic matter [$-H_2O_2$] and after removed organic matter [$+H_2O_2$] of soil sample.

Traditionally, the Langmuir equation has been used to assess K adsorption capacity (M) and K adsorption affinity (K) of soil. In present studies, the K^+ adsorption isotherms were fitted well with the Freundlich for all samples tested (R>0.92; Table 4). The M value of this relation ranged from 329.2

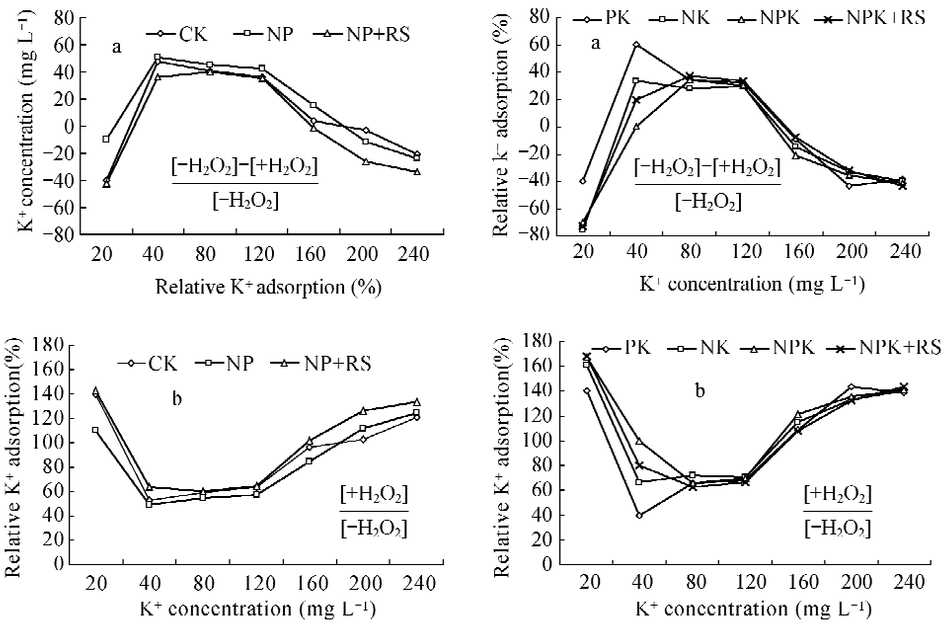

Figure 8 Relative K^+ adsorption, defined as (a) the difference between K^+ adsorption of the before no removed organic matter [$-H_2O_2$] and after removed organic matter [$+H_2O_2$] treatments divided by the no removed organic matter [$-H_2O_2$] treatment, (b) the K^+ adsorption of after removed organic matter [$+H_2O_2$] treatments divided by the no removed organic matter [$-H_2O_2$] treatment, for different fertilization treatments.

mg kg^{-1} to 925.9 mg kg^{-1} in the [$-H_2O_2$] treatments and from 213.2 to 781.3 mg kg^{-1} in the [$+H_2O_2$] treatments. The ΔG was from -20.17 kJ mol^{-1} to -22.87 kJ mol^{-1} in the [$-H_2O_2$] treatments and from -18.14 kJ mol^{-1} to -24.18 kJ mol^{-1} in the [$+H_2O_2$] treatments, suggesting that K^+ adsorption in the tested soils was a spontaneous reaction.

Table 4 Correlation coefficient and fitting parameters (adsorption potential, *M* and adsorption coefficient, *K*) of the Langmuir equation and free energy (ΔG) for different fertilization treatments before no removed organic matter [$-H_2O_2$] and after removed organic matter [$+H_2O_2$]

Treatment	[$-H_2O_2$]				[$+H_2O_2$]			
	R	*M*(mg kg^{-1})	*K*	ΔG(kJ mol^{-1})	*R*	*M*(mg kg^{-1})	*K*	ΔG(kJ mol^{-1})
CK	0.992	755.7	0.438	−20.89	0.969	751.9	0.435	−20.86
PK	0.993	329.2	0.619	−22.87	0.986	327.9	0.600	−22.69
NP	0.953	777.2	0.384	−20.14	0.982	724.1	0.270	−18.14
NK	0.966	580.8	0.519	−21.86	0.982	485.4	0.780	−24.18
NPK	0.950	699.3	0.447	−21.01	0.977	213.2	0.694	−23.52
NP+RS	0.958	925.9	0.386	−20.17	0.984	781.3	0.431	−20.80
NPK+RS	0.961	763.4	0.428	−20.76	0.980	322.6	0.620	−22.88

Oxidization of SOC increased in the Langmuir equation in all tested soils. The lowest of the increased magnitude was in CK and PK (5%), the greatest in NPK and NPK+RS (from 57.7% to 69.5%), and in between in the other treatments (PK, NP, NK and NP+RS, from 3.4% to 16.4%). The *M* value fell in the order of K fertilizer (PK, NK, NPK and NPK+RS) <no K fertilizer (NP and NP+RS) in the [$-H_2O_2$] treatment, and in the order of K fertilizer (PK, NK, NPK and NPK+RS) <no K fertilizer (NP and NP+RS) for the [$+H_2O_2$] treatment. The parameters of *K* in the Langmuir equation were significantly correlated to the total percentage of illite peak area and non-exchangeable K^+ in the <5 μm soil particles ($p = 0.032$, $p = 0.045$), but not to SOC content or exchangeable K^+.

4 Discussion

Yield decline in the NP plots was observed in early rice and late rice. This suggests that native soil K supply, K mineralized from subsoil and rice stubble residues, plus K in irrigated water and rain was insufficient to sustain an average rice yield of approximately 10–12 t ha^{-1} $year^{-1}$ in a double rice cropping system. Similar rice yields were obtained in the NP plots in other experiments on this site (*Liao* et al., 2008, 2009). In the long term experiment in northern China, the yield decline in the NP plots was sharp in initial years, but it remained at a stable level after a few years (*Shen* et al., 2004). In present studies, the rice yields of both early rice and late rice tended to increase over time in the treatments which received K fertilizer or combined application of fertilizer with rice straw. In early rice and late rice cropping seasons, the positive yield trends were observed in balanced application of NPK and combined application of fertilizer (NPK) with rice straw (NP+RS and NPK+RS), while the negative yield trends were observed in the CK, PK, NP and NK treatments with unbalanced nutrient application in the case of omitted N, omitted K and omitted P. These differing trends indicate that fertilizer management is a key factor in determining rice yield trends in the double rice cropping system in southern China. At the experimental site, the causes of increasing yield trends may be the buildup of K content in the soil. The soil in the experimental field was deficient in K (62.3 mg kg^{-1}). The continuous application of K as KCl, and rice straw, probably alleviated hidden K deficiency in the soil, which resulted in a significant increase of rice yield with NPK, NP+RS and NPK+RS treatments (*Liao* et al., 2010).

Results in this study showed that soil clay mineralogy appeared to be significantly changed, corresponding to the fertilization treatments during the 30 years that the field experiment had been running (Fig. 3). The clay mineralogy of the different treatments indicated that high productivity under balanced application of N, P and K (NPK and NPK+RS) resulted in a slight gain in illite content over the unfertilized plot samples (CK), while low productivity under the PK and NP treatments in the case of omitted-N and omitted-K increased the amount of illite (Fig. 3) or non-exchangeable K in the clays (Table 2). Unfertilized K treatments (NP) for 30 years resulted in a lower percentage of illite peak area than that in the CK-treated samples, and furthermore a loss of the K mineral phase. The NPK+RS treatment not only increased the illite content, but also developed very high productivity, which suggests that rice crops absorbed much of the applied K from fertilizer and rice straw. Our results are similar to the results published by *Fan* and *Xie* (2005).

In southern China, results show that 28 years of long-term application of K stimulated mineral transformation of vermiculite into illite (*Fan* and *Xie*, 2005). *Liu* et al. (2008) reported that cropping under unfertilized K led to a substantial decrease in illite content and an increase in mixed-layer illite-chlorite minerals over 23 years of fertilization experiments. In present experiments, the greater percentage of illite peak area in N and K treatments compared to unfertilized plot clays (CK) and the increased percentage of peak area in illite in the fertilized K treatments after 30 years, compared with the initial soil clays (Fig. 4), indicates that illite formation was increased by K addition. The inverse correlation between total illite and total V/CH irrespective of K saturation treatment (Fig. 7), supports the idea that a transformation of vermiculite into illite occurred in the studied soils because of long-term combined application of K fertilizer with N, P or rice straw. The increased percentage of illite peak area in the ML mineral along with free illite (Fig. 4A and 4B) indicated by the laboratory K saturation test of the clay, suggested that K application changed both the free and mixed-layer illite content of the whole-clay and fine-clay fractions. Furthermore, the fertilized K treatments increased the PCI proportion in free illites (Fig. 4), suggesting that the new illite created by the fertilizer treatments was of a small coherent diffracting domain size.

The whole-clay fractions (<5 μm) were more responsive to the fertilization treatments than the

fine-clay fractions (<1μm) (Fig. 3). It was reported that a large part of the chemically active portion of the soils occurred in the coarse clay fractions (*Pernes-Debuyser* et al., 2003). It was also found in our study that the percentage of illite peak area in the fine-clay fraction (<1μm) was negatively related to rice grain yield, suggesting that the K in the fine-clay fraction may be more available for rice uptake. Hence, long-term K storage can occur in the coarse-fraction illites, while the fine fraction is more readily affected by plant growth and K taken up by plants.

The paddy soils contain 31% clay on average. Thus, the 15 cm surface layer will have 5.1×10^5 kg clay ha^{-1} when soil bulk density is about 1.1 g cm^{-3} under flooding conditions (*Liao*, 2010). As illite contains 8% K_2O per layer (*Sparks* and *Huang*, 1985), the average change of 6% of total illite content in the soil clays following K saturation (Fig. 6C) would result in a potential of nearly 2 455.2 K_2O kg ha^{-1}, which can be exchanged within the clay structure yearly in the paddy soils. The K_2O application rate was 240.0 kg ha^{-1} yr^{-1} in the experimental fields, which is well below the amount that can be potentially adsorbed within the clay minerals. Therefore, fertilized K is not only an issue of plant nutrition but also of clay conservation in cropped soils where illite is the main clay mineral. This K can be taken up by plants (*Badraoui* et al., 1992; *Pal* et al., 2001) and the illite is then a long-term exchanger during crop growth each year.

The change in soil chemical and mineralogical properties resulted in significant variation in K^+ adsorption capacity (Fig. 7 and 8). The tested paddy soils adsorbed about 6～15% of the added K^+ at 240 mg $L^{-1}$and 18-27% at 120 mg L^{-1}(Fig. 7). Under those [$+H_2O_2$] oxidized treatments, the K^+ adsorption capacity of the balanced fertilization treatments of N, P and K (NPK and NPK+RS) was higher compared with the unbalanced fertilization treatments of N and P (NP) in the case of omitted K (Fig. 7). We also note that balanced fertilization treatments of N, P and K increased the K^+ proportion in the total soil K pool by 25% compared with those in paddy soils under the unbalanced fertilization treatments of N and P in the case of omitted K in the same experimental site (*Liao* et al., 2010). This result suggests that long-term fertilization influences the K pool size, optimizes K crop recovery, and minimizes K leaching to the water body (*Ji* et al., 2008).

The long-term fertilization caused little variation in SOC but more profound variation in non-exchangeable K^+ in the different treatments. The oxidization tests showed a positive effect of SOC in NPK+RS at the full range of K^+ concentration (up to 240 mg L^{-1}) and in other treatments at moderate K^+ concentration ranging from 20 to 120 mg L^{-1}(Fig. 7). We also note that K^+ adsorption may adsorb mainly on SOC at low K^+ solution content and that the K^+ is fixed in the interlayers of clay minerals at high concentrations. The affinity of K^+ ions for the exchangeable sites in the clay minerals is lower at low K^+ content than at high K^+ content (*Sparks* et al., 1980; *Sparks* and *Liebhardt*, 1981). Different K^+ adsorption capacity among the treatments suggests the importance of mineralogical properties on K^+ absorption. Furthermore, the variation of mineral composition in soil under the long-term fertilization resulted in a larger change of K adsorption capacity in the soil, and the soils with higher illite peak percentage (fertilized K treatments) had higher K^+ adsorption capacity. *Li* et al. (2000) reported similarly that K^+ adsorbing amount was significantly positive correlated to the non-exchangeable K content in reddish paddy soil. Balanced application of N and P with K increases the K^+ concentration in the soil (*Fan* and *Xie*, 2005; *Liao* et al., 2010) and enhances K^+ retention (*Lin* et al., 2007).

The oxidization test was designed to differentiate the K^+ adsorption effects between soil organic matter and soil clay minerals. The K^+ adsorption capacity of the soils oxidized with H_2O_2 accounted for 60-158% compared with those without H_2O_2 oxidization (Fig. 7). This suggests that soil minerals play a more important role in K^+ adsorption than SOC in the experiment's paddy soils, and that the presence of SOC would have reduced K^+ adsorption by soil minerals because of the steric effect of organic matter (*Evangelou* et al., 1986). The H_2O_2 oxidization caused little difference in the K^+ adsorption capacity among different fertilization treatments. However, this is probably because of the alteration of soil

minerals through repeated oxidization.

The significant correlation between parameters K of the Langmuir equation and the total percentage of illite peak area in the <5 μm soil clays and non-exchangeable K^+ in soil, shows the significant effect of the changes in soil minerals and non-exchangeable K^+ content because of fertilization on K^+ adsorption. This is consistent with other studies which have demonstrated that the presence of illite was the premise for K^+ adsorption (*Fan* and *Xie*, 2005). It is known that NH_4^+ ions can substitute for K^+ ions in illite (*Chen* and *Mackenzie*, 1992; *Liu* et al., 2008). The descending order of K^+ adsorption potential (M) of the K fertilizer and no K fertilizer (i.e. PK, NK, NPK, NPK+RS<NP, NP+RS) is in agreement with the theory that chemical adsorption characteristics are determined by the cation radii for fixation in the interlayer site of the minerals (*Sparks* and *Huang*, 1985). Although NPK and NPK +RS had the highest K^+ adsorption capacity, they had a smaller M than the fertilizer treatments of NK and NP+RS under the unoxidized condition (Table 4). This is probably due to a smaller change in soil minerals in NPK and NPK+RS compared with the above-mentioned treatments, and also the fact that the soil minerals have greater effects on K^+ adsorption than SOC. *Murashkina* et al. (2007) investigated K fixation capacity of different particle size fraction in Californian soils derived from granitic alluvium. They reported that coarse clay fractions were actually more active than the clay fraction regarding K fixation. Their coarse fractions were generally a richer vermiculite and therefore prone to fix to K, whereas the clay fractions were dominated by mica, resulting in a lower capacity to fix to K. Among the soil samples of present studies, coarse clay fractions seem to be associated with both a high K release potential (*Liao* et al., 2010) and a large K fixation adsorption capacity (compare Fig. 6). We can then speculate that K^+ would be adsorbed more on the coarser particles as they respond more to K fertilization, which increases the illite peak area percentage in the clay fraction.

Potassium ions may undergo adsorption immediately following fertilization and mineralization of organic matter when solution and exchangeable levels of K^+ are high, and then may be released and become available for uptake by plants and microorganisms when solution and exchangeable K^+ are depleted or fall below a certain level because of plant uptake and leaching (*Murashkina* et al., 2007; *Kolahchi* and *Jalali*, 2006). *Kolahchi* and *Jalali* (2006) reported that plant availability of added K^+ may be reduced because of a large vermiculite fixation potential. *Murashkina* et al. (2007) reported that the presence of vermiculite minerals reduced K^+ availability because of enhanced K^+ fixation; however, the adsorption free energy (ΔG) determined for the soils in our study showed that K^+ adsorption in the paddy soils was a spontaneous reaction (Table 4). This indicates that the recently adsorbed K^+ in the illite-dominant and organic-enriched soils can be readily taken up by crops or microbes. Previous studies indicated that Na^+ and Ca^{2+} facilitated the release of fixed K^+ while K^+ hampered it (*Aharoni* et al., 1993); however, it is still difficult to determine the availability of the newly adsorbed K^+. Further work is needed to study whether the K^+ desorption is nonlinear or rate limited and to detect the critical K^+ concentration in the soil solution at which K^+ can be released from the interlayer sites of clay minerals.

5 Conclusions

This study showed that clay mineralogy changes with fertilizer treatments. The long-term fertilization with combinations of N, P and K, with or without rice straw, did not change the apparent illite content in the soil, because of high K uptake of rice plants under high productivity. At low productivity, however, K application increased the illite content in the soils, while no K application depleted the illite content in the soils. The whole-clay fraction (<5 μm) corresponded more to fertilization treatments than the fine-clay fraction (<1 μm) in terms of the change in soil mineral composition. Long-term fertilization seemed to change V/CH into both free illite and layer illite in mixed-layer illite-chlorite minerals. The greatest effect was in forming PCI. The changes in clay

mineralogy were reflected in K^+ adsorption. The long-term application of chemical or organic fertilizers caused variations in K^+ adsorption. The H_2O_2 oxidization test, which eliminated most of the organic matter, clearly showed positive effects of SOC on K^+ adsorption, especially at comparatively low K^+ solution concentrations (<120 mg L^{-1}). Soil organic C reduced K^+ adsorption by clay minerals at higher K^+ concentrations. Soil minerals, however, played a more important role in K^+ adsorption than SOC, and the changes in soil mineral composition because fertilizer treatments had a large impact on the K^+ adsorption potential, as indicated by the significant correlation between the percentage of PCI peak area and K^+ adsorption potential. The more coarse grained clays (illite) had a greater impact on K^+ fixation. In all fractions, the PCI was highly important in K^+ fixation. It appeared that PCI in the fine fraction was more responsive to cation exchange of K^+ than the other minerals. In this study, we were unable to differentiate the effects of change in soil minerals on K^+ adsorption capacity, but only on the availability of adsorbed K.

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长期施肥对红壤性水稻土含钾黏土矿物组成和钾吸附的影响

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摘　要：通过优化水稻植株对钾的吸收和减少钾在环境中的损失，提高 K^+ 吸附性能有效增加土壤有效钾库容量。我们推测长期不同施肥水稻土化学和矿物学特性的变化可能导致了 K^+ 吸附的响应变化。本研究的目的是采用 X-射线衍射和分解光谱方法确定稻田土壤中不同黏土粒级的矿物组成；测定未经氧化[$-H_2O_2$]前（未除去有机质）和经氧化[$+H_2O_2$]后（除去有机质）的 K^+ 吸附等温线；探讨 K^+ 吸附与土壤的化学和矿物特征变化之间的相关性。结果表明：30 年长期不同施肥处理间土壤有机碳（SOC）的差异较少，但黏土矿物组成的差异较大。<5 μm 黏粒部分比<1 μm 黏粒部分与施肥处理土壤中伊利石的峰面积百分比变化更加对应。<5 μm 黏粒部分总蛭石-绿泥石的峰面积百分比与总伊利石峰面积百分比呈显著负相关（$r=-0.946$，$p=0.000\,6$）。不同施肥处理之间的 K^+ 吸附差异明显。SOC 氧化试验表明在低 K^+ 浓度（≤120 mg/L）时有机碳（SOC）对 K^+ 吸附呈正效应，而在较高的 K^+ 浓度（240 mg/L）时有机碳（SOC）效应为负值。经 SOC 氧化后土壤黏土矿物的 K^+ 吸附量占未经 SOC 氧化土壤的 60%～158%，表明土壤黏土矿物对 K^+ 吸附效应比有机碳对 K^+ 吸附效应强。K^+ 的吸附潜力与结晶不良伊利石的数量呈显著正相关（$r=0.879$，$p=0.012$）。吸附 K^+ 对水稻植株生长的有效性有待进一步深入研究。

关键词：长期定位施肥试验；矿物成分；钾吸附；红壤性水稻土

Acid-extractable potassium in agricultural soils: Source minerals assessed by differential and quantitative X-ray diffraction§ $

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Abstract: Different extraction methods are used world-wide in routine soil analysis to estimate long-term potassium (K) reserves for plants. In Sweden, K extracted with 2 M HCl at 100℃ (K_{HCl}) is frequently used, although with limited understanding of the phases extracted. In the present study we quantified the effects of this extraction on soil minerals in particle size fractions ranging from clay to sand, and estimated their relative contribution to K_{HCl}. The study included three Swedish long-term agricultural field experiments with texture ranging from loamy sand to silty clay, as well as mineral specimens of K feldspar. Total weight loss of particle size fractions was determined, and quantitative and differential X-ray powder diffraction (QXRD, DXRD), applied on solids before and after extraction, was used to quantify the dissolution of individual mineral phases. QXRD and DXRD included spray-drying of samples, addition of an internal standard and full pattern fitting, where a combination of mineral-standard XRD traces were matched with the experimental one. Our results show that K_{HCl} was primarily associated with clay minerals concentrated in the two finest fractions (2 - 20 and <2 μm). Highly expandable and mixed-layer phyllosilicates were quantitatively the most important minerals dissolved. The K was released from micaceous layers in mixed-layer phyllosilicates with a vermiculitic character. Whether di- or trioctahedral, a shared property of the dissolved phases was that they were rich in Fe. In the loamy sand, the coarser fractions (20 - 2 000 μm), where feldspars were prominent, accounted for 35% of K_{HCl}. According to DXRD, there was no significant decrease in K feldspars in any of the samples, and K_{HCl} data for the feldspar specimens suggest that clay minerals contributed at least 70% of K_{HCl} also in the loamy sand. Our study provides insights about the soil minerals that contribute to the long-term K delivery capacity of soils and an explanation for the prior observation that K_{HCl} is a dynamic fraction that can be affected by management.

Keywords: Potassium, soil mineralogy, clay minerals, HCl, acid extraction, potassium dynamics

1 Introduction

The total mineral potassium (K) reserve that is 'potentially' or 'slowly' available to plants is not well characterised in terms of detailed mineralogical properties. Furthermore, there is no universal definition or international standardised analytical method for the measurement of this K pool. Rather, various methods are used world-wide to determine what is often termed reserve, acid-extractable or non-exchangeable K (*Sparks*, 1987; *Andrist-Rangel* et al., 2006), even though the use of the latter name may be misleading as this pool often includes much more K than is potentially available on plant growth

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time scales (*Sha'ato* et al., 2000). The methods commonly used often involve chemical extraction with an acid, typically HCl or HNO_3. A range of studies have also shown that the acid-extractable K pool contributes or is significantly correlated to plant uptake (e.g., *Reitemeier* et al., 1948; *Mortland* et al., 1957; *Ståhlberg*, 1958; *Egnér* et al., 1960; *Becket* and *Clement*, 1973; *Sinclair*, 1979; *Ghorayshi* and *Lotse*, 1986; *Tributh* et al., 1987; *Schneider*, 1997; *Øgaard* et al., 2001; *Rupa* et al., 2001; *Ghosh* and *Singh*, 2001; *Øgaard* and *Krogstad*, 2005; *Andrist-Rangel* et al., 2007). Aside from added mineral fertilisers and manures, the only significant sources of K in soils are K-bearing minerals. However, there are few previous studies on the relationship between acid-extractable K and soil mineralogy (e.g. *Bhonsle* et al., 1992; *Ghosh* and *Singh*, 2001; *Øgaard* et al., 2002; *Simonsson* et al., 2007). This may be the reason why soil mineralogy is seldom given any attention in national advisory systems (*Holmqvist* et al., 2003). In practice, consideration needs only be focused on two groups of minerals, K-bearing phyllosilicates and K-bearing feldspars, which together represent the only K-bearing minerals that are both abundant and widespread components of soils (*Sparks* and *Huang*, 1985).

From 1965 onwards, the Egnér analytical method using 2 M HCl (*Egnér* et al., 1960) has been used within the Swedish agricultural advisory system (*KLS*, 1965; *SJV*, 2006), and since 2001 also in the Swedish Environmental Monitoring of Agricultural Soils and Crops (*Eriksson* et al., 2010). Acid extractions of similar strength are also used for similar purposes in other countries (*Øgaard*, et al. 2001). A study by *Güzel* and *Wilson* (1978) showed that repeated extractions of fractionated soil with 1 M HCl had the greatest effect in the clay fraction and that the main contribution to extracted K appeared to come from mica interlayered montmorillonitic minerals, whereas a separate micaceous phase was only insignificantly affected by the treatment. *Simonsson* et al. (2007) found that the net soil K balance resulting from the interplay of fertilisation and harvesting was a driving force for both fixation and release of non-exchangeable K. Most interestingly, the soil K balance also affected the pool of 2 M HCl extractable K (K_{HCl}), suggesting that this pool is influenced by fixation and release of non-exchangeable K. Thus, it appears that acid-extractable K may contain a large component of K that, although non-exchangeable, is nonetheless a dynamic pool in relation to availability to crops. Except for these observations and the fact that K_{HCl} seems to be related to K in phyllosilicates, there is little direct information on the effect of 2 M HCl extraction on soil minerals, or soil particle size fractions of a sample. Hence, it is not well known which phases actually release K in 2 M HCl, and what common properties may render minerals prone to K release.

The aim of this study was to obtain a deeper understanding of what the 2 M HCl acid extraction is actually measuring from a mineralogical perspective. Specific objectives were to quantify the relative contribution of different particle size fractions to K_{HCl}; to identify, characterise and quantify the K bearing minerals that contribute to this extraction; and to investigate how the contributing minerals are distributed among different particle size fractions. Our approach was to analyse the soil before and after HCl extraction. By combining mineralogical data obtained by differential X-ray diffraction and quantitative X-ray diffraction with data on the geochemical composition of the total soil and of extracted components, we aimed to quantitatively describe the effects of 2 M HCl on soil minerals.

2 Materials and Methods

2.1 Sites and sampling

Soils developed on a range of Quaternary deposits were collected at sites that represented three different reference soils in the World Reference Base for Soil Resources (WRB), and at the same time three different sub-orders in the Soil Taxonomy of the United States Department of Agriculture. The sites were situated in two distinct climatic/vegetation regions in central and southern Sweden (Tab. 1).

Högåsa (Hög) is located 173 km SW of the capital, Stockholm, on a glaciofluvial sand deposit mainly derived from a vast granitic bedrock area 2 – 3 km north of the site (*Fromm*, 1976). Fjärdingslöv (Fjä) is situated in southernmost Sweden 26 km SE of Malmö. The soil is formed in a glacial till with a texture of sandy loam consisting of fragments of Cretaceous rocks, including chalk (*Daniel*, 1977). Kungsängen (Kun), 61 km NNW of Stockholm, is located on a lacustrine postglacial gyttja clay deposit. Its mineralogy is derived partly from the local bedrock of Precambrian gneissic granites and felsic metavolcanic rocks, partly from Ordovician sediments approximately 100 km north of the site (*Möller*, 1993). The profile is to some extent influenced by a shallow groundwater table. Detailed descriptions of the sites, all of them hosting long-term agricultural experiments, have been published elsewhere (*Kirchmann*, 1991; *Kirchmann* et al., 1999; *Kirchmann* et al., 2005), as have studies on K balances (*Andersson* et al., 2007) and mineralogical properties regarding K (*Andrist-Rangel* et al., 2006; *Simonsson* et al., 2009). Samples were air-dried and sieved before further treatment and analysis; the term 'bulk soil' refers to fine earth (<2 mm). Within the sites, soil was pooled to yield representative samples for the soil layers 0 – 5, 5 – 10, 10 – 25, 25 – 40, 40 – 70 and 70 – 110 cm. These samples were subsequently split with a spinning riffler to yield sub-samples for analysis. In addition to the soils, four specimens of different potassium feldspars were obtained from the then Macaulay Institute (now The James Hutton Institute) mineral collection, to help identify its role as a source of K in HCl extracts. These specimens included two microcline feldspars (MIC-11, FEL-6) and one orthoclase feldspar (ORT-11). Quantitative analysis of these feldspars by the X-ray diffraction methods outlined below indicated that all were around 75% pure K feldspar, with the remainder made up mostly of plagioclase feldspar (albite) together with traces of quartz.

Table 1 Site and soil characteristics of the three Swedish study sites: Högåsa (Hög), Fjärdingslöv (Fjä), and Kungsängen (Kun).

Site	Coordinates (WGS84), northwest corner of experiment	Climate/ Vegetation zones	Mean annual prec. (mm)	Mean annual soil temp (C)[a]	Quaternary deposit[b]	Soil type (Soil Taxonomy[c]/ WRB[d])	Soil texture[d]	C_{org} (%)[e]	pH[f] ($CaCl_2$)	CEC[g] (pH 8.2)
Hög	58° 30′20.09″N; 15° 26′56.15 E[h]	Southern boreal	517	7.1[h]	Post glacial reworked sandy deposit	Humic Dystrocryept/ Arenic Umbrisol	Loamy sand	2.5	5.8	9.2
Fjä	55° 24′15.14″N; 13° 13′53.28″E[h]	Northern temperate	660	8.5[h]	Silty to sandy glacial till	Oxyaquic Hapludoll/ Haplic Phaeozem	Sandy loam	2.1	6.7	15.1
Kun	59° 50′12.18″N; 17° 41′11.29″E[h]	Southern boreal	660	5.4[h]	Lacustrine postglacial gyttja clay	Typic Haplaquept/ Gleyic Cambisol	Silty clay	2.8	5.8	24.2

[a] Estimated by adding 1℃ to the mean annual air temperature (USDA Soil Conservation Service 1981); [b] see Quaternary geology maps (1∶50 000) by Fromm (1976) for Hög, Daniel (1977) for Fjä, Möller (1993) for Kun; [c] classification according to Soil Survey Staff (2003) and FAO (2001), respectively; [d] texture based on particle size distribution for the 25 – 40 cm depth: wet sieving (2000 – 60 μm) and sedimentation by the pipette method (<60 μm) (Ljung 1987); [e] organic C determined by combustion using a FlashEA; [f] soil pH analysed in 0.01 M $CaCl_2$ (McLean 1982; Sumner 1994); [g] potential cation exchange capacity ($CEC_{pH8.2}$) after Na saturation (Polemio and Rhoades 1977); [h] coordinates and mean annual temperature according to Kirchmann et al. (2005) for Hög, Kirchmann et al. (1999) for Fjä, Kirchmann (1991) for Kun.

2.2 Soil particle size separation and preparation of feldspar samples

For soil particle size separation, samples from the 5 – 10 cm depth within the Ap horizon were used.

Particle size fractions were obtained by a combination of wet sieving (2 000 - 200 and 200 - 60 μm fractions) and sedimentation in Atterberg cylinders (60 - 20, 20 - 2 and <2 μm fractions) following ultrasonic dispersion (600 W, Amp 100%, 25 mm probe). Sand fractions were concentrated by drying (105℃) and the silt and clay fractions by freeze-drying. Total carbon content was determined in the fractions by combustion using a FlashEA elemental analyser. With the exception of subsoil samples from Fjä, the fractions contained no calcite, and hence total carbon could be assigned to organic carbon. Organic matter (OM) was calculated from total carbon assuming 58% C in the former. The feldspar samples MIC - 11 and FEL - 6 were crushed and hand-ground individually until all particles passed through a 500 μm sieve. For the orthoclase (ORT-11) two different powders were prepared, of 2 - 20 μm and 150 - 200 μm particle size, respectively.

2.3 HCl treatment

Bulk soil from all depths, soil particle size fractions from the 5 - 10 cm depth and feldspars were extracted in 2 M HCl at 100℃ according to the procedure of *Egnér* et al. (1960). Specifically, solids and 25 mL of 2 M HCl per g of air-dry solids were placed in glass flasks in a boiling water-bath for 2 h; the flasks were swirled after 30, 60 and 90 min, and transferred to a cool water-bath after 120 min. After centrifugation (2 000 rpm, 5 min) to prevent loss of HCl treated sample, the extracts thus obtained were filtered (00H filter paper, Munktell Filter AB, Grycksbo, Sweden) and analysed for Al, Ca, K, Mg, Na, P and Fe by Inductively Coupled Plasma-Atomic Emission Spectrometry (ICP-AES, Perkin Elmer Optima 3 000 DV). To reduce the acidity and salinity of the HCl-treated residues, they were washed at least four times with 0.5 M $MgCl_2$ and finally twice with deionised water. Weight loss was calculated based on sample weight before HCl treatment and after freeze drying of the residues.

2.4 Total geochemical analysis

Total elemental analysis was performed on the bulk soil samples from the soil profiles by X-ray fluorescence (XRF) under contract at the University of Southampton. Ring and puck mill (Tema) ground samples (<75 μm) were prepared as fused glass beads using Spectroflux 100B ($4LiBO_2$: $1Li_2B_4O_7$). The instrument used was a Philips MAGIX-PRO with SuperQ4 software and a 4 kW Rh end-window X-ray tube. A solubility ratio of individual oxides was calculated. It was defined as the ratio of (1) oxide concentration in the HCl extract, expressed as a percentage of the dissolved mass, to (2) oxide concentration in untreated soil according to XRF. Accordingly, a ratio >1 indicates that minerals containing the oxide of interest were selectively dissolved by the acid; i.e., the oxide was relatively more concentrated (as a percentage of mass dissolved) in the extract compared to the whole soil. A ratio <1 indicates the opposite. Note that expressing the element in the extract as an oxide is done simply to facilitate comparison with the XRF analyses of the bulk soil; it does not imply the presence of the free oxides in the soil.

2.5 X-Ray Diffraction Methods

X-ray diffraction analysis was performed on bulk soil, soil particle size fractions and feldspar mineral samples. Random powders were prepared by wet McCrone milling of 2.4 g of sample plus 0.6 g of corundum (α Al_2O_3 powder <10 μm), added as an internal standard, and spray drying of the resulting slurries directly from the mill (*Hillier*, 1999; *Hillier*, 2003). All random powders were run on a Siemens D5 000 diffractometer, using Co Kα radiation selected by a diffracted beam monochromator, scanning from 2 to 75° 2θ in 0.02° steps and counting for 5 s per step. Quantitative mineralogical analysis was carried out by a full pattern fitting method similar to that described for participant 18 (p18) in *Omotoso* et al. (2006), but also including the added corundum as internal standard. With this method, reference patterns of pure minerals and also non-crystalline phases, e.g. organic matter, were fitted to the observed diffraction patterns using least squares minimisation of an objective function. The calculations were made using an Excel spread sheet and the Solver add-in. Small offsets in 2θ between patterns were accommodated by a cubic spline interpolation, as suggested by

Schulze (1986). To our knowledge, the procedure, from preparation of random powders to the full pattern fitting, is the single most reliable quantitative mineralogical method entirely based on X-ray diffraction. Analysis of single samples will henceforth be referred to as 'QXRD'; i. e., quantitative X-ray diffraction.

Using a similar spreadsheet-based optimisation procedure, differential X-ray diffraction (DXRD) patterns (*Schulze*, 1986; 1994) were derived by subtraction of XRD patterns of HCl treated samples from the XRD patterns of the untreated samples. For both QXRD and DXRD the objective function used to minimise the difference between diffraction patterns was the least-squares error criteria as described by *Howard* and *Preston* (1989).

The clay fractions (<2 μm) were also prepared as orientated mounts on glass slides using a filter peel method (*Hillier*, 2003). To facilitate comparison of untreated with HCl-treated clay fractions, all clays were saturated with Mg before preparation of the slides (three washes of 25 mL 1 M $MgCl_2$). All orientated mounts were analysed air-dried, glycolated and after heating to 300℃ for 1 h. Instrument settings were as for the random powder scans, except for a shorter 2 s count per step and 2 - 45° 2θ range.

3 Results

3.1 Weight loss

The weight loss due to HCl treatment of the bulk soil varied between 5 and 21% (Tab. 2), and the weight loss of the individual soil particle size fractions varied between 2 and 38% (Tab. 3). For the size fractions there was a clear relationship between particle size and weight loss, with proportionally larger weight loss from the finer fractions compared with the coarser. The soil from Kun was the only exception, as it also showed an exceptionally large weight loss from the sand (60 - 2 000 μm) fraction. Weight loss of the feldspar specimens varied between 1 and 3% (Tab. 3).

Table 2 Weight loss (%) after extraction (2 M HCl) and K (g kg^{-1}) in extracts from bulk soil (<2 000 μm).

Site	Depth (cm)	Weight loss (%)	K_{HCl} (g kg^{-1})
Hög	0 - 5	9	0.71
	5 - 10	8	0.64
	10 - 25	8	0.57
	25 - 40	7	0.49
	40 - 70	6	0.51
	70 - 110	5	0.49
Fjä	0 - 5	10	1.56
	5 - 10	11	1.44
	10 - 25	11	1.33
	25 - 40	10	1.32
	40 - 70	13	1.51
	70 - 110	21	1.60
Kun	0 - 5	20	5.38
	5 - 10	20	5.15
	10 - 25	20	5.25
	25 - 40	19	5.45
	40 - 70	19	5.88
	70 - 110	19	6.68

Table 3 Results for particle size fractions of soil from 5 - 10 cm depth: Particle size, percentage of fractions in bulk soil (<2 000 μm), weight loss after extraction in hot 2 M HCl, concentration of HCl extractable potassium (K_{HCl}) in fractions, and relative contribution to K_{HCl} of the bulk soil. Where applicable, data are also shown for 'MIC-11' to 'ORT-11', which were feldspar specimens described in Section 2.1 and 2.2.

Site/ Specimen	Fraction (μm)	Particle size distribution (% of <2 000 μm)	Weight loss (% of fraction)	K_{HCl} (g kg fraction^{-1})	Contribution to K_{HCl} of bulk soil (%)
Hög	200 - 2 000	25	2	0.15	10
	60 - 200	43	2	0.13	15
	20 - 60	15	4	0.24	10
	2 - 20	12	24	1.2	37
	<2	4	38	2.4	28
Fjä	200 - 2 000	27	2	0.21	5
	60 - 200	27	2	0.25	6
	20 - 60	14	2	0.32	4
	2 - 20	18	13	1.6	24
	<2	15	33	4.7	61
Kun	60 - 2 000	4	22	2.7	2
	20 - 60	13	5	0.47	1
	2 - 20	34	14	2.2	16
	<2	49	29	7.9	81
MIC-11	<500		2	1.0	
FEL-6	<500		2	1.0	
ORT-11	150 - 200		1	0.49	
ORT-11	2 - 20		3	1.6	

3.2 Chemistry of extracted components

3.2.1 K_{HCl}

The concentration of K_{HCl} was rather constant in the individual profiles, whereas differences were very obvious between the soils: Hög was the lowest, Fjä intermediate and Kun was by far the highest in K_{HCl} (Tab. 2). Among the particle size fractions, there was a clear trend of higher K_{HCl} concentrations extracted from finer fractions than from coarser, with an obvious increase at 20 μm (Tab. 3). Once again, the only exception was the sand fraction of Kun, which, in accordance with the anomalous weight loss for this fraction, showed higher K_{HCl} values than the coarse silt fraction (Tab. 3). Taking the mass in the different size fractions into account also showed that the finer fractions (<20 μm) made the largest contribution to bulk soil K_{HCl} (Tab. 3). However, in Hög, which is a loamy sand, the coarser fractions (>20 μm) accounted for 35% of the bulk soil K_{HCl}. Table 3 also shows K extracted from the feldspar specimens, which will be discussed below in the context of potential sources of K_{HCl} in the soils; it varied between 0.5 and 1.6 g kg^{-1}.

3.2.2 Geochemistry

The total K_2O concentration of the untreated bulk samples from the profiles was around 2.6% at Hög, 2.1% at Fjä and 3.7 - 4.3% at Kun, with a clear increase with depth in the latter soil (Tab. 4). The geochemistry of the part dissolved by the HCl extraction showed the same general trend for all treated soil samples, both bulk soil and fractions, namely $Fe_2O_3 \approx Al_2O_3 > CaO \approx MgO > K_2O > P_2O_5 \approx Na_2O$; Fe and Al oxides together accounted for up to 50%, and $K_2O \leqslant 4\%$ (data not shown). However, as seen in Tab. 4 there was a major difference in the proportions of different oxides in the dissolved part compared with those of the untreated sample, as demonstrated by the solubility ratio (see definition in Section 2.4). With solubility ratios in the range 3-11, P_2O_5, MgO, Fe_2O_3 and CaO were considerably more common in the dissolved part than in the untreated sample. For Na_2O the opposite occurred. K_2O and Al_2O_3 were intermediate; K_2O had slightly lower concentrations in the dissolved part than in the untreated sample, whereas for Al_2O_3 it was the opposite.

Table 4 Total geochemical composition of bulk soil (<2 000 μm) of the untreated samples determined by X-ray fluorescence (XRF; % weight), and solubility ratio for different soils and depths. The solubility ratio was the ratio of (i) the element concentration in the HCl extract expressed as an oxide percentage of the dissolved mass to (ii) the oxide concentration in untreated soil.

Site	Depth (cm)	Total geochemical composition (% weight)									Solubility ratio						
		SiO_2	Al_2O_3	Fe_2O_3	MgO	K_2O	Na_2O	CaO	P_2O_5	TiO_2	Al_2O_3	Fe_2O_3	MgO	K_2O	Na_2O	CaO	P_2O_5
Hög	0-5	78	9.1	1.9	0.44	2.6	2.1	1.1	0.17	0.30	2	7	6	0.4	0.1	3	10
	5-10	77	9.2	2.0	0.45	2.6	2.1	1.1	0.17	0.32	2	7	6	0.4	0.1	4	9
	10-25	77	9.1	1.9	0.43	2.5	2.0	1.1	0.16	0.31	2	7	6	0.3	0.1	3	9
	25-40	78	9.4	2.0	0.45	2.6	2.1	1.0	0.12	0.31	2	9	8	0.3	0.1	3	10
	40-70	78	9.3	2.0	0.47	2.7	2.3	1.0	0.10	0.28	2	10	9	0.4	0.1	3	14
	70-110	79	9.2	1.9	0.48	2.7	2.3	1.1	0.10	0.29	2	11	11	0.4	0.1	4	17
Fjä	0-5	80	7.4	2.4	0.58	2.1	0.89	0.90	0.13	0.40	3	8	7	0.9	0.1	6	8
	5-10	80	7.4	2.5	0.59	2.0	0.83	0.95	0.12	0.40	2	7	6	0.8	0.1	6	7
	10-25	80	7.5	2.4	0.60	2.1	0.81	0.95	0.12	0.41	2	7	6	0.7	0.1	6	8
	25-40	80	7.8	2.8	0.68	2.1	0.83	1.1	0.08	0.43	3	8	7	0.7	0.1	7	8
	40-70	77	8.0	3.0	0.81	2.2	0.89	3.1	0.08	0.41	2	6	5	0.6	0.1	7	6
	70-110	71	6.9	2.6	0.79	2.1	0.79	8.3	0.16	0.37	1	3	3	0.4	0.1	4	3
Kun	0-5	60	15	6.8	2.1	3.7	1.6	1.8	0.28	0.76	1	4	3	0.9	0.1	2	3
	5-10	60	15	6.7	2.1	3.7	1.6	1.8	0.24	0.76	1	4	3	0.8	0.2	2	4
	10-25	61	15	6.9	2.1	3.8	1.7	1.8	0.23	0.76	1	4	3	0.8	0.2	2	4
	25-40	61	15	7.6	2.3	3.9	1.7	1.7	0.17	0.78	1	4	3	0.9	0.2	2	4
	40-70	61	16	7.7	2.4	4.2	1.7	1.6	0.18	0.79	1	4	3	0.9	0.2	2	4
	70-110	60	16	7.0	2.4	4.3	1.7	1.4	0.20	0.80	2	4	4	1.0	0.2	2	5

3.3 Mineralogy

3.3.1 X-ray diffraction of bulk soil-random powders

DXRD patterns of the 5-10 and 40-70 cm depth samples (Fig. 1) show that the extent to which the three soils reacted to the HCl treatment was quite different. The DXRD patterns from the Hög soil showed the least evidence of any mineralogical change during the extraction. Indeed, any changes that may have occurred were either of similar or smaller magnitude than the noise and other aberrant effects in the DXRD patterns, and it was therefore not possible to establish with any certainty the nature of any miner alogical changes in the bulk Hög soil. In contrast, for both the Fjä and the Kun soils, the DXRD patterns showed clear evidence of selective dissolution of phyllosilicates. In the Fjä profile, the positions of non-basal phyllosilicate peaks at approx. 4.52 and 1.51 Å in the DXRD patterns demonstrated that the HCl treatment had solubilised a dioctahedral phyllosilicate. In the 40-110 cm layers, calcite was also dissolved, as evident from the array of distinct peaks at 3.86, 3.04, 2.49, 1.91 and 1.87 Å in the DXRD pattern (see Fjä 40-70 cm in Fig. 1). At Kun, the treatment effect was internally very similar throughout the profile. Both di-and trioctahedral phyllosilicates phases were affected by the HCl treatment, as evident from peaks in the DXRD patterns between 4.45 and 4.67 Å and peaks at both 1.53 and 1.51 Å (Fig. 1).

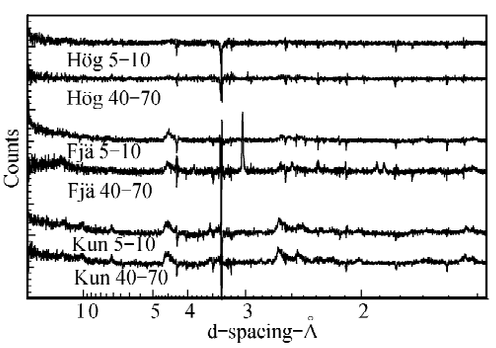

Figure 1 Differential X-ray diffraction (DXRD) patterns from random powders of untreated and 2 M HCl treated bulk soil (<2 000 μm) samples from the 5-10 cm and 40-70 cm depths of the three different soil profiles Hög, Fjä and Kun.

3.3.2 X-ray diffraction of particle size fractions - random powders

The HCl treatment of the fractionated surface soils (5-10 cm depth) had the greatest effect on the two finest particle size fractions; i.e., 20-2 and <2 μm. QXRD analysis showed that there were significantly lower concentrations of several mineral phases in the treated samples compared with the

untreated (Tab. 5). The main minerals affected by the acid treatment were a variety of di- and trioctahedral phyllosilicates. Of these, highly expandable and mixed-layer phyllosilicates were quantitatively the most important minerals dissolved, although the mineralogical analysis of Kun also highlighted a significant contribution from discrete trioctahedral mica (biotite/phlogopite). Kun was the only soil with a significant decrease in several phyllosilicate phases in the sand size fraction (Tab. 5), corresponding with the data on the anomalously elevated weight loss and K_{HCl} for this size fraction. Apart from phyllosilicates, goethite was also affected in many samples, and some organic matter appeared to have dissolved. Notably, the QXRD showed no significant decrease in K feldspars (Tab. 5) in any of the samples, despite their relative abundance in all size fractions.

Table 5 Change in mineralogical composition (% weight of original soil) due to 2 M HCl treatment of soil particle size fractions (5 - 10 cm depth) according to quantitative X-ray diffraction of random powders (QXRD; see Section 2.5). Values represent significant differences between untreated and treated (HCl) samples. Changes were considered significant if confidence intervals (*Hillier*, 2003) did not overlap. A '+' indicates that the mineral was present at quantifiable concentration, but did not change significantly due the treatment; 'tr' indicates that the mineral was detected in the untreated sample only at a concentration below what is possible to quantify; a dash ('—') means that the mineral was not detected in the untreated sample.

Site	Fraction (μm)	Goethite	Musc-ovite	Illite & ML dioct	Fe dioct exp	Chlorite	Trioct mica[a]	Vermi-culite	Hydro biotite	Trioct exp	K feld-spars
Hög	200 - 2 000	tr	+	tr	—	tr	tr	tr	tr	—	+
	60 - 200	tr	+	—	—	tr	tr	tr	tr	—	+
	20 - 60	tr	+	tr	—	tr	tr	tr	tr	—	+
	2 - 20	−1.1	+	−4.7	+	+	tr	tr	−2.9	−1.8	+
	<2	−2.5	−4.2	−4.4	−5.5	+	tr	−1.6	−5.2	+	+
Fjä	200 - 2 000	—	tr	—	—	—	—	tr	tr	—	+
	60 - 200	tr	tr	—	—	—	—	—	tr	—	+
	20 - 60	tr	+	—	—	tr	—	tr	tr	—	+
	2 - 20	tr	+	−5.7	−2.1	tr	tr	tr	−1.2	—	+
	<2	−1.6	+	−8.7	−23	tr	tr	—	−3.1	−2.5	+
Kun	60 - 2 000	−3.6	+	−3.8	—	−2.6	−2.6	+	−4.7	tr	+
	20 - 60	+	+	tr	—	tr	+	tr	tr	—	+
	2 - 20	tr	+	+	—	+	−1.7	tr	−2.8	−1.7	+
	<2	−2.1	+	−11	−1.2	−2.1	−4.8	—	−4.9	−10	+

[a] Includes biotite and phlogopite.

Figure 2 shows DXRD patterns for the <2 μm fractions. These patterns present the clearest evidence of all that the main potentially K bearing phases affected by HCl treatment at all sites were phyllosilicates. Based on the position of the 06*l* peaks at 1.535 Å at Kun, the DXRD pattern showed that the phyllosilicates affected had a dominant trioctahedral character, whereas for Fjä the character was largely dioctahedral since the principal 06*l* peak is at 1.509 Å. Hög was more difficult to assess, but appeared substantially trioctahedral (Fig. 2). A further notable feature of both the Kun and the Fjä DXRD patterns was that the 20*l*, 13*l* band that occurs between about

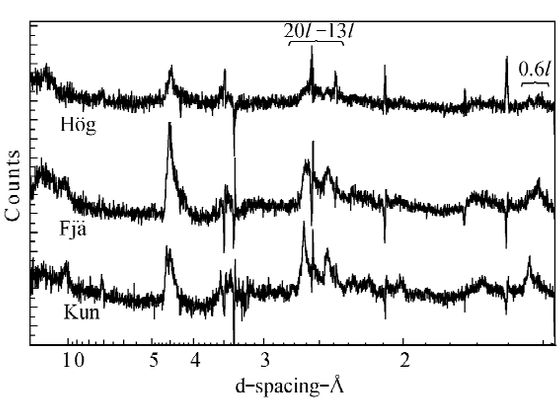

Figure 2 Differential X-ray diffraction (DXRD) patterns from random powders of untreated and 2 M HCl treated clay fractions (<2 μm) samples from the 5 - 10 cm depth of the three soils Hög, Fjä and Kun.

2.7 and 2.2 Å was clearly modulated into two maxima. The significance of this type of pattern with respect to K content of the phyllosilicates is considered in the discussion.

3.3.3 X-ray diffraction of clay fractions – parallel orientated

Examination of the X-ray diffraction patterns obtained from highly orientated <2 μm preparations before and after HCl treatment revealed some further complementary and confirmatory details of the nature of the phyllosilicates solubilised by HCl (Fig. 3 – 5). Thus in all three soils, prominent peaks near to 14 Å in the air-dried traces, which responded more or less to glycolation depending on the sample and collapsed only partially on heating, were either removed completely or drastically reduced in intensity following treatment. Variously expandable components, including mixed-layer minerals, that produced peaks at somewhat greater and lesser spacings than 14 Å in the air-dried traces, were also drastically reduced. Although the detailed interpretation of these changes in terms of the minerals solubilised by HCl is somewhat different for each soil, in general, it is clear that the HCl treatment removed or destroyed the structure of the most expandable (swelling) mineral phases and left behind a micaceous (10 Å) residue phase and an associated mixed-layer component which appeared to tail away from it towards larger d-spacings (Fig. 3 – 5). In addition, peaks in the heated traces before and after HCl treatment indicated that small amounts of chlorite were also solubilised in all three samples.

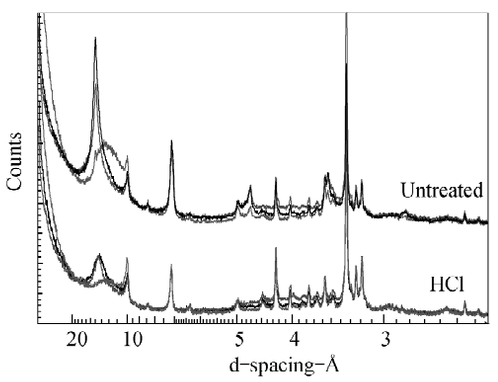

Figure 3 X-ray diffraction patterns of untreated and HCl treated ('HCl') parallel orientated clay fractions from the 5 – 10 cm depth at Högåsa: air-dried (black trace), glycolated (blue) and heated to 300℃ (red).

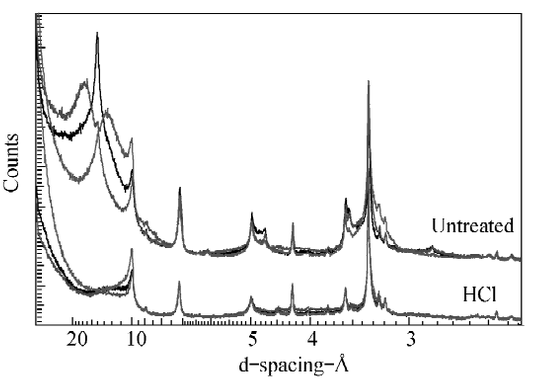

Figure 4 X-ray diffraction patterns of untreated and HCl treated ('HCl') parallel orientated clay fractions from the 5 – 10 cm depth at Fjärdingslöv: air-dried (black trace), glycolated (blue) and heated to 300℃ (red).

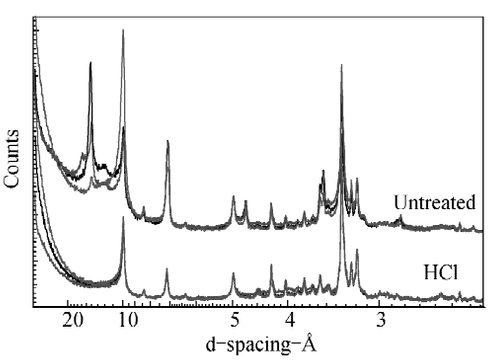

Figure 5 X-ray diffraction patterns of untreated and HCl treated ('HCl') parallel orientated clay fractions from the 5 – 10 cm depth at Kungsängen: air-dried (black trace), glycolated (blue) and heated to 300℃ (red).

4 Discussion

4.1 Potassium sources and size fractions

In essence there are only two common and widespread potential mineral sources of K in soils,

namely feldspars and micaceous phyllosilicates (*Bertsch* and *Thomas*, 1985). In all the soils studied, the overall weight loss due to HCl treatment and the concentration of K in the extract solutions were inversely correlated with particle size. However, the increase in solubility with respect to size fraction appeared not to be gradual, but changed abruptly between the two silt fractions >20 and <20 μm (Tab. 3), suggesting a significant change in mineralogy between these two fractions and/or a surface area effect on solubility. The 20 - 60 μm silt fraction behaved more like the sand fraction, with low weight loss and low K_{HCl}, whereas the fine silt fraction (2 - 20 μm) acted more like the clay fraction. Previous results from the present soils indicated a close relationship between K_{HCl} and K present in phyllosilicates (*Andrist-Rangel* et al., 2006). The present QXRD results before and after extraction demonstrate very clearly that the weight loss and the K released to the extract from the various size fractions was closely related to dissolution of these minerals (Tab. 3 and 5), which were most abundant in the fractions finer than 20 μm. The sand and coarse silt fractions from all soils typically contained less than 6% phyllosilicates. The fine silt fractions, on the other hand, all contained in excess of 20% and the clay fractions more than 50% phyllosilicates (full mineralogy data of the fractions are available from the authors). Following extraction, the concentrations of many of the phyllosilicates in these fractions were reduced considerably (Tab. 5), whereas effects on all other phases, apart from iron oxides, were not apparent. The exceptional behaviour of the sand fraction of Kun, with a large weight loss and relatively high K_{HCl}, is also explicable in terms of its exceptionally high (20%) content of phyllosilicates. Visual inspection of the Kun sand fraction under a binocular microscope indicates that these phyllosilicates are present in sand size rock fragments of shale and phyllite, which are presumably components of the parent material of this soil.

4.2 The role of potassium feldspars

Pot experiments performed long ago demonstrated a relative insignificance of feldspars in providing growing crops with K (Prianischnikow, 1912; Ståhlberg, 1958). Unpublished work with pot experiments and field trials at the Macaulay Institute for Soil Research conducted in the early 1980's, also failed to identify any effects on plant growth from the application of K feldspar to soils (*Sinclair* pers. comm., 2012). Our results are somewhat ambiguous as to whether this is reflected by the present extraction method. Based on the QXRD and on DXRD patterns there was no direct evidence for dissolution of K feldspar in any of the soils or fractions examined (Tab. 5). Compared with all of the bulk soils and most of the particle size fractions, the 1 - 3% weight loss from the feldspar specimens due to HCl treatment (Tab. 3) was relatively small. Detection by X-ray diffraction analysis of a similar extent of feldspar dissolution in the soils is unlikely. Due to the high content of K in these minerals, however, one might suspect that their possible dissolution gave a significant contribution to overall K_{HCl} in some soils. Estimates of the potential feldspar contribution to total K_{HCl} are given in Tab. 6. The calculation is based on the content of K feldspar in different particle size fractions according to QXRD, combined with soil texture data and an estimated extractability of K feldspar of a given particle size, the latter obtained from Tab. 3. We had to assume that feldspar extractability in the soils was similar to that of the pure mineral specimens. This may be an overestimation because the feldspars used in the study were freshly ground mineral specimens, probably with more reactive surfaces than soil minerals that have been exposed to weathering for many years. The most important potential contribution on a relative basis, 12 - 32% of total K_{HCl}, was found in Hög, which is a soil with a poor capacity to release K from soil minerals in the long term (*Simonsson* et al., 2007). However, considering the fact that feldspars constituted as much as approximately 80% of the total K content of this soil (*Andrist-Rangel* et al., 2006), it is clear that the HCl extraction discriminated against dissolution of K from these minerals. Extrapolated to a topsoil layer (0 - 25 cm) with a dry bulk density of approximately 1 300 kg m^{-3}, the estimated feldspar contribution to K_{HCl} was in the range 200 - 700 kg ha^{-1} in this soil. This is of the same order of magnitude as the exchangeable K, which was 70 - 800 kg ha^{-1} in the topsoil (0 - 25 cm)

depending on fertiliser application rate. It can also be compared with the annual off-take in harvested crop products, which was of the order 50 – 100 kg ha^{-1} yr^{-1} (*Simonsson* et al., 2007). Within this context, it can be argued that possible feldspar dissolution in Hög does not represent an appreciable amount of 'reserve K' according to the HCl test. In Swedish extension work, reserve K, as extracted with the present HCl method, is classified according to a scale with five degrees. The content of K_{HCl} in Hög (Tab. 2) puts this soil into the poorest class, '1'; by the same standards, Fjä is a '3' and Kun a '5'. Obviously, any feldspar dissolution during HCl extraction did not appreciably overestimate the long term K delivery capacity of the investigated soils.

Table 6 Content of K feldspar in particle size fractions of soil from 5 – 10 cm depth and their estimated contribution to total K_{HCl} of the soils.

Fraction	K feldspar content (% weight)[a]			Estimated K_{HCl}, from pure K feldspar (g kg^{-1} mineral)[b]	K_{HCl} from K feldspar (g kg^{-1} soil)[c]		
	Hög	Fjä	Kun		Hög	Fjä	Kun
200 – 2 000	16	5.9		0.5 – 1	0.02 – 0.04	0.01 – 0.02	
60 – 200 (in Kun, 60 – 2 000)	11	7.6	11	0.5 – 1	0.02 – 0.05	0.01 – 0.02	0.002 – 0.004
20 – 60	13	11	15	0.5 – 2	0.01 – 0.04	0.01 – 0.03	0.01 – 0.04
2 – 20	10	8.5	14	1 – 3	0.01 – 0.04	0.02 – 0.05	0.05 – 0.14
<2	7.0	3.0	7.6	5 – 15	0.01 – 0.04	0.02 – 0.07	0.19 – 0.56
Sum					0.08 – 0.21	0.06 – 0.18	0.25 – 0.74
Percent of total K_{HCl}					12 – 32%	4 – 13%	5 – 14%

[a] Content of K feldspar in particle-size fractions according to quantitative X-ray diffraction (QXRD); [b] K extraction rates of pure K feldspar in the different particle-size fractions estimated from Tab. 3; [c] product of (a), (b), and particle-size classes' contributions to soil texture (Tab. 3).

4.3 Effects on phyllosilicates

Both QXRD and DXRD showed that the types of phyllosilicates dissolved may be both trioctahedral and dioctahedral depending on the sample. The trioctahedral phases solubilised were almost certainly rich in Fe and Mg. At 1.51 Å; the position of the 06*l* band in the DXRD pattern of the clay fraction (< 2 μm) from Fjä, although clearly dioctahedral, is also indicative of an Fe rich composition for the phase that dominates this pattern. These observations probably explain why the HCl extracts were enriched in Fe and Mg, although the dissolution of Fe oxides, noted particularly in the finer fractions (Tab. 5), may explain some of the extracted Fe, and presumably also P, which is commonly associated with Fe minerals in the soil.

The DXRD patterns of the <2 μm fractions (Fig. 2) and the X-ray diffraction patterns of orientated <2 μm fractions before and after HCl treatment (Fig. 3 – 5) provided the most detail about the nature of the phyllosilicates solubilised by HCl. For the DXRD patterns, perhaps the most interesting feature was the modulation of the 20*l*, 13*l* clay band at 2.7 – 2.2 Å into two distinct maxima (shown in Fig. 2). Such a pattern is not that of a purely expandable (swelling) clay mineral, such as a turbostratic smectite, nor is it similar to the pattern expected from more ordered vermiculites, or those of trioctahedral micas which were solubilised in the Kun samples. Instead, it is the type of pattern expected from some forms of mixed-layer minerals consisting of expandable and non-expandable layers. For example, wetting and drying of smectites in the presence of K causes K fixation and a consequent transformation of the turbostratic 20*l*, 13*l* band to one that is modulated into two distinct maxima (*Plancon* et al., 1978). Similar changes in the form of the 20*l*, 13*l* band are also observed in diagenetic clay minerals of the smectite to illite series, partly as a function of illite (K) content (*Reynolds Jr* and *Walker*, 1993). In essence, K^+ ions in interlayer sites act as keys that lock the oxygen planes of two adjacent 2 : 1 layers into a regular arrangement whereby the relationship between some 2 : 1 layers is no longer a random rotation, but a rotation that is a multiple of 60 or 120°. The observed modulated form

of the 20*l*, 13*l* band therefore indicates that a substantial proportion of the phyllosilicates solubilised by the HCl treatment were mixed-layer phyllosilicates that contained mica or mica-like layers; i. e. , layers rich in K.

Although the phyllosilicates solubilised as revealed by the orientated preparations were different in detail in all three soils, in all cases the most obvious feature they showed was the removal, or significant decrease, of strong 14 Å peaks and a large reduction in the intensity between 14 and 10 Å in the heated traces (Fig. 3 - 5). The effect on the 14 Å peaks suggests the HCl treatment solubilised vermiculitic minerals. The effect on intensity between 10 and 14 Å in the heated traces is indicative of a reduction in the amount of clay showing incomplete collapse, such as may be due to hydroxyl interlayers or rapid rehydration. In either case it may also be related to a predominantly vermiculitic nature for the main components solubilised by HCl.

In summary, the XRD data indicated that the HCl treatment solubilised mixed-layer minerals with a significant component of mica layers and a strong vermiculitic character. Both trioctahedral and dioctahedral minerals were solubilised, depending on the samples, and in all cases the geochemistry indicated that they had Fe and Mg rich compositions. Such mixed-layer clay minerals are almost certainly transformation products of pedogenesis, although we cannot determine what proportion of mica layers may be relicts of weathering reactions related to the degradation of primary micas, as compared with those layers formed by the aggradative process of K fixation and mica layer formation in the soil. In reality it is most likely that both kinds are present. This mineralogical characterisation of the phases that dissolve upon HCl treatment, and that are thus the host phases for K_{HCl}, provide a basis for a better understanding of what K_{HCl} is actually measuring and why such acid tests have historically been adopted as useful indices of the long-term availability of K to crops in a given soil.

4. 4 Connections to field and cropping experiments

HCl extractable K of the presented soils roughly translates to between 1. 2 ton ha^{-1} (Hög) and 12 ton ha^{-1} (Kun) in the topsoil (0 - 20 cm), corresponding to the demand of 30 - 170 years of cropping in the field experiments from which the soils were taken (*Simonsson* et al. , 2007). The pool of K_{HCl} may be up to an order of magnitude greater than the exchangeable K, and approximately corresponds to 25% of the total K content of phyllosilicates in the soil (*Andrist-Rangel* et al. , 2006). Although the current level of exchangeable K may have a marked influence on K concentrations in the crop, K_{ex} is a poor indicator of sustained K uptake by several successive crops. For instance, in the pot experiments of *Mortland* (1957), K uptake of their four consecutive wheat crops exceeded the exchangeable K held by the studied clay minerals several fold.

To what extent the hastened weathering brought about by the extraction in HCl (or any other extractant) may mimic K release under field condition is not easy to assess. It is true that the solubility ratios of Tab. 4 are not obviously consistent with the weatherability of soil constituents under field conditions. Thus, it is notable that under the extremely acid conditions in the extract, K_2O was solubilised to a considerably lesser extent than Al_2O_3 and Fe_2O_3, which are usually conservative constituents during weathering and soil formation. Furthermore, we observe that whereas K release from phyllosilicates in the field has been found to proceed through transformations, where expanded layers of 2 ∶ 1 minerals are formed at the expense of 10 Å ones, commonly resulting in enhanced K fixation capacity of the soil (*Tributh* et al. , 1987; *Øgaard* and *Krogstad*, 2005; *Simonsson* et al. , 2009), the mechanism of K release in the extraction seems to be complete dissolution of the mineral, at least in so far as the mineral structure is totally altered by the acid. Nevertheless, the mineral changes observed in our study follow some general patterns also found in pot experiments, such as the ready availability of K in trioctahedral minerals (e. g. , *Mortland* et al. , 1957; *Ståhlberg*, 1958). In the pot experiments of *Mortland* et al. (1957), four wheat crops grown during 10 months mobilised 39 - 179% of the K extractable by boiling in 1 M HNO_3. Interestingly, their 'vermiculite', which by modern

standards probably should be classified as a mica/vermiculite mixed-layer mineral (hydrobiotite) judging from its high K content, had a high K fixation capacity and was comparable with biotite in its ability to release K to the crop.

As suggested by the data of *Simonsson* et al. (2007), the pool of K_{HCl} may increase or decrease reversibly depending on soil K balance. Reversible K release was a feature of the soils at Fjärdingslöv and Kungsängen, which both have a high capacity to deliver K in the field (*Simonsson*, et al. 2007). The mineralogical characterisation of the present paper allows us to suggest an explanation for this behaviour: The extracted K appeared to be released from mixed-layer minerals, whose structure suggests that they would very likely be active both in fixation and in release of K. Indeed K fixation may be responsible for the modulation of the 20*l*, 13*l* band observed in the DXRD pattern. Additionally, the vermiculitic character, revealed by orientated preparations, suggests high layer charge, and this is also a characteristic likely to enhance K fixation. The Fe rich nature of the fractions solubilised by HCl is also an interesting observation. This is because Fe rich dioctahedral minerals are known to show a greater propensity to fix K, relative to more aluminous dioctahedral varieties (*Eberl* et al., 1986). In part this is thought to be related to the angle of tetrahedral rotation, which alters the size of the ditrigonal holes in the basal oxygen planes. Fe rich clays tend to have less tetrahedral rotation and hence the ditrigonal holes are larger and K fixation is enhanced by the ability of K to penetrate more easily and deeply into the holes in the siloxane surface. It has also previously been noted that the oxidation state of Fe in clay minerals may play an important role in relation to K fixation in soils (*Shen* and *Stucki*, 1994; *Stucki* and *Shen*, 1995; *Stucki* and *Huo*, 1996 and references therein; *Stucki*, 2006). Hence the fact that HCl appears to solubilise Fe rich clays may again be a basis for understanding why K_{HCl} is an effective indicator of long-term K status. Thus our study supports the hypothesis advanced by *Simonsson* et al. (2007) that K_{HCl} is a measure of the quality of the K held in the phyllosilicate pool with respect to its long-term availability to plants.

5 Conclusion

Quantitative and differential X-ray diffraction analysis clearly demonstrated that K extracted by hot 2 M HCl (K_{HCl}) was derived almost exclusively from 2∶1 clay minerals. HCl treatment preferentially dissolved Fe/Mg rich trioctahedral and Fe/Mg rich dioctahedral phyllosilicates. The K released was from trioctahedral micas and from micaceous layers in fine-grained di-and trioctahedral mixed-layer clays with a vermiculitic character. A significant proportion of the mineral K held in the soils studied here was in the form of K feldspar. In the presence of micaceous minerals, the role of K feldspar as a source of K to plants in a long time perspective is not clear. However, our results indicate that K from K feldspar made only little measurable contribution to K_{HCl}. Generally, the largest effect of the HCl treatment was in the clay and fine silt fractions (<20 μm), where phyllosilicates are normally concentrated. An exceptional sand fraction released significant amounts of K during extraction, because it contained reactive phyllosilicates in rock fragments of shale or phyllite, demonstrating that mineralogy rather than particle size is the key factor controlling K release during hot acid extraction.

The majority of minerals affected by the HCl extraction were expandable phyllosilicates most likely formed by pedogenic transformation processes, such as the degradation and transformation of micas. Fe rich phyllosilicates have previously been shown to be relatively more active in the process of K fixation in soils. Our finding, that the extractant preferentially attacked these minerals, establishes a basis for understanding why K_{HCl} appears to be a dynamic fraction that can be affected by management. It also explains why K_{HCl} is an effective and trusted measure of the long-term availability of K to plants. The detailed picture of the mineralogical and geochemical effects of HCl extraction presented in this paper will hopefully increase our understanding of how soil mineralogical properties influence and affect the

long-term K delivery capacity of different soils.

Acknowledgements

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农业土壤中酸提取钾素:利用差分和定量 X 射线衍射法评估源矿物

摘　要:土壤常规分析中通常采用不同提取方法评估长期钾(K)库容量。在瑞典,常用 100℃下 2M HCl 提取 K(K_{HCl}),但对于所提 K 的位置仍知之甚少。本文定量分析了 2M HCl 提取法对从黏粒到砂粒不同粒级土壤矿物的影响,并估算了土壤不同粒级矿物的释钾比例。本研究中包含瑞典三个农业长期定位试验,其质地从壤砂土到粉黏土均有,同时采用了 K 长石作为矿物样品。分析了不同粒级的总失重量,并用定量和差分 X 射线粉末衍射法(QXRD, DXRD)分析了提取前后矿物固相的变化。QXRD 和 DXRD 法包括样品的喷雾干燥、添加内标和全谱拟合,并将矿物标准 XRD 图谱与样品进行对比。结果表明,K_{HCl} 主要来源于黏土矿物中较细的两个粒级(2～20 μm 和<2 μm)。高膨胀和混合层硅酸盐矿物是可被溶解的重要矿物。混合层状硅酸盐中云母层间 K 释放,并呈现蛭石化特征。不论二八面体还是三八面体,其溶解相均富含 Fe。在壤砂土中,以长石为主的粗粒径(20～2 000 μm)释放的 K 占 K_{HCl} 的 35%。DXRD 分析表明,在所有样品中 K 长石均无显著减少。长石样品的 K_{HCl} 数据表明,在黏砂土中黏土矿物释放的 K 对 K_{HCl} 的贡献至少达到 70%。本文为土壤矿物对长期供 K 能力的贡献方面的研究提供了新的思路,并在管理措施对 K_{HCl} 的影响及其动态变化方面给出了一定的解释。

关键词:钾素;土壤矿物学;黏土矿物;盐酸;酸提取;钾素动态变化

Potassium uptake requirement in relation to grain yield and genotypic improvement of irrigated lowland rice in China §

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Abstract: The yield of rice (*Oryza sativa* L.) has improved with the development of new cultivars; however, the role of the potassium (K) uptake requirement ingrain yield and genotypic improvement is still unclear. A data base of 1 199 on-farm measurements comprising >400 modern rice cultivars was collected during 2005—2010 across major irrigated lowland rice production regions of China. This was used to evaluate the relationships among K uptake requirement, grain yield, and genetic improvement. Considering four levels of grain yield (<7.5, 7.5-9, 9-10.5, and >10.5 t ha^{-1}), the reciprocal internal efficiencies of K(RIE-K, kg K per tonne grain produced) were 18.72, 19.40, 20.47, and 21.71 kg K per tonne grain, respectively. The gradual increase in the RIE-K with yield was attributed mainly to the increase in straw and grain K concentration and the decrease in the K harvest index. The RIE-K values for ordinary inbred, ordinary hybrid, and "super" rice were 18.53, 20.07, and 19.87 kg K per tonne grain, respectively. Examining the historical development of rice cultivars, the RIE-K decreased from 40.94 (Nanjing1, early tall, inbred) in the 1950s to 19.82 (IR24, semi-dwarf, ordinary inbred) in the 1970s, and then increased to 20.85 (Shanyou63, modern ordinary hybrid) in the 1980s and 20.55 kg K per tonne grain (II-you084, super rice) in the 2000s. We concluded that the differences in the K uptake requirement according to the grain yield and rice cultivar should be considered when developing a K management strategy and high K efficiency cultivars should be developed for irrigated lowland rice in China.

Keywords: Rice, potassium uptake requirement, genotype, grain yield, reciprocal internal efficiency

1 Introduction

Rice (*Oryza sativa* L.) production in Asia has increased dramatically in recent decades, more than doubling primarily as the result of the adoption of high-yielding cultivars (*Peng* et al., 2000; *Zhang*, 2007). To meet the increasing demand for rice, the first modern high-yielding inbred rice cultivar (IR8) was released by the International Rice Research Institute (IRRI) in 1966 (*Peng* et al., 1999). Breedersat the IRRI continued to develop New Plant Type in the late 1980s(*Virmani* et al., 1982; *Khush*, 1995; Peng et al., 1999) and developed hybrid rice and "super rice" in China(*Yuan* et al., 1994; *Yuan*, 2001; *Yuan*, 2003). In practice, the rice yield response to potassium (K) fertilization is generally lower than that observed for nitrogen (N) and phosphorus (P) (*Fageria* et al., 2003). Consequently, farmers prioritize N and P fertilization. The amount of K fertilizer applied is usually insufficient in rice production in Asia, especially in double- and triple-cropping rice systems, and the most intensive cropping rice systems clearly have a K deficit (*Dobermann* et al., 1995; *Dobermann* et al., 1998; *Witt* et al., 1999; *Dawe* et al., 2000; *Cassman* et al., 2003). At issue is whether current K management strategies practiced by farmers are adequate to support higher rice yields to meet the

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§ J. Plant Nutr. Soil Sci. 2013, 176, 400-406

demands of growing populations (*Dobermann* et al., 1998; *Dobermann* and *Cassman*, 2002). Understanding rice K uptake requirements is crucial to devise optimal K management practices.

Previous studies have reported wide variation in plant K uptake requirements with yield and genotypic improvement(*Dobermann* et al., 1996; *Liu* et al., 2001; *Hu* and *Wang*, 2004; *Doberman*, 2007; *Tabien* et al., 2008; *Wang* et al., 2011; *Zhang* et al., 2011). For example, *Dobermann* et al. (1996) found that the K uptake requirement for a rice grain yield between 4 and 8 t ha^{-1} ranged from 17-30 kg K per tonne grain produced. Compared to inbred rice, hybrid rice takes up more K due to the heterosis advantage (*Singh* et al., 1998; *Inthapanya* et al., 2000; *Fageria* et al.,2003). *Liu* et al. (2001) found that inbred rice had greater K internal efficiency than did hybrid rice. However, *Hu* and *Wang* (2004) reported no significant difference in the K internal efficiency between inbred and hybrid rice. These differences indicated that it is important to understand the variation in K requirements and their driving factors when devising K management strategies for rice production.

Previous studie shave typically estimated the rice K uptake requirement in site-specific field experiments conducted at relatively few locations with small numbers of tested cultivars. Very few studies have attempted to determine the K uptake-yield relationship across widely differing environmental and management conditions. Therefore, this study collected > 400 modern rice cultivars for K response trials across major irrigated lowland rice production regions of China. Our objectives were to(i) evaluate the changes in plant K uptake requirement with increasing grain yield, and (ii) determine the differences in plant K uptake requirements associated with genotypic improvement.

2 Material and methods

2.1 Database

The database analyzed in this study included 1 199 measurements of rice grain yield (13.5% moisture content) and plant K uptake. Data were collected from on-farm trials in collaboration with other partners during 2005—2010 in South China and the Yangtze River Region, the major irrigated rice agro-ecological regions in China. Like *Witt* et al. (1999) and *Buresh* et al. (2010), we excluded data with a harvest index (HI) < 0.4, as a low HI results mainly from disease, weeds, or insect pests. In our field trials, 491 rice cultivars were planted, including ordinary inbred (n=64), ordinary hybrid (n=398), and "super" rice (n=29).

The cropping system was double-season rice (early and late rice) in South China and single-season rice (middle rice) in the Yangtze River Region. Crop management for all on-farm trials followed standard rice high-yielding practices. All sites were under favorable irrigation conditions and local commercial high-yielding rice cultivars were grown. The planting date and density were recommended by local agricultural research institutes. The optimal N, P, and K fertilizer application rates were based on soil N, P, and K testing. N application averaged 150 (range 45-255) kg N ha^{-1}. P application averaged 75 (range 15-210) kg P_2O_5 ha^{-1}. K application averaged 90 (range 45-300) kg K_2O ha^{-1}.

2.2 Historical cultivar field experiment

The historical cultivar experiment was conducted at Yangzhou University experimental station, Jiangsu Province, China (32°30′N, 119°25′E) during the rice growing season (May to October) in 2009. The experiment involved five *indica* cultivars representative of the rice cultivars grown historically in China from the 1950s to 2000s: Nanjing1 (early tall, inbred, 1950s), Zhenzhu'ai(dwarf, inbred, 1960s), IR24 (semi-dwarf, ordinary inbred, 1970s), Shanyou63 (semi-dwarf, ordinary hybrid, 1980s), and II-you084 ("super" rice, hybrid, 2000s). The upper of 20 cm of soil was sandy loam with 2.04% organic matter, 106.2 mg kg^{-1} alkali-hydrolyzable N, 28.5 mg kg^{-1} available P, and 93.6 mg kg^{-1} available K.

The experimental plot area was 20 m^2. Plots were arranged in a completely randomized block design

with three replicates. Rice seeds were sown in a nursery plot on May 10 and seedlings were transplanted on June 8 at a hill spacing of 0.2×0.2 m with two seedlings per hill, except for one seedling per hill for hybrid rice. The total N rate was 240 kg N ha^{-1}, of which 120, 24, and 96 kg N ha^{-1} were applied at the basal, tillering, and panicle initiation stages, respectively. Basal applications of 40 kg P_2O_5 ha^{-1} and 117 kg K_2O ha^{-1} were made to all plots before transplanting. Crop management followed the standard rice high-yielding practices.

2.3 Plant-sampling analysis

At maturity, ten hills were sampled diagonally from a 5 m^2 harvest area to determine the above-ground total dry weight and harvest index. Plant samples were divided into straw (leaf+culm+chaff) and grain at maturity. All plant samples were oven-dried at 70℃ until a constant weight was reached for biomass measurements. Grain yields were reported at 13.5% standard moisture. The samples were ground and the grain and straw K concentrations were determined using the method of *Walinga* et al. (1995).

2.4 Data analysis

The reciprocal internal efficiency of K (RIE-K) is the amount of K in the above-ground plant dry matter per tonne of grain production. The harvest index (HI) is the grain yield expressed as a proportion of the total above-ground plant dry matter (kg grain per kg total above-ground dry matter). The K harvest index (KHI) is defined as the K accumulation in grain as a proportion of the K accumulation in the above-ground plant dry matter (*Witt* et al., 1999).

Data were analyzed statistically using one-way analysis of variance (ANOVA) at a 0.05 level of probability followed by Duncan's test and the *t*-test, using SPSS 16.0 (*Guarda* et al., 2003).

3 Results and discussion

3.1 Grain yield, K concentration, and K uptake

Considering all 1 199 on-farm measurements in this study, the rice grain yield (at 13.5% moisture) averaged 8.67 (range 4.40 - 12.33) t ha^{-1} (Table 1). The mean grain yield in our dataset was much higher than the average yield worldwide (4.26 t ha^{-1}) and in China (6.44 t ha^{-1}) during 2005—2010 (*FAO*, 2012). The relatively higher grain yield in this study was attributed mainly to good field management practices. The mean HI was 0.51 (range 0.42 - 0.62). Using a dataset from six Asian countries for 1995—1997, *Witt* et al. (1999) reported a lower HI (0.47). The higher HI in this study resulted mostly from the newer commercial high-yielding rice cultivars used. *Peng* et al. (2000) reported a positive historical cultivar trend in HI.

Table 1 Grain yield, harvest index (HI), K concentrations K in grain and straw, K uptake into above-ground plant parts, K harvest index (KHI, kg K in grain per kg K in total above-ground plant dry matter), and K requirement per tonne grain produced (RIE-K) at maturity for irrigated lowland rice in China (n=1 199). Grain yield is expressed at 13.5% moisture, whereas other yield and weight variables are on an oven-dry basis.

Parameter	Unit	Mean	SD	Minimum	25% Q	Median	75% Q	Maximum
Grain yield	t ha^{-1}	8.7	1.4	4.4	7.7	8.6	9.7	12.3
HI	kg kg^{-1}	0.51	0.03	0.42	0.49	0.50	0.52	0.62
K in grain	g kg^{-1}	2.94	0.47	2.11	2.50	2.98	3.30	3.98
K in straw	g kg^{-1}	20.27	3.80	15.10	16.90	19.50	23.20	29.80
K uptake	kg ha^{-1}	173	46	64	136	166	204	295
KHI	kg kg^{-1}	0.13	0.02	0.08	0.11	0.13	0.15	0.19
RIE-K	kg	19.8	3.6	11.1	16.7	19.7	22.6	27.8

SD=standard deviation; Q=quartile.

The mean K concentration in grain was 2.94 (range 2.11 - 3.98) g kg^{-1}, while the mean K concentration in straw was 20.27 (range 15.10 - 29.80) g kg^{-1} (Table 1). The wide variation in the K concentration in grain and straw can be explained mainly by the wide range of planting cultivars, environment, and management conditions in our study. The K uptake in the above-ground plant dry matter averaged 172.8 (range 63.9 - 294.7) kg ha^{-1}. On average, KHI and RIE for K were 0.13 and 19.80 kg K per tonne grain, respectively. *Witt* et al. (1999) reported a smaller RIE (16.94 kg K per tonne grain) for rice, which was attributed mainly to a higher KHI (0.17) with a much lower straw K concentration (14.50 g kg^{-1}) and relatively similar grain K concentration (3.00 g kg^{-1}) as compared our results. Across the 1199 on-farm data, a significant correlation between rice grain yield and plant above-ground K uptake was found (Fig. 1). Our dataset explained 56.1% of the variation in the plant K uptake in above-ground dry matter.

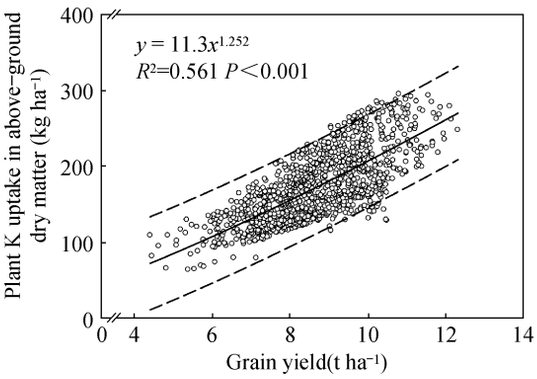

Figure 1 Relationship between grain yield (at 13.5% moisture) and K uptake into above-ground plant parts at maturity based on farm experiments conducted in major irrigated lowland rice production regions in South China and the Yangtze River Region during 2005-2010 (n=1 199). The solid line is the fitted curve regression of plant K uptake on grain yield. The dashed lines represent the 95% confidence interval.

3.2 K uptake requirement with increasing grain yield

To further understand the K uptake requirement in relation to grain yield, we divided the entire dataset (Table 1) into four grain yield levels: <7.5 (n=248, mean=6.81), 7.5 - 9 (n=456, mean=8.24), 9 - 10.5 (n=396, mean=9.70), and >10.5 (n=99, mean=11.06) t ha^{-1}. For these four groups, the average RIE-Kvalues were 18.72, 19.40, 20.47, and 21.71 kg K per tonne grain yield produced (Fig. 2), respectively. The RIE-K increased with grain yield.

For yields<7.5 and 7.5 - 9 t ha^{-1}, the average grain K concentration was stable at about 2.91 g kg^{-1} (Fig. 3a). Then, the average grain K concentration increased (from 2.94 to 3.06 g kg^{-1}) from yield level 9 - 10.5 t ha^{-1} to the level >10.5 t ha^{-1}. The straw K concentration increased from 19.52 (<7.5 t ha^{-1}) to 22.33 g kg^{-1} (>10.5 t ha^{-1}) with increasing yield (Fig. 3b). The HI kept relatively stable at about 0.50 (Fig. 3c). This result indicated that the higher grain yield was related to increased biomass production. KHI decreased from 0.14 to 0.12 from <7.5 t ha^{-1} to >10.5 t ha^{-1} (Fig. 3d).

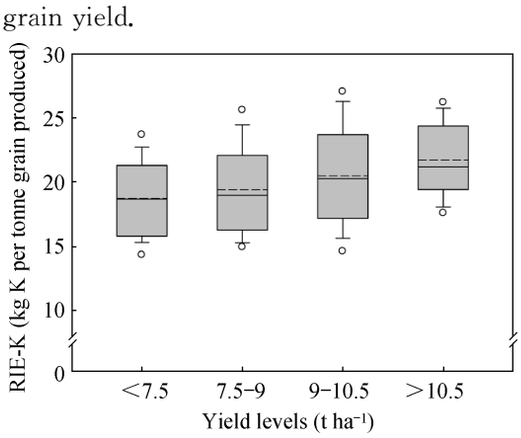

Figure 2

With increasing grain yield, the increase in the RIE-K was attributed mainly to the straw and grain K concentration increase and KHI decrease, especially for the straw K concentration, which increased about 14.4%. K nutrition in plants is first thought to meet the demand for basic biochemical and physiological functions, including osmotic regulation, photosynthesis, and carbohydrate transportation (*Fageria* et al., 2003; *Römheld* and *Kirkby*, 2010). However, the higher yield means greater biomass production with a greater possibility of disease, such as rice blast, brown leaf spot, and stem rot, which ultimately contribute to greater susceptibility to lodging and reduced yield (*Fageria* et al., 2003). Hence, the higher K uptake requirement at high yield levels indicated the demand for abiotic or biotic stress resistance in plants.

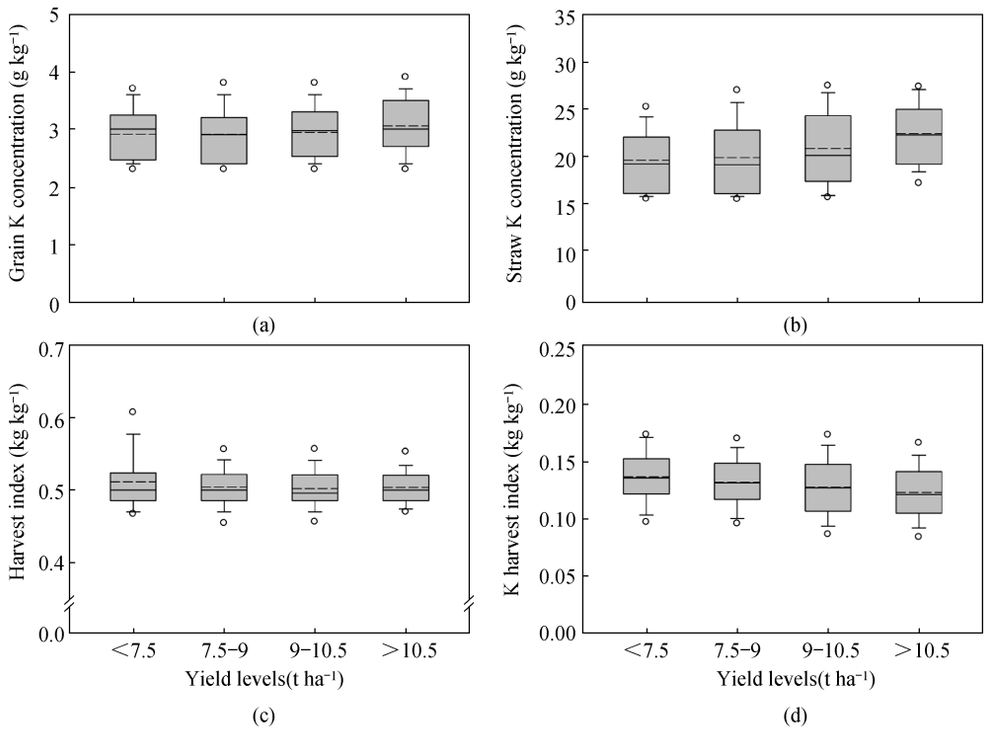

Figure 3

3.3 K uptake requirement with evolution of rice cultivars

In China, more than 50% of the rice cultivars planted were hybrid and "super" rice, and the proportion has tended to increase (*Li* and *Yuan*, 2000; *Yuan*, 2003). In this study, we divided the entire dataset (Table 1) into three cultivar groups: ordinary inbred (n=185, 64 cultivars), ordinary hybrid (n=837, 398 cultivars), and "super" rice(n=177, 29 cultivars). For these three groups, the respective rice grain yields were 8.13, 8.65, and 9.33 t ha^{-1}(Table 2). However, ordinary inbred rice had the highest HI (0.52), reflecting the greater biomass production of ordinary hybrid and "super" rice. Some studies have reported similar results (*Zong* et al., 2000; *Zhang* et al., 2009; *Zhang* et al., 2011).

For all cultivar groups, the K concentration in grain was highest in the ordinary inbred (3.04 g kg^{-1}) and smallest in "super" rice(2.86 g kg^{-1}), whereas the straw K concentration was highest in "super" rice (20.37 g kg^{-1}) and smallest in ordinary inbred (19.66 g kg^{-1}) (Table 2). A high grain K concentration would improve rice grain quality (*Wang* et al., 2004). In practice, ordinary inbred rice grain is chosen in China because of its good quality. The total K uptake values in the above-ground dry matter in ordinary inbred, ordinary hybrid, and "super" rice grain yield were 151.7, 174.6, and 186.4 kg ha^{-1}, respectively. *Zhang* et al. (2011) also reported that hybrid rice had significantly greater K uptake in above-ground dry matter compared to inbred rice.

Table 2 Grain yield, harvest index (HI), concentrations of K in grain and straw, K uptake into above-ground plant parts, K harvest index (KHI), and K requirementt^{-1} grain produced (RIE-K) at maturity of ordinary inbred, ordinary hybrid, and "super" rice in China. Grain yield is expressed at 13.5% moisture, whereas other yield and weight variables are on an oven-dry basis.

Cultivars	Cultivar tested	n	Grain yield	HI	K in grain	K in straw	K uptake	KHI	RIE-K
			(t ha^{-1})	(kg kg^{-1})	(g kg^{-1})		(kg ha^{-1})	(kg kg^{-1})	(kg)
Ordinary inbred	64	185	8.1±1.4	0.52±0.04	3.04±0.48	19.66±3.35	152±40	0.14±0.02	18.5±3.0
Ordinary hybrid	398	837	8.7±1.3	0.50±0.03	2.93±0.47	20.39±3.87	175±45	0.13±0.02	20.1±3.6
"Super" rice	29	177	9.3±1.3	0.50±0.03	2.86±0.44	20.37±3.90	186±49	0.13±0.03	19.9±3.8

Mean±standard deviation; n=number of observation.

The RIE-K was highest in ordinary inbred (18.53 kg K per tonne grain), which was attributed mainly to the low straw K concentration and high KHI compared to ordinary hybrid (20.07 kg K per tonne grain) and "super" rice (19.87 kg K per tonne grain) cultivar groups (Table 2). The KHI of the ordinary inbred was 0.14 and higher than values for the other cultivar groups. Compared to ordinary hybrids, the RIE-K for "super" rice was slightly lower, indicating that the greater K uptake for "super" rice was due mainly to increased biomass production rather than luxurious accumulation in the plant.

To understand the relationship between K uptake requirement and rice cultivar improvement further, we chose five representative historical cultivars to verify this relationship. Across these five cultivars, grain yield increased from 4.58 t ha^{-1} for Nanjing1 to 11.20 t ha^{-1} for II-you084 (Table 3). The increase in grain yield from the early tall inbred cultivar (Nanjing1) to the dwarf inbred cultivar (Zhenzhu'ai) was caused mainly by the significant improvement in HI (from 0.38 and 0.53), while that from the semi-dwarf ordinary inbred cultivar (IR24) to the ordinary hybrid cultivar (Shanyou63) and "super" rice (II-you084)was attributed mainly to increased biomass production (data not shown). *Peng* et al. (2000) reported similar results.

Table 3 Grain yield, harvest index (HI), concentrations of K K in grain and straw, K uptake into above-ground plant parts, K harvest index (KHI), and K requirementt^{-1} grain produced (RIE-K) at maturity of historical cultivars released from the 1950s until the present in Jiangsu Province, China. Grain yield is expressed at 13.5% moisture, whereas the other yield and weight variables are on an oven-dry basis.

Cultivars	Grain yield	HI	K in grain	K in straw	K uptake	KHI	RIE-K
	(t ha^{-1})	(kg kg^{-1})	(g kg^{-1})		(kg ha^{-1})	(kg kg^{-1})	(kg)
Nanjing1	4.6a	0.38a	3.66d	26.74c	187b	0.08a	40.9d
Zhenzhu'ai	7.5b	0.53c	2.88a	26.71c	169a	0.11bc	22.7c
IR24	8.7c	0.51b	2.94a	20.49a	173a	0.13d	19.8a
Shanyou63	10.2d	0.52bc	3.15c	22.30b	212c	0.13d	20.9b
II-you084	11.2e	0.52bc	2.85a	22.79b	231d	0.12cd	20.6b

Different letters in the same column indicate significant differences among values at $p < 5\%$.

Of the five cultivars tested, Nanjing1 had the highest concentrations of K in grain and straw: 3.66 and 26.74 g kg^{-1}, respectively (Table 3). The K uptake ranged from 169.4 kg ha^{-1} (Zhenzhu'ai) to 230.5 kg ha^{-1} (II-you084). The K uptake for II-you084 (230.5 kg ha^{-1}, 11.20 t ha^{-1}) was significantly higher than for Shanyou63 (212.0 kg ha^{-1}, 10.17 t ha^{-1}) and IR24 (172.8 kg ha^{-1}, 8.72 t ha^{-1}). The KHI increased with historical cultivar release from 0.08 (Nanjing1) to 0.13 (Shanyou63), and subsequently decreased to 0.12 (II-you084).

From Nanjing1 to Zhenzhu'ai, the RIE-K decreased significantly from 40.94 to 22.67 kg K per tonne grain, which was caused mainly by the grain K concentration decrease from 3.69 to 2.88 g kg^{-1} and KHI increase from 0.07 to 0.11. From IR24 to Shanyou63, the RIE for K increased from 19.82 to 20.85 kg K per tonne grain, which was attributed mainly to the grain and straw K concentration increases from 2.94 to 3.15 g kg^{-1} and from 20.49 to 22.30 g kg^{-1}, respectively. From Shanyou63 (ordinary hybrid) to II-you084 ("super" rice), the RIE-K decreased slightly from 20.85 to 20.55 kg K per tonne grain. Compared to the ordinary inbred cultivar, the ordinary hybrid rice and "super" rice had higher K uptake requirement sowing to the higher straw K concentration. These reflected the demand for K to cope with stress in plants with high biomass production. In contrast, *Zhang* et al. (2009) reported that the "super" rice N uptake requirement was not increased compared to requirements in ordinary hybrid and inbred rice to produce high grain yields. This indicated that differences in the K uptake requirement among rice cultivars require developing different K management strategies for irrigated lowland rice in China.

4 Conclusions

Limited information about variation in the rice K uptake requirement according to the grain yield and rice cultivar is the major cause of failed field K management practices. Our results suggest that the rice K uptake requirement has a pronounced effect on grain yield and varies with rice genotype. Considering four yield levels, the gradual increase in the RIE-K with increasing yield was attributed mainly to the straw and grain K concentration increases and KHI decreases. For modern rice cultivars, the grain yield and K uptake were highest for "super" rice compared with ordinary hybrid and ordinary inbred rice. The RIE-K of the ordinary inbred was the smallest because of the lowest straw K concentration. Historically, with the change from early tall to semi-dwarf cultivars, the gradual decrease in RIE was caused by the decreased K concentration in grain and straw and KHI increase. The modern ordinary hybrid and "super" rice require greater K uptake than do ordinary inbred cultivars, as a result of their higher straw K concentrations. The large variation in K uptake requirement among grain yields and rice cultivars in this study shows the importance of developing different K management strategies and the possibility of breeding high K efficiency cultivars of irrigated lowland rice in China.

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产量提高和品种改良条件下中国水稻的钾素吸收规律

摘　要:水稻新品种的应用可以提高籽粒产量,但籽粒需钾量随产量和基因型如何变化目前仍不清楚。2005—2010 年期间,收集了 400 多个现代水稻品种,进行了覆盖中国水稻主要种植区域的 1 199 个田间试验,建立了数据库。运用该数据库评估钾素需求之间的关系。当籽粒产量分别为<7.5、7.5～9、9～10.5、>10.5 t/hm^2 时,对应的每 t 粮食需钾量(RIE-K, kg/t)分别为 18.72、19.40、20.47、21.71 kg 钾。随着产量增加,每 t 籽粒需钾量逐渐增加,其原因主要是由于秸秆和籽粒中钾浓度的增加而钾收获指数的减少。常规稻、普通自交系和超级稻的 RIE-K 分别为 18.53、20.07、19.87 kg/t 粮食。20 世纪 50 年代水稻品种(Nanjing1,早期高,近交系)的 RIE-K 为 40.94 kg/t,20 世纪 70 年代(IR24,半矮秆,普通自交系)下降到 19.82 kg/t,20 世纪 80 年代(汕优 63,现代普通混合)提高到 20.85 kg/t, 2000 年(II-you084,超级稻)为 20.55 kg/t 粮食。因此,建立钾素综合管理策略时需考虑作物产量和水稻品种,同时开发高效利用钾素的水稻品种。

关键词:水稻; 钾素吸收规律; 基因型; 籽粒产量

Improving potassium acquisition and utilisation by crop plants §

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Abstract: To avoid loss of yield, crops must maintain tissue potassium (K) concentrations above 5 - 40 mg K g^{-1} DM. The supply of K from the soil is often insufficient to meet this demand and, in many agricultural systems, K fertilisers are applied to crops. However, K fertilisers are expensive. There is interest, therefore, in reducing applications of K fertilisers either by improving agronomy or developing crop genotypes that use K fertilisers more efficiently. Agronomic K-fertiliser use-efficiency is determined by the ability of roots to acquire K from the soil, which is referred to as K uptake-efficiency (KUpE), and the ability of a plant to utilise the K acquired to produce yield, which is referred to as K utilisation-efficiency (KUtE). There is considerable genetic variation between and within crop species in both KUpE and KUtE, and chromosomal loci affecting these characteristics have been identified in *Arabidopsis thaliana* and several crop species. Plant traits that increase KUpE include (1) exudation of organic compounds that release more non-exchangeable soil K, (2) high root K uptake-capacity, (3) early root vigour, high root: shoot ratios, and high root length densities, (4) proliferation of roots throughout the soil volume, and (5) high transpiration rates. Plant traits that increase KUtE include (1) effective K redistribution within the plant, (2) tolerance of low tissue K concentrations, and, at low tissue K concentrations, (3) maintenance of optimal K concentrations in metabolically active cellular compartments, (4) replacement of K in its non-specific roles, (5) redistribution of K from senescent to younger tissues, (6) maintenance of water relations, photosynthesis and canopy cover, and (7) a high harvest index. The development of crop genotypes with these traits will enable K fertiliser-applications to be reduced.

Key words: Arabidopsis thaliana / breeding / fertiliser / nutrient use-efficiency

1 Introduction

Potassium (K) is required for plant growth and fecundity, and lack of K restricts the establishment, development and yield of crops (*Rengel* and *Damon*, 2008; *Fageria* et al., 2011). Potassium is required for the activity of many enzymes, including those of energy metabolism, protein synthesis and solute transport, contributes significantly to cell turgor, especially in rapidly expanding cells, and acts as a counter cation for anion accumulation and electrogenic transport processes (*Amtmann* et al., 2006; *White* and *Karley*, 2010). To fulfil its biochemical roles, K concentrations of 100 - 150 mM must be present in metabolically active compartments, such as the cytosol, the nucleus, the stroma of chloroplasts, and the matrix of mitochondria (*Britto* and *Kronzucker*, 2008; *White* and *Karley*, 2010). However, K can be replaced as an osmoticum in mature cells by sugars, organic acids and compatible solutes, and the role of K^+ in vacuolar charge balancing can be taken by other cations, such as Na^+, Ca^{2+} and Mg^{2+} (*White* and *Karley*, 2010). The lowest sustainable vacuolar K^+ concentration appears to be 10 - 20 mM, and tissue concentrations of 5 - 40 mg K g^{-1} dry matter (DM) are generally considered adequate for most crops (*Greenwood* et al., 1980; *White* and *Brown*, 2010; *White* and *Karley*, 2010).

Plants acquire K from the rhizosphere solution (*Karley* and *White*, 2009; *White* and *Karley*, 2010; *White* and *Greenwood*, 2013). In many agricultural soils, K supply is insufficient to sustain the rapid

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growth of young plants and, therefore, K fertilisers are required to maximise production in both intensive and extensive agricultural systems (*Rengel* and *Damon*, 2008; *Fageria*, 2009; *Römheld* and *Kirkby*, 2010; *Fageria* et al., 2011; *White* et al., 2012). Inorganic K fertilisers commonly applied to crops include KCl, KNO_3, K_2SO_4, $K_2SO_4 \times MgSO_4$ and KH_2PO_3 (*Fageria*, 2009; *White* and *Greenwood*, 2013). Additional sources of K for plant nutrition include crop residues and composts, which contain 3 – 11 kg K t^{-1} DM, animal manures, which contain 17 – 27 kg K t^{-1} DM, biosolids, which contain 1.7 – 2.1 kg K t^{-1} DM, and industrial biproducts, such as food wastes, meat and bone meal, and paper crumble (*Broadley* et al., 2004; *Defra*, 2010). The global consumption of K fertilisers was 19.6 million tons of K in 2009 and is predicted to increase to 26.6 million tons of K by 2015 (*FAO* 2011, 2012). Economically viable rock reserves are currently estimated to be 7.8 billion tons of K and global resources are estimated to be 205 billion tons of K (*US Geological Survey*, 2012), which is sufficient to support the agricultural demand for inorganic K fertilisers for many centuries. An absolute scarcity of K fertilisers is, therefore, unlikely in the immediate future. However, rising energy prices, which affect the mining, processing, distribution and application of K-fertilisers, will increase the price of K fertilisers. Similarly, the introduction of statutes designed to improve the environment will influence the use, availability and cost of K fertilisers. Thus, it is clear that improving the efficiency with which crops acquire K from the soil, or utilise K to produce yields, will have both economic and environmental benefits. Improving K-fertiliser use-efficiency will not only reduce the costs associated with the use of K fertilisers, but also prevent losses of K to the environment through leaching. Sustainable food security will require reducing K inputs, whilst maintaining or increasing crop yields.

Many definitions of "mineral use efficiency" can be found in the literature (*Baligar* et al., 2001; *White* et al., 2005; *White and Brown*, 2010). In this article the agronomic K-fertiliser use-efficiency (KUE) is defined as crop dry matter (DM) yield per unit K supplied as fertiliser (g DM g^{-1} K_s). This is numerically equal to the product of plant K content (K_{plant}) per unit of K supplied (g K_{plant} g^{-1} K_s), which is referred to as plant K uptake-efficiency (KUpE), and crop yield per unit plant K content (g DM g^{-1} K_{plant}), which is referred to as plant K utilisation-efficiency (KUtE). In general, plant K content can be estimated from shoot K content, and KUtE can then be expressed as the reciprocal of shoot K concentration if the entire shoot is harvested (*White* et al., 2010). Improvements in KUE can be achieved agronomically, through improved fertiliser-management practices, or genetically, by cultivating crop genotypes that acquire and/or utilise K more effectively (*Rengel* and *Damon*, 2008; *Fageria*, 2009; *White* et al., 2010; *Fageria* et al., 2011; *White* and *Greenwood*, 2013). This article identifies plant traits required to improve KUE and highlights recent insights to the genetics of KUpE and KUtE in crop plants.

2 Potassium acquisition by crops

Most soils contain 0.3 – 25 g K kg^{-1} soil (*Mengel* et al., 2001; *Fageria*, 2009). The K available to crops, a large proportion of which resides in the topsoil, is present as K in the soil solution, as exchangeable K associated with cation exchange sites, and as non-exchangeable K associated with clay lattices (*Tinker* and *Nye*, 2000; *Rengel* and *Damon*, 2008; *Fageria*, 2009; *Römheld* and *Kirkby*, 2010; *White* and *Greenwood*, 2013). These fractions generally sum to less than 2 – 10% of the total K in a soil. The K concentration in the soil solution generally ranges from 0.1 to 1 mM and represents only 0.1 – 0.2% of the total K in a soil. The interchange between K in solution and the exchangeable K is rapid, but the interchange between K in solution and the non-exchangeable K is relatively slow. The amount of K in the soil solution, exchangeable and non-exchangeable fractions, and the rates of interchange between these fractions, determine the temporal availability of K to crops (*Tinker* and *Nye*, 2000; *Karpinets* and *Greenwood*, 2003; *Römheld* and *Kirkby*, 2010). The remainder of the soil K,

typically 90－98% of the total K in a soil, is effectively unavailable to an annual crop. The ability of soils to supply the K requirements of crops varies greatly (*White* and *Greenwood*, 2013). Some soils can release more K than is required by a crop, such that no additional K fertiliser is necessary, whilst other soils have no capacity to retain or supply K to plants and must receive sufficient K fertiliser each year to meet the entire requirement of the crop (*White* and *Greenwood*, 2013). In many regions of the world, the amount of K fertiliser applied to crops is less than the quantities of K removed in produce and crop residues together with the losses of K to the wider environment (*Römheld* and *Kirkby*, 2010). This has resulted in a gradual decline in the K content of agricultural soils.

Crop K acquisition is determined principally by the delivery of K to the root surface and the kinetics of K uptake by root cells (*White* and *Karley*, 2010). Both local diffusion through the rhizosphere and transpiration-driven mass flow of the soil solution contribute to the delivery of K to the root surface (*Barber*, 1995; *Jungk* and *Claassen*, 1997; *Tinker* and *Nye*, 2000). Potassium in the rhizosphere then enters root cells through K transporters in their plasma membranes (*Britto* and *Kronzucker*, 2008; *Karley* and *White*, 2009; *White* and *Karley*, 2010). The relationship between K uptake and K concentration in the rhizosphere generally follows the sum of a hyperbolic and a linear function, which can be attributed to the combined activities of several distinct types of K transporters with contrasting kinetic properties (*Britto* and *Kronzucker*, 2008; *White* and *Karley*, 2010). Factors affecting K acquisition by plants include: (1) the release of root exudates, such as organic acids, that solubilise non-exchangeable K in soils and increase the K concentration in the soil solution, (2) the proliferation of roots through the soil volume, which not only increases the surface area for K uptake but also reduces the distance required for K diffusion and water flow, (3) the rate of K uptake across the plasma membrane of root cells, which influences the K concentration in the rhizosphere solution and the rate of K diffusion to the root surface, and (4) the transpiration rate, which drives mass flow of the soil solution towards the root (*Jungk* and *Claassen*, 1997; *Tinker* and *Nye*, 2000; *Rengel* and *Damon*, 2008; *White and Karley*, 2010).

Most K enters roots across the plasma membranes of epidermal and cortical cells and is transported symplastically to the xylem (*Karley* and *White*, 2009; *White* and *Karley*, 2010). In recent years, the molecular identities of K transporters catalysing K influx to root cells from the rhizosphere, and K efflux from stellar cells to the xylem have been identified (*Britto* and *Kronzucker*, 2008; *Karley* and *White*, 2009; *White* and Karley, 2010). At rhizosphere K concentrations greater than about 100 nM, H^+/K^+ symporters encoded by members of the *KT/HAK/KUP* and *CHX* gene families can catalyse K influx to root cells against its electrochemical gradient utilising the pH and voltage gradients generated by plasma membrane H^+-ATPases. Orthologs of the H^+/K^+ symporter AtHAK5 of *Arabidopsis thaliana*, which is induced by K-starvation, appear to contribute significantly to K nutrition at low rhizosphere K concentrations (*Gierth* et al., 2005; *Qi* et al., 2008; *Rubio* et al., 2008, 2010; *Pyo* et al., 2010; *White* and *Karley*, 2010; *Alemán* et al., 2011). At rhizosphere K concentrations greater than about 1 mM, a variety of K-permeable channels catalyse K influx to root cells utilising the voltage gradient across the plasma membrane (*Karley* and *White*, 2009; *White* and *Karley*, 2010). Orthologs of the inward-rectifying K channel (KIRC) formed by AtAKT1 and AtKT1 in *A. thaliana* appear to be most significant for plant K nutrition (*Hirsch* et al., 1998; *Broadley* et al., 2001; *Gierth* et al., 2005; *Rubio* et al., 2008, 2010; *Honsbein* et al., 2009; *Pyo* et al., 2010; *White* and *Karley*, 2010; *Alemán* et al., 2011). Orthologs of the outward-rectifying K channel (KORC) AtSKOR of *A. thaliana* appear to be responsible for loading K into the xylem (*Gaymard* et al., 1998; *White* and *Karley*, 2010).

Plant growth and crop yield generally follow the law of diminishing returns with increasing K phytoavailability (Fig. 1; *Greenwood* et al., 1980). Provided the K supply to the roots matches the minimal demand of the plant, and NH_4^+ is absent from the rhizosphere, plant roots can acquire sufficient K for growth from solutions containing micromolar K concentrations (*Asher* and *Ozanne*, 1967; *Wild* et

al., 1974; *Spear* et al., 1978ab; *Siddiqi* and *Glass*, 1983a; *White*, 1993; *White* and *Karley*, 2010). Crop demand for K varies during development and is directly related to N demand. Annual crops exhibit a characteristic time course of K acquisition and internal K redistribution during their life cycle. Seed K must support the initial growth of seedlings, but seed K reserves are only sufficient for a brief period (often less than a phyllochron), before plant growth must be supported by K uptake by the root system (*White* and *Veneklaas*, 2012). Thus, the K concentration in plant tissues is related to the ability of the roots to acquire K from the soil and tissue growth rates. Although the patterns of K accumulation vary among cultivars, many arable crops, including wheat, maize, rice and canola, often reach their maximal K content at anthesis and K is redistributed from senescing leaves to the seed, although some field crops, such as sorghum, soybean, lupin and sunflower, continue to acquire significant quantities K from the soil during seed maturation (*Hanway* and *Weber*, 1971; *Hocking* and *Pate*, 1978; *Hocking* and *Steer*, 1983; *Karlen* et al., 1988; *Feil* et al., 1992; *Hocking*, 1994; *Dobermann* et al., 1998; *Malhi* et al., 2007; *Rose* et al., 2007, 2008; *Fageria* et al., 2011).

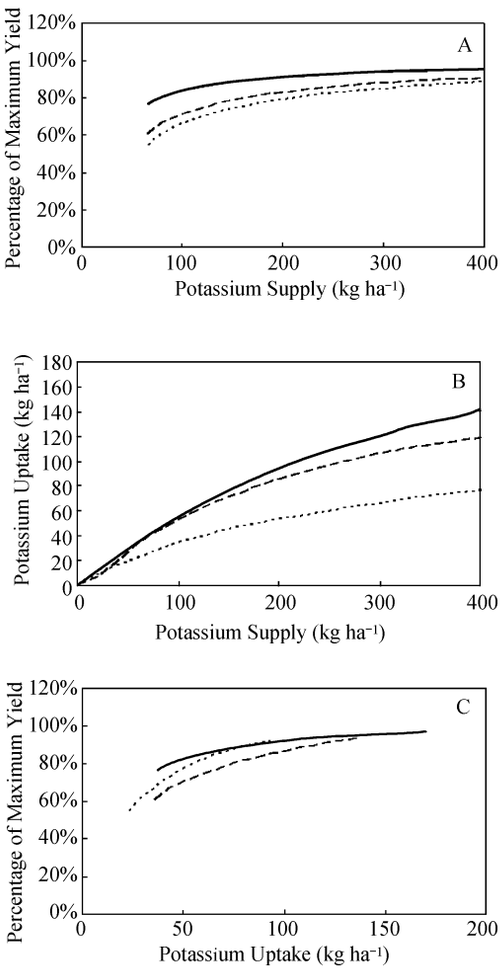


Figure 1 Relationships between (A) yield and soil potassium supply, (B) potassium uptake and soil potassium supply, and (C) yield and potassium uptake of spring wheat (solid line), broad bean (dashed line) and potato (dotted line) crops growing at Wellesbourne, UK. Data for Panel A were derived from the equations of *Greenwood* et al. (1980). Data for Panel B were calculated using the model of *Zhang* et al. (2007a).

If root K acquisition is insufficient to meet the K demand for new growth, characteristic biochemical, physiological and morphological responses occur both to increase K acquisition from the soil and to cope with reduced tissue K concentrations (*Amtmann* et al., 2006; *White* and *Karley*, 2010). To improve K acquisition, the number, activity, or affinity for K of transporters in the plasma membrane of root cells is increased (*White* and *Karley*, 2010). It has been speculated that increasing the number or activity of K transporters might improve K acquisition in heterogeneous soils with local patches of high K availability, whereas increasing the affinity of K transporters might benefit K acquisition when the K concentration in the soil solution is constantly low. Physiological adaptations to low K supply include the replacement of vacuolar K with alternative osmotica, redistribution of K from mature to developing tissues, and reducing plant growth to maintain appropriate tissue K concentrations for cell function. Tissue concentrations of sugars, especially sucrose, amide nitrogen, amino acids (lysine, arginine and tyrosine), and polyamines, such as putrescine and agmatine, increase greatly when plants lack K, as do tissue concentrations of readily available cations, such as Na^+, Ca^{2+} and Mg^{2+} (*Amtmann* et al., 2006; *Hermans* et al., 2006; *White* and *Karley*, 2010; *Wakeel* et al., 2010, 2011), which reduces tissue K requirements (*Johnson*, 1973; *Barraclough* and *Leigh*, 1993).

3 Variation in KUE among angiosperm species

Plant species differ in their growth response to K supply, their ability to acquire K from the soil

(KUpE) and their ability to utilise K physiologically (KUtE) for vegetative and reproductive growth (Fig. 1; *Bartholomew* and *Janssen*, 1929; *Asher* and *Ozanne*, 1967; *Johnson*, 1973; *Wild* et al., 1974; *Hoveland* et al., 1976; *Spear* et al., 1978ab; *Woodhouse* et al., 1978; *Greenwood* et al., 1980; *Steingrobe* and *Claassen*, 2000; *Wang* et al., 2000; *Jungk*, 2001; *El Dessougi* et al., 2002; *Høgh-Jensen* and *Pedersen*, 2003; *Brennan* and *Bolland*, 2004; *Trehan*, 2005; *Grant* et al., 2007; *Garendás* et al., 2008; *Samal* et al., 2010; *Hafsi* et al., 2011). In general, cereals, grasses and brassicas often attain maximum growth at a lower K supply than legumes or other eudicots, and compete best in K-limited environments (*Asher* and *Ozanne*, 1967; *Hoveland* et al., 1976; *Pretty* and *Stangel*, 1985; *Grant* et al., 2007; *Hafsi* et al., 2011). Similarly, cereal, brassica and legume crops often require less K fertiliser for maximum yields than many vegetable, solanaceous or beet crops (Fig. 1A; *Greenwood* et al., 1980; *Pretty* and *Stangel*, 1985; *Mengel* et al., 2001; *Trehan*, 2005; *Brennan* and *Bolland*, 2004, 2007; *Fageria*, 2009; *Kuchenbuch* and *Buczo*, 2011). However, this ranking is not always observed and probably depends upon soil characteristics and other environmental variables.

In principle, the ability of a plant species to achieve maximal growth at a lower K supply than another species can be a consequence of better KUpE or KUtE. The physiological K requirement of a plant is determined by its critical tissue K concentration, its ability to remobilise K from older to younger tissues, and its growth rate. Better K acquisition allows the physiological K requirement to be met at a lower K availability in the soil and better physiological utilisation allows more biomass to be produced at a lower K supply. The tissue K concentration at which K-deficiency symptoms appear in leaves is generally lower in cereals and grasses than in legumes and most eudicots (*Johnson*, 1973; *Spear* et al., 1978a; *Brennan* and *Bolland*, 2004). Cereals and grasses generally acquire K better, and have lower physiological K requirements, than most eudicots (Fig. 1B, C; *Greenwood* et al., 1980; *Pettersson* and *Jensén*, 1983; *Mengel* et al., 2001; *Brennan* and *Bolland*, 2004, 2007; *Trehan*, 2005, *Rose* et al., 2007; *Fageria*, 2009; *Wang* et al., 2011).

Differences in KUpE between plant species have been attributed to contrasting abilities of their root systems (1) to release non-exchangeable K from the soil, (2) to exploit the soil volume, and (3) to effect high-affinity, high-capacity K uptake by cells (*Greenwood* et al., 1980; *Jungk* and *Claassen*, 1997; *Steingrobe* and *Claassen*, 2000; *Wang* et al., 2000, 2011; *Jungk*, 2001; *Trehan*, 2005; *Rengel* and *Damon*, 2008; *Samal* et al., 2010; *Hafsi* et al., 2011). Plant species differ in their strategies to acquire K when its availability in the rhizosphere is low (*Jungk* and *Claassen*, 1997; *Wang* et al., 2011). For example, grasses, cereals and brassicas mobilise considerable quantities of soil K from the non-exchangeable fraction by minimising K concentrations in the rhizosphere through the expression of high-affinity, high-capacity K uptake-systems in roots, whereas grain amaranth and sugar beet also access non-exchangeable K through copious exudation of organic compounds, particularly organic acids (*Wang* et al., 2000, 2011; *Høgh-Jensen* and *Pedersen*, 2003; *Shi* et al., 2004). Legumes, such as alfalfa and pea, and potato are relatively ineffective in acquiring non-exchangeable K from the soil (*Wang* et al., 2000; *Høgh-Jensen* and *Pedersen*, 2003). The ability of cereal and brassica roots to exploit the soil volume more effectively than legume roots is associated with higher growth rates, greater root: shoot biomass ratios, and the development of long root hairs (*Høgh-Jensen* and *Pedersen*, 2003). The ability of wheat, in particular, to acquire K effectively has been attributed to its large root system (*Samal* et al., 2010; *Wang* et al., 2011). Similarly, the ability of ryegrass to acquire K and out-compete red clover in mixed swards has been attributed to greater root length and the abundance of root hairs (*Mengel* and *Steffens*, 1985). Improved physiological K utilisation can be achieved by the redistribution of K to tissues with immediate K requirements and through a greater capacity to maintain appropriate cytoplasmic K concentrations, either by anatomical adaptations or by greater substitution of K for other solutes in the vacuole (*Rengel* and *Damon*, 2008; *Wakeel* et al., 2011). Interestingly, Na can substitute for K in the vacuoles of many, but not all, plant species (*Mengel* et al., 2001; *Wakeel* et

al., 2011).

4 Variation in KUE within crop species

Considerable variation in growth and yield responses to K supply, KUE, KUpE and KUtE, has been reported among existing genotypes of many crop species (*Dobermann* et al., 1988; *Baligar* et al., 2001; *Rengel* and *Damon*, 2008; *Fageria*, 2009; *White* and *Karley*, 2010; *Fageria* et al., 2011). Variation in KUE has been correlated with either KUpE or KUtE, depending upon the plant species studied and the conditions under which it was grown (*Siddiqi* and *Glass*, 1983a; *Chen* and *Gabelman*, 2000; *George* et al., 2002; *Yang* et al., 2003; *Damon* and *Rengel*, 2007; *Damon* et al., 2007; *Zhang* et al., 2007b; *Liu* et al., 2009; *White* et al., 2010). Variation in KUpE or KUtE has been observed among genotypes of cereals, including rice, wheat, barley, sorghum, and maize, legumes, such as common bean, broad bean, soybean, lupin and alfalfa, seed-oil and vegetable brassicas, including *B. napus* (canola, oilseed rape), *B. oleracea*, *B. rapa* and *B. juncea*, cassava, sweet potatoes and solanaceous crops, including tomato and potato, and cotton (Tab. 1). In addition, genetic variation in herbage K concentration has been reported in several grass and clover species, which have been studied principally because of the negative economic consequences of grass tetany in ruminant animals when their diets contain high K:(Ca+Mg) ratios (*Asher* and *Ozanne*, 1977; *Smith* et al., 1999; *Baligar* et al., 2001; *Kunelius* et al., 2003; *Dürr* et al., 2005; *Christian* et al., 2006; *El-Nashaar* et al., 2009).

Table 1 Selected studies demonstrating genetic variation within crop species in yield or biomass response to K supply, K uptake efficiency (KUpE=K content: K supply) and physiological K utilisation efficiency (KUtE=yield or biomass: K content). Data are expressed as quotients (maximum value: minimum value) of n genotypes. Abbreviations: −K, measurement taken at suboptimal K supply, P=data expressed as whole plant biomass, S=data expressed on shoot biomass, G=data expressed on grain yield, T=data expressed on tuber yield, R=data expressed on root yield.

Species	Yield response to K supply	KUpE	KUtE	Genotypes, Experiment	Key Reference
Rice (*Oryza sativa*)	yes	—	1.51	—	Baligar et al. (2001)
	—	—	5.94 S, −K	$n>134$	Yang et al. (2003)
	1.41 G	1.54 S, −K	1.53 G, −K	$n=9$	Yang et al. (2004)
	5.92 G	1.98 G	2.29 G	$n=15$	Fageria (2009)
	—	1.42 S	1.46 S,	$n=28$	Liu et al. (2009)
	no, G	1.86 P, −K	2.49 G, −K	$n=6$	Fageria et al. (2010)
Wheat (*Triticum aestivum*)	—	1.80 S, −K	1.47 S, −K	$n=24$	Woodend et al. (1987)
	—	6.52 G, −K	2.34 G, −K	$n=12$	Woodend & Glass (1993)
	1.14 G	2.15 P, −K	1.34 G, −K	$n=4$	Zhang et al. (1999)
	1.18[a]	2.15[a] S, −K	1.74 G[b]	[a]$n=4$, [b]$n=58$	Guoping et al. (1999)
	—	2.58 G	1.61 G	$n=21$	El Bassam et al. (1998)
	—	—	1.50	—	Baligar et al. (2001)
	1.76 G	2.75 S, −K	yes G, −K	$n=12$	Damon & Rengel (2007)
Barley (*Hordeum vulgare*)	1.74[a]	1.71[b] P, −K	1.78[b] P, −K	$n=5$[a]; $n=10$[b]	Glass & Perley (1980)
	—	—	1.23 P	$n=11$	Pettersson & Jensén (1983)
	6.46 P	5.54 P, −K	2.84 P, −K	$n=27$	Siddiqi & Glass (1983a)
Wild Oat (*Avena fatua*)	1.48 P	1.56 P, −K	1.09 P, −K	n=3, 6 wk	Siddiqi et al. (1987)
Sorghum (*Sorghum bicolor*)	—	—	1.91	—	Baligar et al. (2001)
Maize (*Zea mays*)	—	1.86 S	1.33 S	$n=18$	Feil et al. (1992)
	—	—	2.55	—	Baligar et al. (2001)
Common bean (*Phaseolus vulgaris*)	1.93 S	4.36 S, −K	1.44 S, −K	$n=5$	Shea et al. (1968)
	—	6.04 S	8.46 G	$n=10$	Fageria et al. (2001)

续 表

Species	Yield response to K supply	KUpE	KUtE	Genotypes, Experiment	Key Reference
Faba bean (*Vicia faba*)	—	yes G	yes G	n=28, F_1	Stelling et al. (1996)
Soybean (*Glycine max*)	1.60 G	—	—	n=5	Sale & Campbell (1987)
Lupin (*Lupinus angustifolius*)	1.76 S	1.23 S, −K	1.57 S, −K	n=8	Brennan & Bolland (2004)
Alfalfa, lucerne (*Medicago sativa*)	—	—	1.63	—	Baligar et al. (2001)
Canola, oilseed rape (*Brassica napus*)	1.12 2.40 S	1.58 3.50 −K	1.52 3.13 S, −K	n=4 n=84, E1	Brennan & Bolland (2007) Damon et al. (2007)
Brassica oleracea	— — —	— — 17.9 S	1.67 S 2.32 S 3.37 S	n=22, kale n=60, kale n=343, DFS, GE1	Kopsell et al. (2004) Vilar et al. (2008) White et al. (2010)
Chinese cabbage (*Brassica rapa*)	—	—	2.30 S	n=142, DH	Wu et al. (2008)
Indian mustard (*Brassica juncea*)	—	1.54 S	1.44 S	n=3	Shi et al. (2004)
Spinach (*Spinacia oleracea*)	—	—	3.90 S	n=327	Grusak & Cakmak (2005)
Cassava (*Manihot esculenta*)	1.69 P	—	1.32 P, −K	n=12	Spear et al. (1978ab)
Sweet potato (*Ipomoea batatas*)	yes	9.46 −K	3.18 R, −K	n=84	George et al. (2002)
Tomato (*Solanum lycopersicum*)	1.94 P 2.06 P —	1.05 P, −K 1.40 P, −K 1.84 S	1.82 P, −K 1.62 P, −K 1.24 S	n=6 n=9 n=5	Makmur et al. (1978) Chen and Gabelman (1995) Sánchez-Rodríguez et al. (2010)
Potato (*Solanum tuberosum*)	2.15T 1.51T —	1.18 −K 2.83 −K —	3.68 T, −K 1.54 T, −K 2.15 S	n=3 n=10 n=26	Trehan & Sharma (2002) Trehan et al. (2005) Kärenlampi & White (2009)
Cotton (*Gossypium hirsutum*)	2.08 P 3.36 P 5.80 P	1.99 −K 2.39 P, −K 8.87 P, −K	1.25 P, −K 1.45 P, −K 1.42 P, −K	n=4 n=8 n=25	Zhang et al. (2007) Yang et al. (2011) Zia-ul-hassan et al. (2011)

The same traits that have been found to contribute to differences in KUpE between plant species have also been observed to contribute to differences in KUpE among genotypes within crop species (*Jungk* and *Claassen*, 1997; *Baligar* et al., 2001; *Høgh-Jensen* and *Pedersen*, 2003; *Trehan*, 2005; *Nawaz* et al., 2006; *Rengel* and *Damon*, 2008; *Fageria*, 2009; *White* et al., 2010; *Yang* et al., 2011; *Zia-ul-hassan* and *Arshad*, 2011). For example, genotypes of potato with greater KUpE mobilise more non-exchangeable K, have a more extensive root system and exhibit a higher K uptake-capacity than other genotypes (*Trehan*, 2005; *Trehan* et al., 2005; *Trehan* and *Sharma*, 2002); genotypes of tomato with greater KUpE maintain rapid root growth and have a greater K uptake-capacity when the K supply is low (*Chen* and *Gabelman*, 1995, 2000); genotypes of barley with greater KUpE have a greater K influx or net uptake capacity when grown with a low K supply (*Glass* and *Perley*, 1980; *Pettersson* and *Jensén*, 1983; *Siddiqi* and *Glass*, 1983b); and genotypes of rice (*Yang* et al., 2003; *Jia* et al., 2008), soybean (*Sale* and *Campbell*, 1987), maize (*Nawaz* et al., 2006) and cotton (*Yang* et al., 2011; *Zia-*

ul-hassan and *Arshad*, 2011) with higher KUpE all have longer roots at low K supply than inefficient genotypes.

Differences in KUtE within crop species have been attributed to effective K redistribution within the plant, from older tissues to developing tissues, and a greater ability to maintain appropriate cytoplasmic K concentrations (*Rengel* and *Damon*, 2008; *White* et al., 2010; *Wakeet* et al., 2011). For example, barley varieties that are less susceptible to K starvation have greater ability to mobilise K from the vacuole to the cytoplasm of root cells at low K supply (*Memon* et al., 1985) and growth of tomato genotypes in Na-rich, K-limiting conditions correlates with the ability for Na to substitute for K as a vacuolar osmoticum (*Figdore* et al., 1989). The ability to maintain water relations, photosynthetic activity and a high harvest index when grown at low K supply all contribute to both KUtE and KUE (*Yang* et al., 2004; *Rengel* and *Damon* 2008; *Fageria*, 2009). Genotypic differences in harvest index contributing to variation in yields at low K supply have been observed in rice (*Yang* et al., 2004), wheat (*Woodend* and *Glass*, 1993; *Zhang* et al., 1999, *Damon and Rengel*, 2007), common bean (*Fageria* et al., 2001), broad bean (*Stelling* et al., 1996), and sweet potato (*George* et al., 2002).

5 The genetics of KUE

Crop genotypes with greater KUE, KUpE and KUtE might be developed through conventional breeding or modern biotechnological approaches. From the forgoing discussion it would appear that there is sufficient genetic variation in KUE, KUpE and KUtE within crop species for either conventional phenotypic or genetic marker-assisted breeding programmes to deliver improved genotypes. Moreover, the heritability of KUE, KUpE and KUtE is often high (*Makmur* et al., 1978; *Harada* and *Leigh*, 2006; *Ghandilyan* et al., 2009b; *White* et al., 2010). However, recent studies have indicated that KUE, KUpE and KUtE are controlled by multiple interacting chromosomal loci (QTL) and that strong interactions between genotype and environment can occur (*Stelling* et al., 1996; *Wu* et al., 1998; *Koyama* et al., 2001; *Schneider* et al., 2002; *Atienza* et al., 2003; *Lin* et al., 2004; *Harada* and *Leigh*, 2006; *Villalta* et al., 2008; *Ghandilyan* et al., 2009b; *Kanter* et al., 2010; *Prinzenberg* et al., 2010; *White* et al., 2010; *Willems* et al., 2010; *Ahmadi* and *Fotokian* 2011; *Frary* et al., 2011; *Cheng* et al., 2012). For example, QTL influencing shoot K concentration (KUtE) in *Arabidopsis thaliana* differ between well-watered and drought conditions (*Ghandilyan* et al., 2009b) and QTL influencing shoot K concentration in *Brassica oleracea* differ between glasshouse and field environments (*White* et al., 2010). Thus, breeding programmes addressing KUE must consider carefully the conditions under which a crop will be grown.

Much of our knowledge of the molecular biology of K uptake and movement within plants has been obtained using *Arabidopsis thaliana* (*Britto* and *Kronzucker*, 2008; *Karley* and *White*, 2009; *White* and *Karley*, 2010; *Alemán* et al., 2011). Similarly, *A. thaliana* has been used to provide insight to the genetics of KUE, KUpE and KUtE in plants (*Harada* and *Leigh*, 2006; *Ghandilyan* et al., 2009b; *Kanter* et al., 2010; *Prinzenberg* et al., 2010). Four chromosomal loci (QTL) affecting shoot K concentration (KUtE) expressed on a fresh weight basis were mapped to *A. thaliana* chromosomes 2 (at 40 cM), 4 (at 43 cM) and 5 (at 82 and 106 cM), and three QTL affecting shoot K concentration expressed on a dry matter basis were mapped to chromosomes 3 (at 0 cM), 4 (at 43 cM) and 5 (at 106 cM) in a recombinant inbred population developed from a cross between the Landsberg *erecta* (L*er*) and Cape Verde Island (CVI) accessions (*Harada* and *Leigh*, 2006). Eleven QTL affecting shoot K concentration expressed on a fresh weight basis were mapped to chromosomes 1 (11, 21, 95 cM), 2 (42, 48 cM), 3 (7 cM), 4 (4, 33 cM) and 5 (5, 27, 71 cM) in a population developed from a cross between the accessions Sq－1 and Sorbo (*Kanter* et al., 2010). Two QTL affecting rosette K concentration expressed on a dry matter basis, that were independent of dry matter accumulation, were

observed on chromosomes 2 (18 cM) and 5 (85 cM) when plants were grown under well watered conditions and one QTL was observed on chromosome 4 (55 cM) when plants were grown under drought conditions in a recombinant inbred population developed from a cross between the L*er* and Antwerp-1 (An-1) accessions (*Ghandilyan* et al., 2009b).

The QTL on chromosome 1 at 21 cM, chromosome 2 at 40 cM, and chromosome 5 at 71 cM and 106 cM, co-localized with QTLs affecting shoot concentrations of caesium (Cs), which is a chemical analog of K, expressed on a fresh weight basis observed in various *A. thaliana* genetic mapping populations (*Payne* et al., 2004; *Kanter* et al., 2010). The QTL on chromosome 1 at 21 cM and on chromosome 2 at 40 cM and 48 cM co-localized with QTL for seed K concentration occasionally observed in both the L*er* × CVI and L*er* × Col genetic mapping populations (*Waters and Grusak*, 2008). The QTL on the bottom of chromosome 3 co-localized with QTL associated with seed K concentration occasionally observed in four genetic mapping populations (L*er* × CVI, L*er* × Kond, L*er* × An-1, L*er* × Eri-1) of *A. thaliana* (*Vreugdenhil* et al., 2004; *Ghandilyan* et al., 2009a). The QTL on chromosome 4 at 33 cM colocalised with a QTL for seed K concentration occasionally observed in the L*er* x Kond and L*er* x An-1 populations (*Ghandilyan* et al., 2009a). The QTL on chromosome 5 at 27 cM and at 82 cM co-localized with QTL for seed K concentration occasionally observed in four genetic mapping populations (L*er* x Col, L*er* x Kond, L*er* x An-1, L*er* x Eri-1) of *A. thaliana* (*Waters* and *Grusak*, 2008; *Ghandilyan* et al., 2009a). Many genes encoding putative K transporters are located within these QTL (*Harada* and *Leigh*, 2006; *Kanter* et al., 2010).

Chromosomal loci (QTL) affecting KUpE, KUtE and KUE have also been identified in *Brassica oleracea* using a Doubled Haploid population generated from a cross between a rapid-cycling oriental kale (A12DHd) and a calabrese genotype (GDDH33) derived from "Green Duke" (*White et al.*, 2010). Nine QTL affecting KUtE and five QTL affecting KUpE were indentified in studies performed in glasshouse and field environments. The QTL for specific traits differed between glasshouse and field environments (*White* et al., 2010). A QTL associated with KUtE in glasshouse-grown plants (chromosome C7 at 62.2 cM) was confirmed using substitution lines (*White* et al., 2010). This QTL corresponded to a segment of chromosome 4 of *A. thaliana* containing genes encoding the K transporters AtKUP9, AtAKT2, AtKAT2 and AtTPK3 and to a *Brassica rapa* BAC sequence (KBrB085J21) containing an orthologue of AtKUP9 (*White* et al., 2010). In recent years, QTL influencing shoot K concentrations in rice (*Wu* et al., 1998; *Koyama* et al., 2001; *Lin* et al., 2004; *Ahmadi* and *Fotokian*, 2011, *Cheng* et al., 2012), tomato (*Villalta* et al., 2008), *Medicago truncatula* (*Arraouadi* et al., 2012) and *Miscanthus* (*Atienza* et al., 2003) have also been identified. In rice, the locus SKC1, which affects shoot K concentration under saline conditions, encodes *OsHKT8*, a gene encoding a Na transporter expressed predominantly in the parenchyma cells surrounding the xylem (*Ren* et al., 2005). A candidate gene associated with the K1 locus affecting K concentration in sugar beet is *skt*, which encodes a putative K channel (*Schneider* et al., 2002).

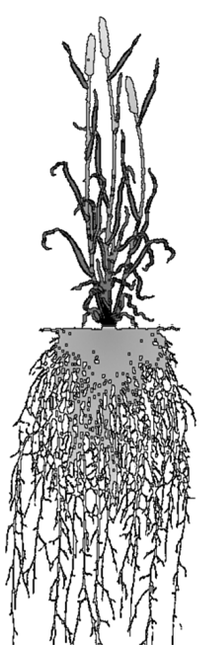
6 Prospects for improving KUE by crop plants

Although K concentrations in most agricultural soils are high, there is often insufficient phytoavailable K to support maximal crop growth. Thus, large amounts of K fertiliser are applied in intensive agricultural systems to maximise crop production. In extensive agricultural systems, the K demand of high-yielding crops is rarely met. In both agricultural systems, crop production can benefit from the development of crops, or genotypes of selected crops, that yield well in environments with low soil K phytoavailability either because they acquire K more efficiently or they utilise K acquired more effectively in producing yield.

There is considerable genetic variation between and within crop species in both KUpE and KUtE.

Plants with higher KUpE: (1) exude organic compounds that release more non-exchangeable soil K, which increases both K phytoavailability and the rate of K delivery to the root surface, (2) have a high K uptake-capacity, which not only accelerates K diffusion to the root surface but can also mobilise both exchangeable and non-exchangeable K, (3) invest biomass in their root system, exhibit early root vigour, high root/shoot ratios, and high root length densities, which not only increase the surface area for K uptake but also reduce the distance required for K diffusion and water flow, (4) proliferate roots throughout the soil volume and exploit local patchiness in K supply, and (5) have higher transpiration rates, which accelerates the mass flow of the soil solution to the root surface (Fig. 2). Plants with higher KUtE: (1) distribute K effectively from root to shoot, (2) tolerate low tissue K concentrations, and, at low tissue K concentrations, (3) maintain optimal K concentrations in metabolically active cellular compartments, (4) replace K in its non-specific osmotic and charge-balancing roles, (5) redistribute K from senescent to younger tissues, (6) maintain water relations, photosynthesis and canopy cover, and (7) have a high harvest index (Fig. 2).

Sufficient genetic variation in KUE, KUpE and KUtE appears to exist within crop species to develop high-yielding genotypes that will require less K fertiliser. These might be developed through selection for yield on soils with low K phytoavailability, or for phenotypic traits known to contribute to improved KUpE or KUtE screened in high-throughput laboratory or glasshouse assays. In addition, since genes and chromosomal loci affecting KUpE and KUtE have been identified, in both the model plant *Arabidopsis thaliana* and in various crop plants, this knowledge might be used to develop molecular markers for marker-assisted breeding programmes or transgenic plants.



Potassium Utllization Efficiency (KUtE)

Increasing photosynthesis
Accelerating canopy development
Increasing canopy longevity
Increasing harvest index
Tolearting lower tissue K^+ concentrations
Replacing K^+ in non-essential functions
Partitioning K^+ to metabolic cell compartments
Redistributing K from senescent to developing tissues
Redistributing K from root to shoot

Potassium Acquisition Efficienty (KUpE)

Increasing early root vigour
Increasing root biomass or root/shoot ratio
Increasing root surface area (lateral rooting, root hairs)
Increasing root length density
Improving root architecture for soil foraging
Increasing exudation of organic compounds
Increasing K^+ uptake capacity of root cells
Increasing affinity for K^+ of transport proteins
Increasing water uptake through transpiration

Figure 2 Potential targets for improving K use-efficiency.

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提高作物对钾素的吸收和利用

摘　要:作物组织中钾素浓度须维持在5～40 mg/g(以干重计)以上才能避免减产,土壤中的钾通常不足以满足这种需

求，很多农业体系中需要施用钾肥。但是钾肥价格昂贵，因而人们着眼于通过改进农业措施或筛选钾高效利用基因型以减少钾肥的施用。农业中钾肥的利用率是由作物钾素吸收率(KUpE)和钾素利用率(KUtE)决定的。钾素吸收率是指作物根系从土壤中吸收钾素的能力，钾素利用率是指作物体利用所吸收到的钾素以获得产量的能力。作物种内和种间钾素吸收率和利用率均存在较大基因差异，染色体位点对这些特点的影响已经在拟南芥和其他几种作物上得到证实。可提高钾素吸收率的作物特性包括：(1)分泌有机物，促进非交换性钾的释放；(2)较高的根系吸钾能力；(3)早期根系活力较强，具有较高的根冠比，根系较长，根系密度较大；(4)根系在土体中扩散；(5)较高的蒸腾速率。可提高钾素利用率的作物特征包括：(1)植物体内钾的高效再分配；(2)耐低钾能力；(3)在钾浓度较低时，通过细胞代谢来维持理想的钾浓度；(4)在钾浓度较低时，钾的非特异性代换能力；(5)在钾浓度较低时，从老部位到新部位钾素的再分配；(6)在钾浓度较低时，维持适当的水分、光合作用和郁蔽度；(7)较高的收获指数。研发具有这些特征的基因型作物有利于减少钾肥的施用。

关键词：拟南芥；育种；肥料；养分利用率

Citrus leaf nutrient-status: A critical evaluation of guidelines for optimal yield in Israel §

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Abstract: Maintaining orchards with trees at optimal leaf nutrient concentrations is one of the key issues for maximizing yield. Experiments for evaluating and updating guidelines are very rare since they require several years of field experiments with mature fruit-bearing trees. In the present paper, we first evaluated the Israeli guidelines for citrus by comparing them to the Israeli orchard leaf mineral status using a 10 year leaf mineral database (results of 20244 leaf analyses from commercial orchards all over Israel). Then, we created an updated guideline using a second database (the Israeli National Wastewater Effluent Irrigation Surveys database; INWEIS). This database summarizes yield and leaf mineral concentrations of commercial orchards from all over Israel. The data were collected from 122 orchards: 39 orchards of 'Oroblanco' Pomelit (*Citrus grandis*), 33 orchards of 'Michal' mandarin (*C. reticulata*), 30 orchards of 'Star Ruby' grapefruit (*C. paradise*), and 20 orchards of 'Shamouti' oranges (*C. sinensis*) over a 7 year period. Based on the first database, there was a disagreement between recommendations and the leaf nutrient status (e.g. the Israeli Ministry of Agriculture recommendations were higher than orchard median values), which indicated that the growers and/or the recommendations need to be corrected. Based on the INWEIS database a new guideline was set. It was found that the optimal leaf nutrient concentrations for grapefruit trees are 1.7 to 2.1% dry weight (DW) for N, 0.08 to 0.010% DW for P, 0.37 to 0.48% DW for K, and 0.33 to 0.45% DW for Mg. For orange trees, the optimal leaf nutrient concentrations are 1.9 to 2.3% DW for N, 0.11 to 0.14% DW for P, 0.80 to 1.00% DW for K, and 0.19 to 0.26% DW for Mg. For mandarin trees, the optimal leaf nutrient concentrations are 2.0 to 2.4% DW for N, 0.09 to 0.12% DW for P, 0.55 to 0.69% DW for K, and 0.19 to 0.26% DW for Mg. Maintaining leaf nutrient concentrations within these ranges will support maximal yields of 110 to 120 t ha^{-1} for grapefruit, 65 to 70 t ha^{-1} for orange, and 60 to 70 t ha^{-1} for mandarin cultivars.

Key words: Critical values / magnesium / nitrogen / phosphorus / potassium / upper envelope curve

1 Introduction

Maintaining leaf nutrient concentrations at an optimal level is one of the key issues for profitable citrus orchards. The first recommended guidelines for citrus were developed in the USA more than half a century ago (*Bathurst*, 1943; *Chapman*, 1949; *Reuther* and *Smith*, 1951). The USA guidelines were updated (*Embleton* et al., 1973; *Obreza* et al., 2011), based on field experiments (for example *Alva* et al., 2006). The mineral values in those guidelines are related to spring flush leaves that are 4 to 6 months old, sampled from non-fruiting twigs (*Obreza* et al., 2011). The USA guideline was adopted by growers and agricultural consulting services all over the world. In Israel, Brazil, Morocco, and South Africa, however, instead of sampling leaves from non-fruiting branches the growers are guided to sample leaves from fruiting branches (*Raveh* et al., 2007).

In general, sampling 4 - 6 month-old leaves from fruiting branches is simpler than sampling leaves from non-fruiting branches since leaves located adjacent to fruit are identified much faster. Yet, leaf nutrient concentrations from fruiting branches are usually lower than those from non-fruiting branches (*Khan* et al., 2001), reflecting the sink strength of the fruit. In countries where the recommendations

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are based on leaves sampled from fruiting branches (e. g. Brazil, Morocco, South Africa, and Israel), there are different recommendations for the various groups of varieties (e. g. oranges, grapefruit or mandarins; *Raveh* et al., 2007). The different recommendations are a result of differences in sink strength of the various fruits. On the other hand, in countries where the recommendations are based on leaves sampled from non-fruiting branches, the recommendation is the same for all the varieties (*Obreza* et al., 2011). *Khan* et al., (2001) tried to find a conversion factor between the two types of leaf recommendations. However, one factor does not take into account that fruits of different size are differ in nutrient sink-strength). As a result, whenever we incorporate leaf recommendation information, while changing the type of sampled leaves, the guidelines must be evaluated.

Experiments for evaluating and updating guidelines are very rare since they require several years of field experiments with mature bearing trees, which is expensive (*Alva* et al., 2006). Additionally, the correlations found between yield and leaf nutrient concentrations in these field experiments are generally weak: model coefficient of determination (R^2) values of about 0.25 and lower (*Alva* et al., 2006; *Kohli* et al., 1998). This phenomenon is a result of uncontrollable factors such as climate conditions (e. g. air temperature and precipitation), biotic stress and tree fertility (e. g. alternate bearing varieties or tree age) that change from one year to another and might dominate the nutrient responses. Standardizing these data (e. g. given as percent of maximal yield for each of the examined years (*Alva* et al., 2006) may reduce the effect of uncontrollable factors. Using the "upper envelope" curve for data analyses (where yield to nutrient response curves are based on maximal yield values along the different mineral concentration range), also called the "boundary line" (*Ben-Asher* et al., 2006; *Feizaisl* et al., 2010; *Sumner*, 1987), will minimize the uncontrollable factor effects. In the present paper we use data from commercial citrus orchards from all over Israel for evaluating and updating the Israeli citrus leaf mineral guidelines for optimal yield.

2 Materials and method

2.1 Database sources

For our study we used two citrus databases from Israel in which leaves from fruit-bearing branches were analyzed. The first one was a summary of all the leaf analyses done for Israeli citrus orchards from 1993 to 2004. This database was received from the Israeli Field Services Laboratories and included results of 20 244 leaf analyses from commercial orchards from all over the country: 35% of which are from grapefruit (*Cirus paradisi*, mainly 'Star Ruby' and 'Marsh'), 14% from pummelo (*Citrus maxima*, mainly 'Oroblanko'), 22% from orange (*Citrus* sinensis, mainly 'Shamouti' and 'Valencia'), 27% from mandarin (*Citrus reticulata*, mainly 'Nova', 'Mineola', 'Michal'), 1% from lemon (*Citrus* limon, mainly 'Interdonato'), and another 1% from other species (*Fortunella spec.*, mainly 'Kumquat'). About 42% of the analyses came from orchards located along the coastal area of Israel (e. g. from the Sharon Plain, or from Shfelat Yehuda). Another 31% came from the southern area of Israel (the Western Negev), and about 27% from the northern area of Israel (e. g. from the Western Galilee, the Eastern Galilee, and the Jezrael Valley).

The second database came from the Israeli National Wastewater Effluent Irrigation Surveys (INWEIS; *Anonymous*, 2006), in which 122 commercial citrus orchards were monitored for yield and leaf mineral concentrations over a 7 year period (1998—2005). This database represents 39 orchards of 'Oroblanco' Pomelit (*C. grandis*), 33 orchards of 'Michal' mandarin (*C. reticulata*), 30 orchards of 'Star Ruby' grapefruit (*C. paradise*), and 20 orchards of 'Shamouti' oranges (*C. sinensis*). These trees were grafted on three different rootstocks: sour orange (*C. aurantium*; 73 orchards), Troyer citrange (*C. sinensis* × *P. trifoliate*; 40 orchards) or Volkhamer lemon (*C. volkameriana*; 9 orchards). The orchards were located along the coastal area and the northern area of Israel (16 orchards

from the Western Galilee, 2 orchards from the Eastern Galilee, 22 orchards from the Jezrael Valley, 66 orchards from the Sharon Plain, 5 orchards from Shfelat Yehuda, and 11 orchards from Western Negev). Out of these 122 orchards 27 orchards were irrigated with brackish water, 11 orchards were irrigated with tertiary-treated reclaimed water, and 88 orchards were irrigated with secondary-treated reclaimed-water. Fertilization of the orchards was based on the Israeli Ministry of Agriculture recommendations. For more details regarding climate conditions, irrigation water quality, and soil characteristics see the INWEIS (*Anonymous*, 2006).

2.2 Characterizing citrus leaf mineral status in Israeli commercial orchards

Our work was focused on the following nutrients in leaves: nitrogen, phosphorus, potassium and magnesium. The four elements were analyzed after digestion of the leaves using sulfuric acid with hydrogen peroxide. Potassium concentration was analyzed by flame photometer (Model 410, Sherwood Scientific Ltd., Cambridge, UK), while nitrogen, phosphorus and magnesium concentration were analyzed with spectrophotometer (San++ion analyzer, Skalar Inc., GA. USA). The Field Services Laboratory database results were sorted for grapefruits, oranges, easy-peelers and lemons (four citrus fruit types). For each fruit type, we first divided the nutrient concentration data into subgroups based on constant step intervals (e.g. step intervals of 0.1% dry weight (DW) for N, K, and Mg, and of 0.01% DW for P). Next we characterized the occurrence (percent of population) of each step interval as well as its median value. The median values were compared to the local recommendation (given by the Extension Services of the Ministry of Agriculture).

2.3 Leaf mineral guidelines for optimal yield

The correlation between leaf nutrient concentrations (N, P, K, and Mg) and yield was characterized based on the INWEIS database (*Anonymous*, 2006). In this database the 'Star Ruby' variety represents the grapefruit group, the 'Shamouti' variety represents the orange group, and the 'Michal' mandarin variety represents the easy-peeler group (there was also information regarding 'Oroblanco' Pomelit; however, these results were in good agreement with those of the grapefruit and therefore these data were not shown). Data were analyzed using the "upper envelope" curve concept (*Ben-Asher* et al., 2006; *Feizaisl*, et al., 2010; *Sumner*, 1987). Yield-to-mineral response curves were based on a mathematical regression for the maximal yield values found along the various nutrient concentrations in leaves (done separately for N, P, K, and Mg). For each nutrient we first characterized the range of its measured values (minimal and maximal values), then the range was divided mathematically into ten equal step intervals. From each step interval only the datum that was characterized by the highest yield was used for the calculation of "upper envelope" curve regression. Each regression is based on a set of ten data points (the points that were characterized by the highest yield), one point from each of the ten step interval.

The element concentration (N, P, K, and Mg) for maximum yield (the optimal value) was derived from the regression (the regressions were differentiated to find local maxima). Since the chemical analysis itself has its own error, the optimal element concentration for maximum yield is given as a range; calculated from the optimal value±the chemical analysis error. The chemical analysis error was evaluated by the Israeli Field Service Laboratories using the WAPAL (*Anonymous*, 2010) concept; the same sample was analyzed by the various Israeli field service laboratories and the variability among the laboratories was calculated (uncertainty value of 10% for N and P, 12% for K, and 15% for Mg; given by Dr. Raya Vulkan, Gilat Field Service laboratory director).

When sampling leaves from fruiting branches, leaf mineral concentration is strongly affected by the nutrient sink-strength of its adjacent fruit. It might be that different varieties of the same group (grapefruit, orange and mandarin) might also be different in their nutrient sink-strength. To ensure the results found are also applicable for the other varieties of grapefruit, orange, or mandarin, we compared their leaf nutrient distribution patterns to those of other representative varieties of the same group

(using the Israeli Field Services Laboratories 1993—2003 database). The 'Star Ruby' grapefruit was compared to 'Marsh' grapefruit, 'Shamouti' orange was compared to 'Navel' orange, and the 'Michal' mandarin variety was compared to 'Or' mandarin (we would have preferred to compare the relation between yield to leaf nutrient concentration of different varieties of the same group; unfortunately such data do not exist).

3 Results

3.1 Characterizing citrus leaf nutrient status in Israeli commercial orchards

The range of leaf N, P, K and Mg concentrations in Israeli orchards and their median values are given in Figs. 1, 2, 3 and 4, respectively. All nutrients were characterized by normal distributions with the exception of K that sometimes showed more than one peak (see K distribution for orange leaf; Fig 3). In most of the cases median values were below the recommendation, or at its lower range, apart from Mg where median values and the recommendations were in good agreement (Fig. 4). The differences between the recommendation range and the median value varied and in extreme cases reached greater than 50% difference (for example, K recommendation for lemon ranged between 0.9% to 1.5% DW, while the median value of the orchard population was 0.6 % of DW; Fig. 3).

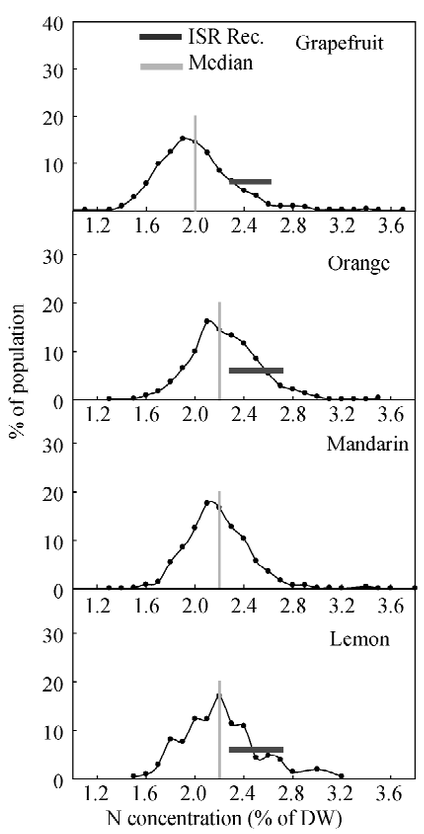

Figure 1 Leaf nitrogen concentration (N) ranges in grapefruit, orange, mandarins and lemon orchards in Israel measured from 1993 to 2004. The horizontal bars represent the Israeli Extension Service recommendations (ISR Rec.), whereas the vertical bars represent the median value of the population (currently there is no recommendation value for the mandarins).

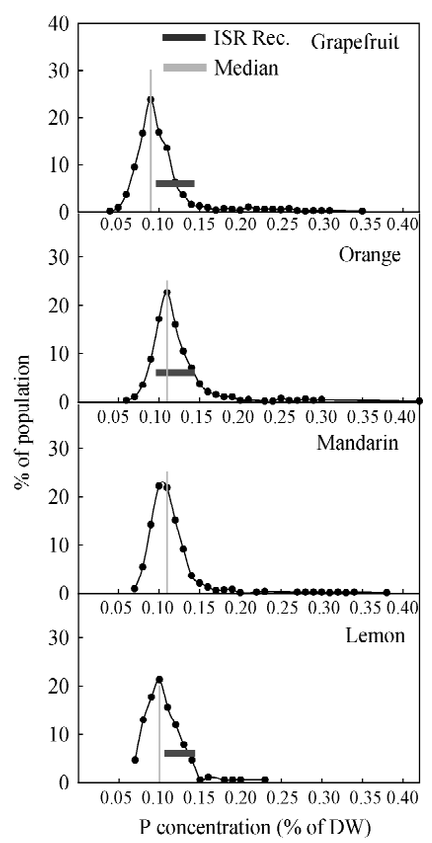

Figure 2 Leaf phosphorus concentration (P) ranges in grapefruit, orange, mandarins and lemon orchards in Israel measured from 1993 to 2004. The horizontal bars represent the Israeli Extension Service recommendations (ISR Rec.), whereas the vertical bars represent the median value of the population (currently there is no recommendation value for the mandarins).

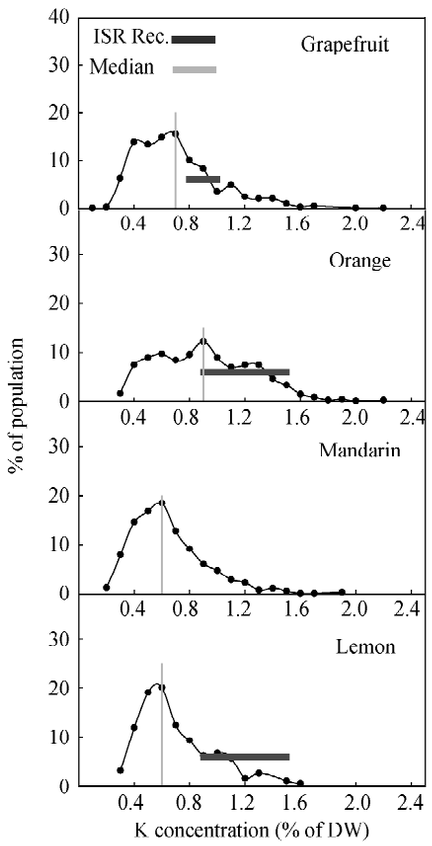

Figure 3 Leaf potassium concentration (K) ranges in grapefruit, orange, mandarins and lemon orchards in Israel measured from 1993 to 2004. The horizontal bars represent the Israeli Extension Service recommendations (ISR Rec.), whereas the vertical bars represent the median value of the population (currently there is no recommendation value for the mandarins).

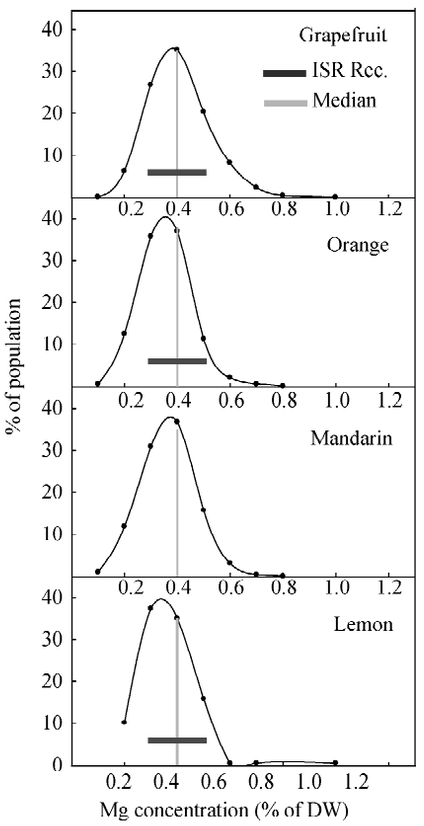

Figure 4 Leaf magnesium concentration (Mg) ranges in grapefruit, orange, mandarins and lemon orchards in Israel measured from 1993 to 2004. The horizontal bars represent the Israeli Extension Service recommendations (ISR Rec.), whereas the vertical bars represent the median value of the population (currently there is no recommendation value for the mandarins).

3.2 Leaf mineral guidelines for optimal yield

The relation between leaf nutrient concentrations and yield for 'Marsh' grapefruit, 'Shamouti' orange, and 'Michal' mandarin are presented in Figs. 5, 6, 7, and 8 (yield to N, P, K and Mg relation, respectively). For each nutrient and variety combination, we calculated the optimal nutrient range that allowed maximal yield (using the envelope curve technique and the given accuracy of the mineral measurement analyses). The optimal mineral concentration ranges ranged from 1.7 to 2.4% DW for N, from 0.08 to 0.14% DW for P, and from 0.19 to 0.45% DW for Mg. Among the different citrus varieties, the optimal leaf nutrient ranges were usually lower for 'Marsh' grapefruit, with the exception of Mg, for which the 'Marsh' grapefruit range was almost twice as high as those of 'Shamouti' orange or 'Michal' mandarin. Based on our data, the calculated optimal ranges can support a yield of 110 - 120 t ha^{-1} for 'Marsh' grapefruit, 65 - 70 t ha^{-1} for 'Shamouti' orange, and 60 - 70 ha^{-1} for 'Michal' mandarin.

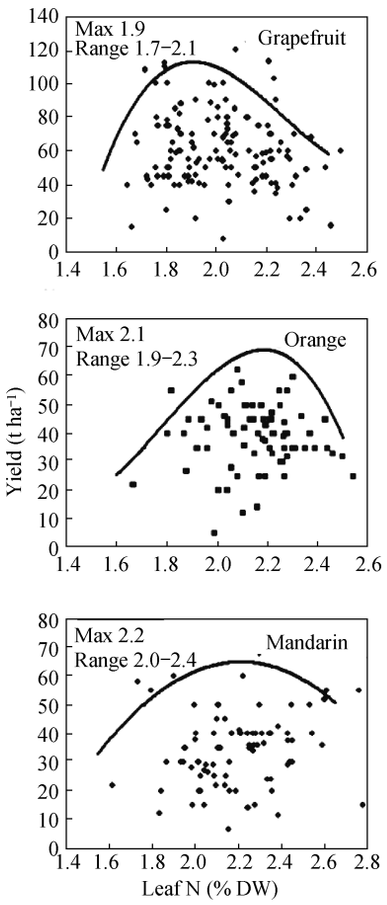

Figure 5 The relation between leaf nitrogen (N) concentration and yield for 'Marsh' grapefruit, 'Shamouti' orange, and the 'Michal' mandarin and the optimal range associated with maximal yield. The response regression equations of the envelopes were $y=35\ x^3-236\ x^2+520\ x-365$ ($R^2=0.828$), $y=21\ x^3+110\ x^2-186\ x+103$ ($R^2=0.915$), and $y=-7\ x^2+33\ x-30$ ($R^2=0.699$), for 'Marsh' grapefruit, 'Shamouti' orange, and 'Michal' mandarin, respectively. The optimal range was calculated based on the envelope curve technique in combination with the chemical measurement accuracy. Number of data points was 210, 140, and 231 for 'Marsh' grapefruit, 'Shamouti' orange, and 'Michal' mandarin, respectively.

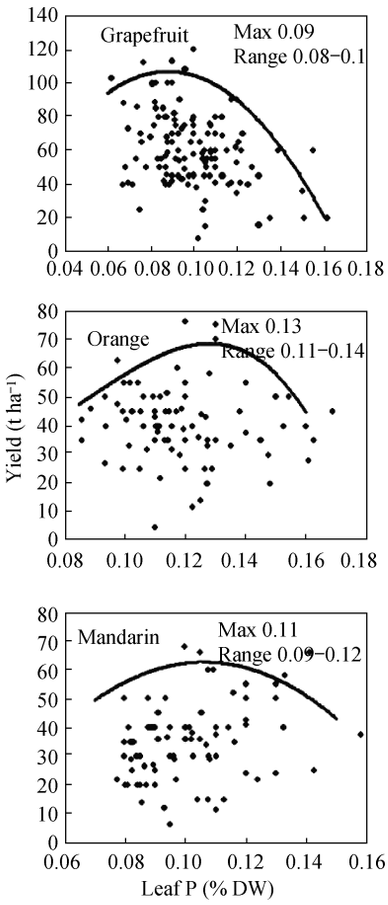

Figure 6 The relation between leaf phosphorus (P) concentration and yield for 'Marsh' grapefruit, 'Shamouti' orange, and 'Michal' mandarin and the optimal range associated with maximal yield. The response regression equations of the envelopes were $y=-1\ 649\ x^2+290\ x-2$ ($R^2=0.965$), $y=-15\ 465\ x^3+4\ 137\ x^2-299\ x+10$ ($R^2=0.815$), and $y=-1\ 013x^2+214x-5$ ($R^2=0.614$), for 'Marsh' grapefruit, 'Shamouti' orange, and 'Michal' mandarin, respectively. The optimal range was calculated based on the envelope curve technique in combination with the chemical measurement accuracy. Number of data points was 210, 140, and 231 for 'Marsh' grapefruit, 'Shamouti' orange, and 'Michal' mandarin, respectively.

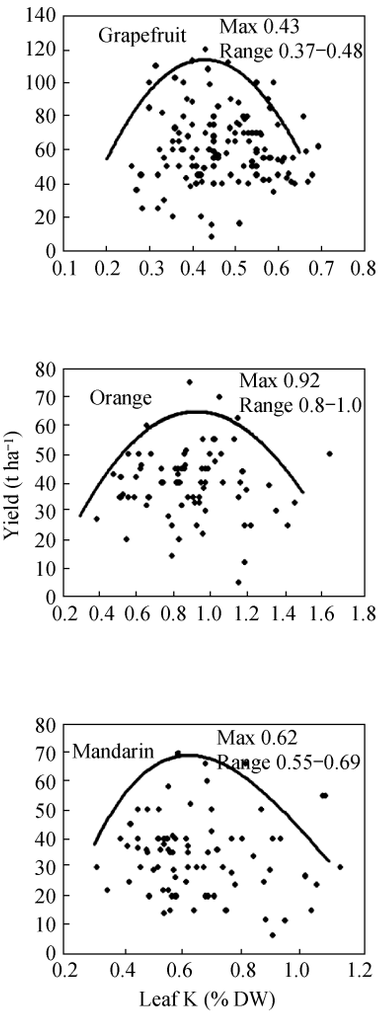

Figure 7 The relation between leaf potassium (K) concentration and yield for 'Marsh' grapefruit, 'Shamouti' orange, and 'Michal' mandarin and the optimal range associated with maximal yield. The response regression equations of the envelopes were $y=-113\ x^2+97\ x-9$ ($R^2=0.946$), $y=x^3-11\ x^2+18\ x-2$ ($R^2=0.842$), and $y=17\ x^3-55\ x^2+50\ x-7$ ($R^2=0.954$), for 'Marsh' grapefruit, 'Shamouti' orange, and 'Michal' mandarin, respectively. The optimal range was calculated based on the envelope curve technique in combination with the chemical measurement accuracy. Number of data points was 210, 140, and 231 for 'Marsh' grapefruit, 'Shamouti' orange, and 'Michal' mandarin, respectively.

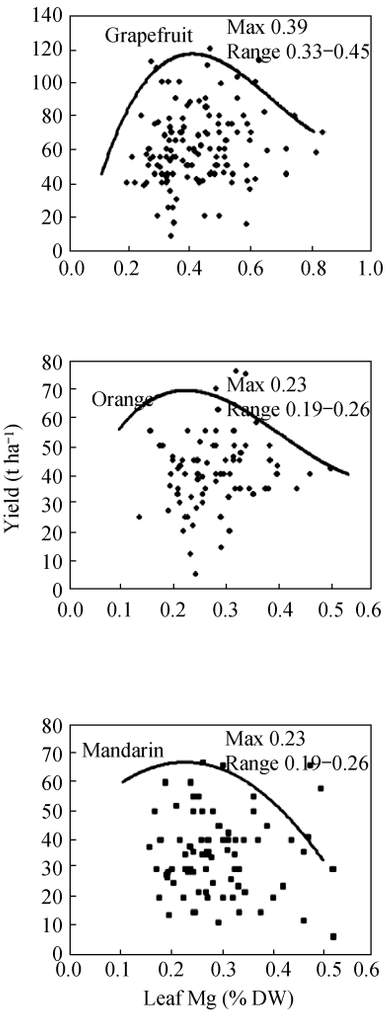

Figure 8 The relation between leaf Magnesium (Mg) concentration and yield for 'Marsh' grapefruit, 'Shamouti' orange, and 'Michal' mandarin and the optimal range associated with maximal yield. The response regression equations of the envelopes were $y=72\ x^3-144\ x^2+81x-2$ ($R^2=0.966$), $y=116\ x^3-146\ x^2+49\ x+2$ ($R^2=0.793$), and $y=-45\ x^2+20\ x+9$ ($R^2=0.961$), for 'Marsh' grapefruit, 'Shamouti' orange, and 'Michal' mandarin, respectively. The optimal range was calculated based on the envelope curve technique in combination with the chemical measurement accuracy. Number of data points was 210, 140, and 231 for 'Marsh' grapefruit, 'Shamouti' orange, and 'Michal' mandarin, respectively.

To ensure that the results that we found are also applicable for the other varieties of grapefruits, oranges, or mandarins, we compared the leaf mineral distributions of the examined varieties to those of other varieties of the same group. The comparison was based on the Israeli Field Services Laboratories 1993—2003 database. The 'Star Ruby' grapefruit was compared to 'Marsh' grapefruit, 'Shamouti' orange was compared to 'Navel' orange, and 'Michal' mandarin was compared to 'Or' mandarin. The results for N, P, K, and Mg are presented in Figs. 9, 10, 11, and 12, respectively. In general, leaf nutrient ranges of the compared varieties were relatively similar. The similar pattern of distribution ensures that under the Israeli growth conditions, varieties of the same group (e.g. grapefruit, orange, and mandarin) can also share similar recommendations for optimal yields. A summary of the current Ministry of Agriculture recommendations as well as the new recommendations that were derived from the above study are given in Tab. 1.

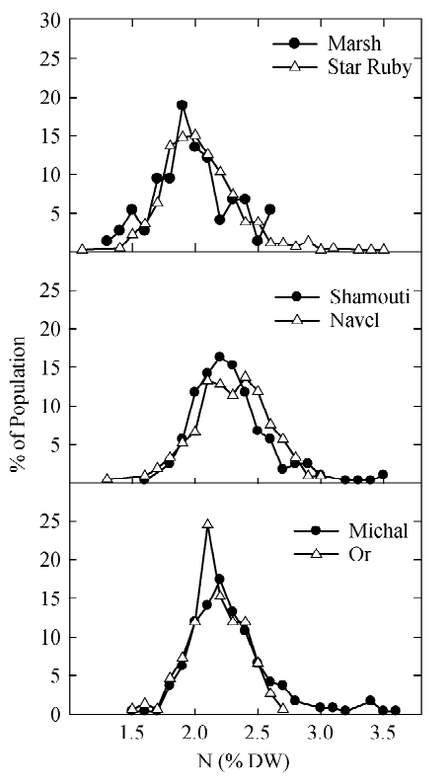

Figure 9 Comparison of leaf nitrogen concentration (N) ranges in different citrus varieties from the same group. The 'Star Ruby' grapefruit was compared to 'Marsh' grapefruit (upper figure), 'Shamouti' orange was compared to 'Navel' orange (middle figure), and 'Michal' mandarin variety was compared to 'Or' mandarin (lower figure).

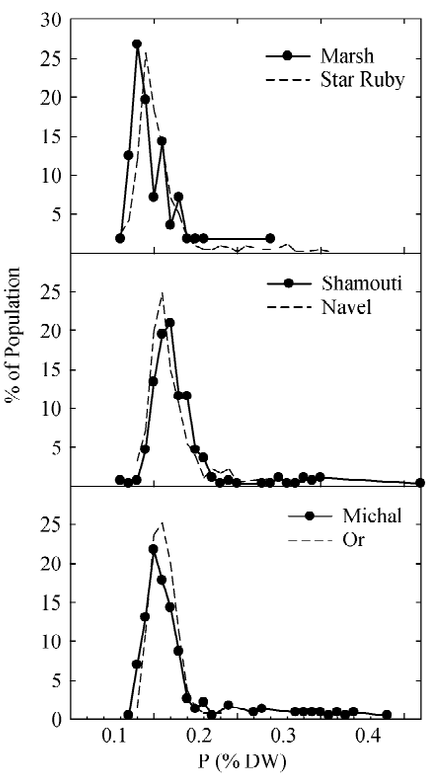

Figure 10 Comparison of leaf phosphorus concentration (P) ranges in different citrus varieties from the same group. The 'Star Ruby' grapefruit was compared to 'Marsh' grapefruit (upper figure), 'Shamouti' orange was compared to 'Navel' orange (middle figure), and 'Michal' mandarin variety was compared to 'Or' mandarin (lower figure).

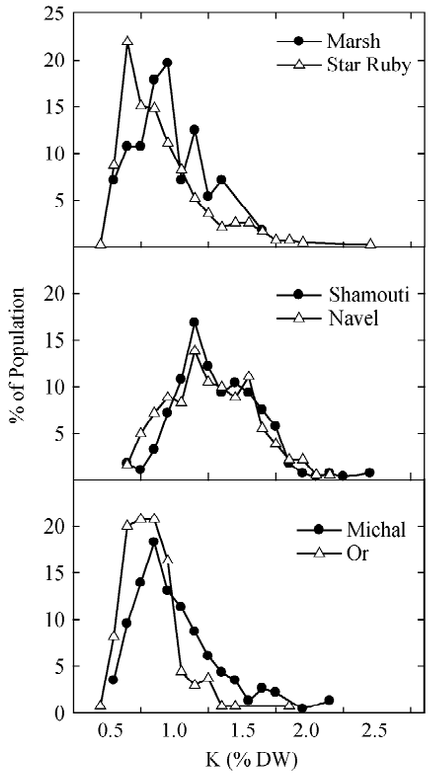

Figure 11 Comparison of leaf potassium concentration (K) ranges in different citrus varieties from the same group. The 'Star Ruby' grapefruit was compared to 'Marsh' grapefruit (upper figure), 'Shamouti' orange was compared to 'Navel' orange (middle figure), and 'Michal' mandarin variety was compared to 'Or' mandarin (lower figure).

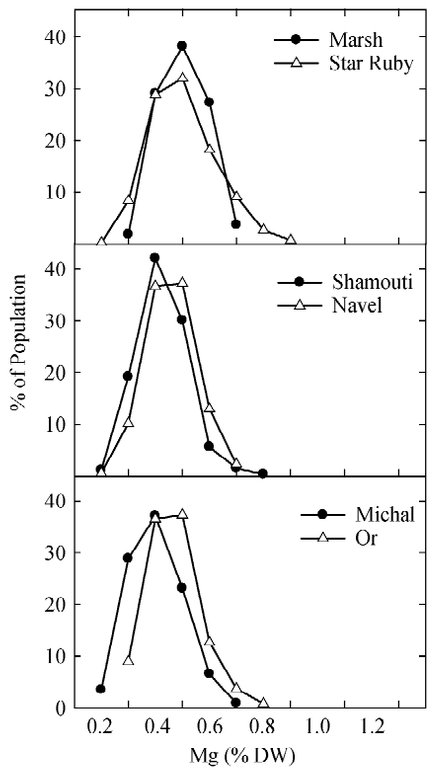

Figure 12 Comparison of leaf magnesium concentration (Mg) ranges in different citrus varieties from the same group. The 'Star Ruby' grapefruit was compared to 'Marsh' grapefruit (upper figure), 'Shamouti' orange was compared to 'Navel' orange (middle figure), and 'Michal' mandarin variety was compared to 'Or' mandarin (lower figure).

Table 1 Orchard median value, the Extension Services recommendations (*Raber*, 2011), and the new recommendations for leaf N, P, K, and Mg concentrations for citrus in Israel.

Citrus group	Element	Orchard median value (%DW)	Extension Service recommendations (%DW)	The new recommendations (%DW)
Grapefruit	N	2.0	2.3–2.6	1.7–2.1
	P	0.09	0.09–0.10	0.08–0.10
	K	0.7	0.36–0.75	0.37–0.48
	Mg	0.4	0.3–0.4	0.33–0.45
Orange	N	2.2	2.3–2.7	1.9–2.3
	P	0.11	0.095–0.105	0.11–0.14
	K	0.9	0.45–1.0	0.80–1.00
	Mg	0.4	0.3–0.4	0.19–0.26
Mandarin	N	2.2		2.0–2.4
	P	0.11		0.09–0.12
	K	0.6		0.55–0.69
	Mg	0.4		0.19–0.26
Lemon	N	2.2	2.3–2.7	
	P	0.10	0.11–0.14	
	K	0.6	0.90–1.50	
	Mg	0.4	0.3–0.4	

4 Discussion

Developing or updating guidelines for leaf nutrient concentrations for orchards is very rare, while evaluations of such guidelines are usually never done. Here we examined for the first time the relation between the Israeli citrus leaf mineral guidelines and the leaf mineral status of commercial orchards. The similarity between the two was relatively weak (e. g. orchard leaf nutrient median was usually lower than the recommendation). It was unclear what the source for such disagreement was. The fact that the recommendation ranges differed from the orchard median values does not mean that recommendations are wrong or that growers do not know how to fertilize their orchards. Yet, it is clear that either the recommendations or the fertilization regime applied by the growers is incorrect. Is the difference a result of a non-realistic recommendation values that, even under heavy fertilization regimes, are difficult to achieve? Is it a result of not being cost-effective; the balance between the fertilization costs for growers versus the additional profit from yield increases? Is it a result of adopting a guideline that was developed for non-fruiting branches (as in the USA) while growers still sampled leaves from fruiting branches? Yet, the lack of agreement between the nutrient recommendations and observed levels in commercial orchards reveals the importance of the evaluation process.

Leaf nutrient studies are typically conducted with mature commercial orchards over several years where those data from different years are usually normalized (*Alva* et al. , 2006). In the present paper we also used data that were collected over several years from mature trees. Yet, instead of basing our results on a few specific orchards, our results were based on 20 – 39 commercial orchards located all over Israel. Such an approach ensures that our results represent the current various growing areas and growth conditions. Recently, the citrus growers from the north of Israel examined the accuracy of our results. They examined about 120 new data points of yield to leaf nitrogen concentration from commercial grapefruit orchards. After analyzing their data they came to similar results; maximal yield for grapefruit trees is achieved at leaf nitrogen concentration of 1. 96% DW.

In Israel, the leaf mineral guidelines were updated several times over the years. For example, during the early seventies, leaf nitrogen recommendations based on total leaf nitrogen concentration were replaced by recommendations that were based on leaf nitrate content (*Bar-Akiva*, 1973). Thirty-five years later, after revealing that the nitrate does not reflect leaf nitrogen concentration (*Wutscher*, 1984; 1987), the recommendation was changed back to total nitrogen (*Raveh* et al. , 2007).

5 Conclusions

The Israeli Ministry of Agriculture's guideline corrections were usually based on adopting other countries' guidelines as well as on field observations and committee decisions (Mr. Dubi Raber, Citrus Fertilization and Irrigation Extension Service expert; personal communication). Here, we present for the first time an update recommendation based on the local varieties that were growing under the local climate conditions and the current agro-techniques used by local growers. In order to maintain relevant Israeli guidelines, once in a while the guidelines should be re-evaluated. Additionally, adapting new guidelines should never be done without evaluating their results.

Acknowledgments

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柑橘叶片养分状况:指导以色列柑橘获得最佳产量的重要依据

摘　要:维持果树叶片最佳养分含量是实现产量最大化的重要问题之一。对果园管理指导意见的评估和更新试验非常少,因为这些需要对成年果树进行多年田间试验。在本文中,我们先根据一个十年果树叶片矿质养分含量的数据库(来自整个以色列经营性果园 20 244 片叶子的分析结果),将以色列柑橘种植指导手册中的叶片养分状况与该数据库中的果树

叶片情况进行了对比，对这些指导手册进行了评价。然后，我们利用第二个数据库（以色列国家废水污水灌溉调查数据库，INWEIS）对指导手册进行了更新。该数据库中的数据来自全以色列超过 7 年的 122 个果园，其中 39 个 Oroblanco 波米丽（*Citrus grandis*）园，33 个 Michal 柑橘（*C. reticulata*）园，30 个 Star Ruby 柚子（*C. paradise*）园，以及 20 个 Shamouti 橙（*C. sinensis*）园。从第一个数据库可以看出，指导手册中的建议与叶片养分状况不符（比如，以色列农业部推荐值高于果园平均含量），说明栽培者需要改进措施或者推荐技术需要得到矫正。根据第二个数据库（INWEIS），形成了新的指导意见。研究表明，柚子叶片最佳养分含量 N 为 1.7%～2.1%，P 为 0.08%～0.10%，K 为 0.37%～0.48%，Mg 为 0.33%～0.45%（均以干重计）。橙子叶片最佳养分含量 N 为 1.9%～2.3%，P 为 0.11%～0.14%，K 为 0.80%～1.00%，Mg 为 0.19%～0.26%。柑橘叶片最佳养分含量 N 为 2.0%～2.4%，P 为 0.09%～0.12%，K 为 0.55%～0.69%，Mg 为 0.19%～0.26%。叶片养分含量维持在上述范围内，柚子产量将可达 110～120 t/hm^2，橙子产量可达 65～70 t/hm^2，柑橘产量达 60～70 t/hm^2。

关键词：关键值；镁；氮；磷；钾；上包络曲线

第二部分
钾肥管理

Potassium management

Potassium fertilizer management in winter oilseed rape production in China §

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Abstract: Optimal potassium (K) fertilization is beneficial for oilseed-rape (*Brassica napus* L.) yield and quality. However, the discrepancy between the high K demand of winter oilseed rape and low soil fertility and insufficient potassium input has limited the sustainable development of oilseed rape production. A series of on-farm experiments in the key winter oilseed-rape domains of China was conducted from 2004 to 2010 to evaluate K-fertilizer management for winter oilseed rape. Currently, the average NH_4OAc-extractable K content in the 0 - 20 cm soil layer is 89.1 mg kg^{-1} indicative of "slight deficiency". In addition, farmers in China usually fail to use sufficient K fertilizer in oilseed-rape production, the average mineral-potassium-fertilizer input in 2010 being only 35 kg K ha^{-1}, far lower than the recommended rate of potassium for winter oilseed rape. Adequate potassium fertilization significantly raises seed yield. The average yield increase rate for the major production regions due to K-fertilizer application was 18.5%, and the average K fertilizer-use efficiency 36.1%. Based on the negative correlation between yield response to potassium fertilization and available soil K content, a soil - K-test index was established for winter oilseed rape with a threshold value for NH_4OAc-extractable soil K of 135 mg kg^{-1}. When available soil K-content is below this threshold value, more K fertilizer should be applied to achieve high seed yield and to increase soil fertility. The major challenge for K-fertilizer management in winter oilseed-rape production in China will be to guide farmers in the different regions in making reasonable use of K fertilizer through soil K-testing technology in order to maintain both seed yield and soil fertility.

Key words: Potassium, fertilizer, oil, winter oilseed rape, China

1 Introduction

Oilseed rape (*Brassica napus* L.) is widely grown throughout the world as an edible oil and feed crop, and is a promising bio-diesel crop. In recent decades, a rapid global increase has occurred in oilseed-rape production so that in 2010 the total area devoted to its cultivation worldwide was over 31.6 million hectares, with a total production of 59.1 million tons (Tab. 1). Breeding high-yield cultivars has greatly raised oilseed-rape yield, the world average increasing over 200% in the last 50 years, from less than 0.57 t ha^{-1} in 1961 to 1.86 t ha^{-1} in 2010 (*FAOSTAT*, 2011). Additionally, increasing input of mineral nutrients has also played an important role which together with optimizing fertilization has significantly enhanced oilseed rape yield, quality, and nutrient-use efficiency (*Orlovius*, 2003; *Rathke* et al., 2006; *Zou*, 2010).

Table 1 The worldwide production of oilseed rape in 2010 (data from *FAOSTAT*, 2011)

Region	Planting area/$\times 10^4$ ha	Proportion/%	Production/$\times 10^4$ ton	Proportion/%	Yield/t ha^{-1}
China	737.0	23.3	1 308.2	22.1	1.78
Canada	651.4	20.6	1 186.6	20.1	1.82
India	553.0	17.5	641.0	10.9	1.16

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续 表

Region	Planting area/$\times 10^4$ ha	Proportion/%	Production/$\times 10^4$ ton	Proportion/%	Yield/t ha^{-1}
Australia	172.9	5.5	218.1	3.7	3.17
France	146.5	4.6	481.6	8.2	3.29
Germany	146.1	4.6	569.8	9.6	3.90
Ukraine	86.3	2.7	147.0	2.5	1.70
Poland	76.9	2.4	207.8	3.5	2.70
UK	65.3	2.1	223.0	3.8	3.42
USA	60.7	1.9	111.4	1.9	1.92
World	3 168.1	100	5 907.1	100	1.86

Potassium as a plant mineral nutrient is involved in numerous physiological and biochemical processes vital for healthy and high-yielding crops (*Marschner*, 2012). In general, its uptake by oilseed rape is substantial, *i.e.*, 290 – 373 kg K ha^{-1} and greater than any other mineral nutrient (*Orlovius*, 2003). Adequate K fertilization is thus essential for achieving high seed yield and quality (*Khan* et al., 2004; *Govahi* and *Saffari*, 2006; *Fanaei* et al., 2009; *Zou* et al., 2011a). Nevertheless, because K-deficiency symptoms may not necessarily be readily visible or observed in the field due to rapid redistribution of K within the plant, the fundamental importance of K may not be recognized or appreciated (*Römheld* and *Kirkby*, 2010). Additionally, the high cost of K fertilizer also restricts application so that in many developing countries K fertilization has been neglected (*Orlovius*, 2003). In China, approximately 22.8% of the farmers do not even apply mineral K fertilizer in oilseed-rape production (*Xu*, 2012). This inadequate use of K results not only in low crop yield but also in depletion of soil fertility (*Liu* et al., 2003; *Mussgnug* et al., 2006; *Wang* et al., 2007).

The strategy for K-fertilizer recommendation based on NH_4OAc-extractable soil K and corresponding yield response to K fertilizer has been successfully applied to many crops, including oilseed rape (*MAFF*, 2000; *Mallarino* et al., 2003; *Orlovius*, 2003; *Brennan* and *Bolland*, 2006). The breeding of high-yield varieties of winter oilseed rape and improvements in agronomic practice in China has resulted in significant increases in average seed yield since the 1980s (*Fu* et al., 2003). These developments mean that K-fertilizer management of the crop should be reassessed and optimized, especially in view of the widespread deficiency of available soil K and increases in winter oilseed-rape production (*Zou* et al., 2011b). Reevaluation and refinement of soil K testing needs therefore to be undertaken to improve K-fertilizer management of high-yield intensive cultivation necessary for oilseed rape production.

In China, winter oilseed rape is mainly distributed in the Yangtze River Basin and Guanzhong area (Fig. 1) where the total planting area and total production of the crop accounts for 89.7% and 90.6%, respectively, of the total oilseed rape cultivated. However, inadequate K fertilization can be a serious problem limiting sustainable development of winter oilseed-rape production in these regions. This paper reviews the work of our group on K fertilization in the Yangtze River Basin from 2004 to 2010. The specific objectives of our investigation were as follows: (1) to quantify the characteristics of crop K uptake for different varieties; (2) to monitor soil K fertility and farmers' fertilization practices in the regions studied; (3) to estimate the influences of K-fertilization recommendations on seed yield, quality, and fertilizer-use efficiency at regional level, and (4) to develop a soil－K-test index and fertilizer-recommendation strategy, with the aim of providing guidance on optimal K-fertilizer management and achievement of sustainable development of oilseed-rape production in China.

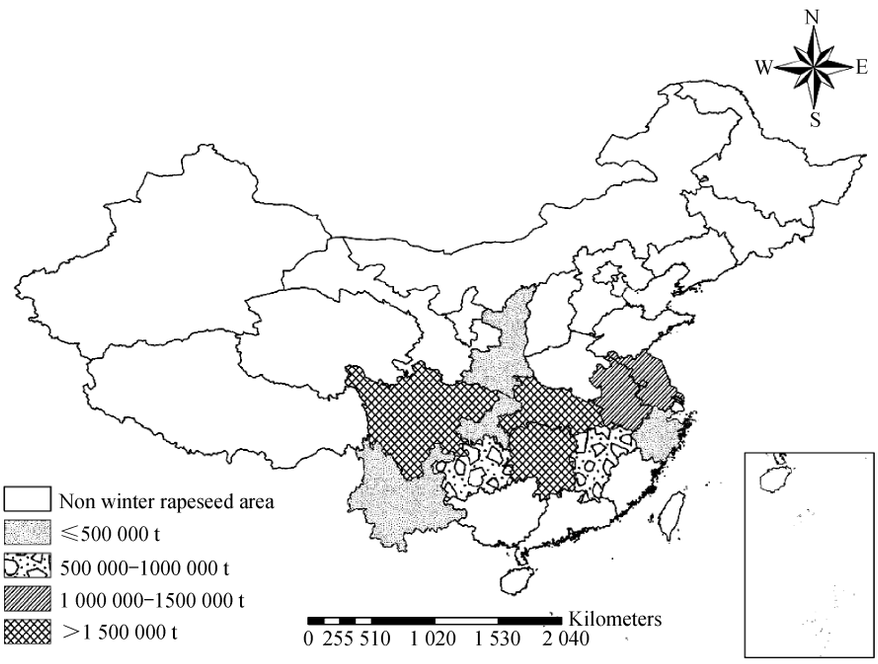

Figure 1 The production of winter oilseed rape in China in 2010.

2 Materials and Methods

Detailed descriptions of the experimental sites, the major soils and climate characteristics, experimental approaches, fertilizer surveys, and other results since 1996 can be found elsewhere (*Lu* et al., 1996; *Liu* et al., 2001; *Li* et al., 2008; *Xu* et al., 2010; *Liu* et al., 2011; *Liu*, 2011; *Zou*, 2010; *Zou* et al., 2011a, b). Here, we mainly provide information needed to discuss the results K fertilizer application trials for winter oilseed rape conducted from 2004 to 2010 in the Yangtze River Basin. During an initial period, the recommended fertilizer application rate (180 kg N ha^{-1}, 39 kg P ha^{-1}, 100 kg K ha^{-1}) for winter oilseed rape was determined through a series of field-plot experiments (*Lu* et al., 2003; *Zou*, 2010). These experiments were followed by studies of the effects of K fertilization on the seed yield at regional level.

2.1 General site characteristics

The Yangtze River Basin is an important agricultural production region that occupies an area of approximately 5.8 × 10^5 km^2 and accounts for 36.1% of the total agricultural area in China (*China Statistical Yearbook*, 2011). The average annual temperature and precipitation are 15℃-18℃ and 1 060 - 1 270 mm, respectively. Winter oilseed-rape followed by rice is one of the most prevalent crop rotations used in the region. The harvests of rice typically last from late September to early October. In the following oilseed rape crop, seedlings are usually transplanted in order to save time, mitigate against sudden climate changes in winter and to achieve high yield. The farmers sow the seeds in the middle of September, 30 - 40 d after which oilseed-rape seedlings with four to five leaves are transplanted by hand to double rows spaced approximately 0.3 m apart with 0.2 - 0.3 m between plants, corresponding to 105 000 plants ha^{-1}. Winter oilseed rape is harvested in early May of the following year. The local double low rapeseed cultivars (*Brassica napus* L. with low glucosinolate and erucic acid concentrations), such as Zhongshuang, Zhongyouza, Huashuang, and Huayouza, are widely grown in these regions, and the average seed yield is 1.75 t ha^{-1}, with a range of 0.96 t ha^{-1} to 2.44 t ha^{-1} (*China Statistical Yearbook*, 2011).

2.2 Experimental details

At each experimental site, two treatments (without K fertilizer and with K fertilizer) were arranged according to a completely randomized block design with three replicates. The treatments were as

follows: (1) Without K fertilizer treatment (0-K): only N and P fertilizer were applied to ensure that a lack of macronutrients other than K did not limit the crop growth. The N- and P-fertilizer recommendation rates were determined by the local soil and fertilizer work station based on the site and climatic conditions. The N rates varied from 120 to 300 kg N ha^{-1}, and the P rates varied from 5 to 17 kg P ha^{-1}. (2) With K fertilizer treatment (+K): the N and P fertilizer application rates were the same as for the first treatment at each site. The optimal K rate at each site was determined based on local recommendations. The average K-application rate was 89 kg K ha^{-1}, with a range of 57 to 117 kg K ha^{-1}, depending on site conditions. From 2004 to 2010, 732 field experiments were conducted in the key winter oilseed-rape domains of the Yangtze River Basin.

The N, P, and K fertilizers used in the experiment consisted of urea (46% N), superphosphate (5% P), and potassium chloride (50% K), respectively. In addition, 7.5 kg of borax (11% B) per ha was applied to all plots as a basal fertilizer to ensure an adequate boron supply because the low average soil hot-water B content of only 0.38 mg kg^{-1} in the Yangtze River Basin (*Zou*, 2010). The plot size was 40 m^2. Farmers carried out all water management and pest-control measures of the plots in accordance with commonly used methods.

2.3 Measurements

Initial soil samples were collected at depths of 0 to 20 cm before basal fertilizer application. Soil-chemical determinations made on the dried sieved soil included soil organic matter, alkali-hydrolyzable N, Olsen-P, NH_4OAc-K, and soil pH. Soil samples from 74 experiments with the same fertilizer application rate (180 kg N ha^{-1}, 39 kg P ha^{-1}, and 100 kg K ha^{-1}) were also extracted with Agro Service International solution (ASI, 0.25 mol L^{-1} $NaHCO_3$ - 0.01 mol L^{-1} EDTA-0.01 mol L^{-1} NH_4F) and Mehlich-3 extraction (M3, 0.2 mol L^{-1} HOAc-0.25 mol L^{-1} NH_4NO_3 - 0.015 mol L^{-1} NH_4F - 0.013 mol L^{-1} HNO_3 - 0.001 mol L^{-1} EDTA) to determine ASI-K and M3-K content (*Hunter*, 1980; *Mehlich*, 1984), respectively.

Plant sampling followed the same protocol at all experimental sites. The complete plants of the whole experimental plot were harvested to determine seed yield. The seeds were cleaned, oven-dried at 60℃, and weighed. Six oilseed-rape plants from each replicate were collected at harvest for measurement of yield components, harvest index, and K concentration in plant tissue. Straw yields were estimated from the oven-dry seed yield of the plots and the seed-to-straw ratio of six plant samples. The K concentrations of seed and straw were measured using a flame photometer after wet oxidative digestion of the oven-dried plant material. Seed protein, oil, and fatty acid composition were measured using near-infrared reflectance spectroscopy (Vector 22/N, Bruker, Sweden).

2.4 Data analysis

Potassium fertilizer-use efficiency (KUE) was estimated using the difference between the K-fertilizer treatment and the 0—K plot, as described by *Zhang* et al. (2008):

$$\mathrm{KUE} = \frac{K_{+\mathrm{K}} - K_{0-\mathrm{K}}}{F_{+\mathrm{K}}} \times 100 \quad (1)$$

where K_{+K} and K_{0-K} are the shoot K uptake with the K-fertilizer treatment and without K-fertilizer treatment, respectively. F_{+K} is the mineral K fertilizer-application rate of the K-fertilizer treatment. The KUE is expressed in %.

The relative yield is calculated as follows:

$$Relative yield = \frac{Y_{0-\mathrm{K}}}{Y_{\mathrm{K}}} \times 100 \quad (2)$$

where Y_{+K} and Y_{0-K} are the seed yield with the optimal K fertilizer treatment and without K fertilizer treatment, respectively. It is expressed in %.

The soil—K-test index was established based on the relationship between the available soil K

content and the relative yield (*MAFF*, 2000). If the relative yield is less than 60%, then the available soil K is extremely deficient and K-fertilizer application will enhance seed yield significantly. If the relative yield is more than 90%, then the yield increase by the K-fertilizer application will be less than 10%, at which point the available soil K content is considered to be at or above the optimal level. The relative yields are usually divided into five levels: < 60%, 60%-75%, 75%-90%, 90%-95%, and > 95%. These levels correspond to the classifications of the available soil K as "extremely deficient," "deficient," "slightly deficient," "optimal", and "abundant," respectively. A logarithmic function is widely used to describe the relationship between available soil K content and the relative yield and to define the critical available soil K content (*Mallarino* et al., 2003; *Brennan* and *Bolland*, 2006). The available soil K content is usually considered the threshold value when the relative yield is 90% (*Cate* and *Nelson*, 1971).

3 Current status of potassium fertilizer application for winter oilseed rape

3.1 The characteristics of K uptake in winter oilseed rape

Understanding crop nutrient uptake is a prerequisite for making recommendations for adequate fertilization. The dynamics of dry-matter accumulation, K concentration, and K uptake under adequate nutrient supply (180 N ha^{-1}, 39 kg P ha^{-1}, and 100 kg K ha^{-1}) for two major winter oilseed-rape varieties (Huashang No. 5 [HS] and Zhongyouza No. 12 [ZYZ]) is shown in Fig. 2. During the seedling period (0 - 130 d) growth rate was low due to the low temperature. During this period until stem elongation, dry matter accounted for 27.1% and 26.6% of total crop dry matter at harvest for HS and ZYZ, respectively. With rise in temperature in the following spring, the oilseed rape underwent rapid

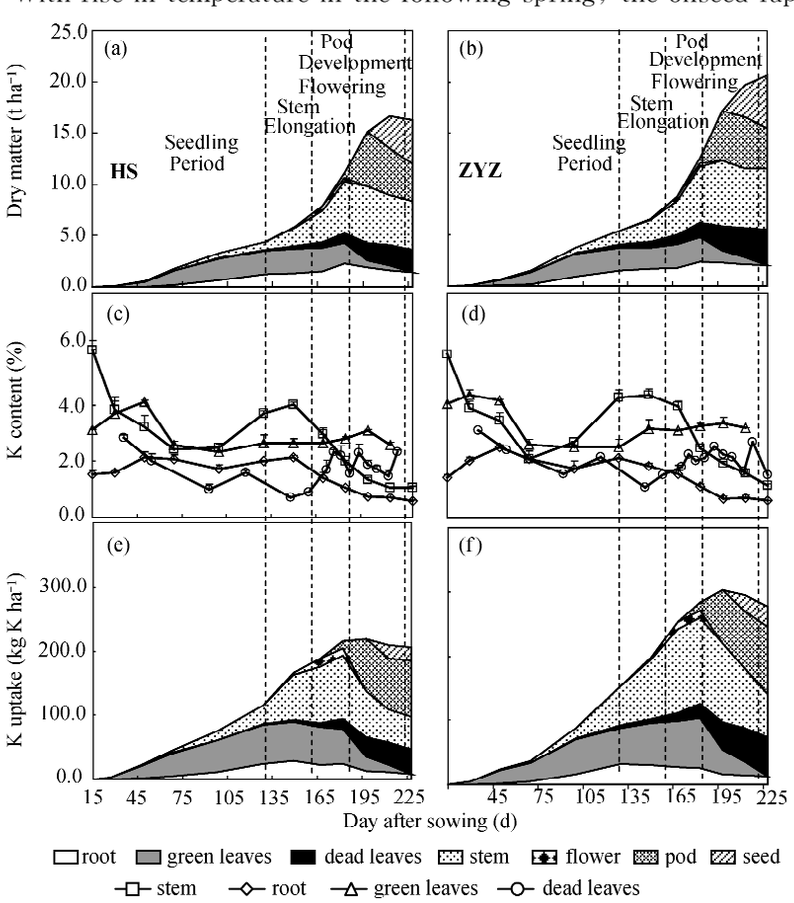

Figure 2 Dynamics of dry matter accumulation, K concentration and K uptake in the different parts of winter oilseed rape from Sep. 2009 to May. 2010 in Wuhan (modified from *Liu*, 2010). Winter oilseed rape was sown on September 25, 2009 and harvested on May 13, 2010. The planting density was 100 000 plants ha^{-1}.

growth and from the start of stem elongation in March to pod formation, the highest daily dry matter-accumulation rates were 151.2 kg ha^{-1} d^{-1} and 179.0 kg ha^{-1} d^{-1} for HS and ZYZ, respectively. Overall, the dynamics of dry-matter accumulation for the two varieties were similar. However, because of the higher seed-yield potential for ZYZ, the total accumulated dry matter for ZYZ was much higher. The average seed yields were 5.20 and 4.27 t ha^{-1} for ZYZ and HS, respectively.

The dynamics of dry-matter accumulation of the various organs differed markedly. The growth of roots ended as soon as flowering was over, as also reported by *Barraclough* (1989) whereas the stem dry matter accumulated until the pod development period. After the seedling period, dry matter formation of green leaves began to decrease and the DM yield of dead leaves increased significantly. By harvest there were almost no green leaves present and dead leaves made up 13.2% and 16.9% of the total dry matter at final harvest for HS and ZYZ, respectively.

The differences in K concentration in the various parts were similar for the two varieties (Fig. 2c, d). During the early stages of seedling emergence, the K concentration in the stems was 5.96% and 5.81% for HS and HYZ, respectively, and gradually decreased with further growth of the plants until winter. However, the K concentration in the stems increased again following regrowth of the stems in the early spring reaching a second peak in the middle of stem elongation. Crop growth also significantly influenced the K concentration of the roots. From germination to stem elongation, the K concentration in the roots varied at around 2%. However, when the roots stopped growing during the flowering period, the root content of K gradually declined. For the green leaves, the K concentration was the highest in the early stages of germination and seedling emergence. However, 70 d later, the K concentration in the green leaves stabilized at about 3% until harvest. In contrast to the K concentration in green leaves, the K concentration in dead leaves fluctuated widely, especially during the flowering period. This fluctuation may have been associated with K redistribution from mature to young tissues but could also have resulted from K leaching caused by rainfall especially from the dead leaves (*Potter*, 1991) during the associated rainy season.

As mentioned by *Orlovius* (2003), the main uptake period of K ends as soon as flowering is over. The maximum K uptakes were 218.9 kg K ha^{-1} and 303.0 kg K ha^{-1} for HS and ZYZ, respectively (Fig. 2e, f) and the average K uptakes per 100 kg of seed were 5.12 kg K and 5.82 kg K for HS and ZYZ, respectively. However, in practice, because of the redistribution of K and the fact that the uptake of K in dead leaves was not taken into account, only 168.0 kg K ha^{-1} and 215.5 kg K ha^{-1} for HS and ZYZ, respectively, were considered at harvest, which underestimates total K uptake of the crop. Furthermore, at harvest, 50.7% and 30.5% of the total K uptake on average was stored in the pods and stems, respectively, with only a small part of the K (an average of 13.5%) transported to the seeds. These high levels of K in pods and stems mean that the use of crop residues in fertilization is crucial in maintenance soil K fertility and optimizing mineral—K-fertilizer input.

3.2 Fertilizer K input

Balanced fertilization management is the key to achieving maximum yield. Nevertheless, as the recent survey in the major winter oilseed-rape production regions demonstrated (Tab. 2), the insufficiency of K input in winter oilseed rape in comparison to the total K uptake is a serious problem; approximately 22.8% of the farmers do not even apply mineral K fertilizer. The most frequently used K fertilizer was compound fertilizer reaching 75.5%. The straight K fertilizer, mainly KCl, was used only in Hunan, Hubei, Anhui, Jiangsu, and Zhejiang provinces.

Mineral fertilizer was the dominant potassium source in the winter oilseed-rape planting system, accounting for 60% of the total K input. The average K inputs in 2010 were 35 kg K ha^{-1} and 23 kg K ha^{-1} from mineral fertilizer and organic manure, respectively. In the different regions, the amount of total potassium input was similar, but the sources of potassium were different. In the upper Yangtze River Basin, in the provinces of Yunnan, Chongqing, and Sichuan, the rate of mineral—K application

was lower than the rate of organic K because of the farmers' low income and the high livestock density. However, in the middle and lower Yangtze River Basin, more farmers relied on mineral K fertilizer to obtain the high yield.

Table 2 K fertilizer varieties and application rates in winter oilseed-rape cropping systems in the major production regions in 2010 (data from *Xu*, 2012).

Province	*n*	Proportions of different K fertilizer varieties/%					Average application rate/kg K ha^{-1} [b]		
		KCl[1]	K_2SO_4	KH_2PO_4	Compound fertilizer[a]	Without fertilizer[a]	Mineral fertilizer	Organic manure[c]	Total
Guizhou	165	0	0	0.6	79.4	20.6	32	26	58
Yunnan	62	1.6	0	0	66.1	33.9	15	56	71
Chongqing	100	0	0	0	34.0	66.0	7	98	105
Sichuan	195	1.0	0	0	68.7	30.3	22	32	54
Hubei	473	10.6	0	3.8	75.9	18.9	42	14	56
Hunan	281	16.7	0.4	0.4	68.0	27.8	43	14	57
Jiangxi	144	0	0.7	0	75.7	24.3	33	6	39
Anhui	153	6.5	0	0	96.7	1.3	47	20	67
Jiangsu	118	3.4	0	0	94.9	6.8	36	19	55
Zhejiang	65	6.2	0	0	63.1	30.8	35	16	51
Winter oilseed rape regions	1 848	6.4	0.1	1.1	75.5	22.8	35	23	58

[a] The proportion for each fertilizer is calculated based on all samples, multiple answers were possible.
[b] The average K application rates are the averages of all surveyed fields, including the fields that did not receive K fertilizer.
[c] Crop residues are not included in the organic manure.

3.3 Available soil K content

An adequate supply of K is essential for high yield and quality. At present, the average NH_4OAc-extractable K content in the 0 - 20 cm soil layer in the major winter oilseed-rape production region averages 89.1 mg kg^{-1} and ranges from 7.1 to 250.0 mg kg^{-1} (Tab. 3). According to the soil K index for winter oilseed rape in the Yangtze River Basin (*Zou* et al., 2011a), the NH_4OAc-K content in approximately 88.9% of the soils is below the threshold value (135 mg kg^{-1}), indicating that it is imperative to exercise adequate K-fertilizer management to improve soil fertility in these regions. In most provinces, the available soil K content was in the range 60 to 135 mg kg^{-1}. However, in some provinces, such as Guizhou, Sichuan, Hubei, and Anhui, the available soil K content in more than 25% of the soils is less than 60 mg kg^{-1}. In addition to differences in soil characteristics (*Zhang* et al., 2009), it is possible that the lower total K-fertilizer input is also one of the major reasons for this deficiency. In addition, the K-fertilizer input and straw management of previous crops influence available soil K content (*Singh* et al., 2002). Thus, to achieve stability and high yields of oilseed rape, it is important to implement rational K-fertilizer management to enhance soil K fertility in the winter oilseed-rape production regions.

Table 3 NH_4OAc-K content in the 0 - 20 cm soil layer in the major winter oilseed-rape production regions in China.

Province	*n*	Average /mg kg^{-1}	Range /mg kg^{-1}	Frequency distribution of NH_4OAc-K content /%				
				< 25 /mg kg^{-1}	25 - 60 /mg kg^{-1}	60 - 135 /mg kg^{-1}	135 - 180 /mg kg^{-1}	180 /mg kg^{-1}
Guizhou	70	103.8±55.1[a]	31.0 - 250.0	0.00	30.00	44.29	15.71	10.00
Yunnan	25	113.0±49.9	36.0 - 230.0	0.00	12.00	56.00	24.00	8.00
Chongqing	26	80.9±30.6	15.0 - 135.0	3.85	15.38	80.77	0.00	0.00
Sichuan	111	80.9±35.7	23.0 - 189.0	1.80	32.43	59.46	4.50	1.80
Hubei	153	87.5±40	7.1 - 189.0	3.27	24.84	58.82	10.46	2.61
Hunan	46	98.3±45.5	30.0 - 250.0	0.00	21.74	65.22	4.35	8.70
Jiangxi	9	87.3±32.6	35.0 - 143.3	0.00	22.22	66.67	11.11	0.00
Anhui	91	78.7±38.0	28.0 - 225.0	0.00	35.16	58.24	2.20	4.40

续 表

Province	n	Average /mg kg^{-1}	Range /mg kg^{-1}	Frequency distribution of NH_4OAc-K content /%				
				< 25 /mg kg^{-1}	25 - 60 /mg kg^{-1}	60 - 135 /mg kg^{-1}	135 - 180 /mg kg^{-1}	180 /mg kg^{-1}
Jiangsu	58	81.9±18.3	37.0 - 143.0	0.00	6.90	91.38	1.72	0.00
Zhejiang	19	90.4±20.4	51.0 - 159.0	0.00	5.26	89.47	5.26	0.00
Shanxi	29	112.7±35.7	13.0 - 200.0	3.45	6.90	79.31	6.90	3.45
Winter oilseed-rape regions	640	89.1±40.8	7.1 - 250.0	1.41	24.02	63.42	7.38	3.77

[a] mean±standard deviation.

4 Effects of optimum K fertilization

4.1 Winter oilseed rape yield

It has been demonstrated that optimal K fertilization can significantly enhance crop yield (*Pettigrew*, 2008). The average optimal K-application rates varied slightly in the different provinces, with an average of 89 kg K ha^{-1} and a range from 57 kg K ha^{-1} to 117 kg K ha^{-1}, which might relate to the seed yield level and the available soil K content (Tabs. 2, 3). Although there were large variations in the yields in different provinces, possibly associated with different cultivars and environmental conditions, a significant increase in seed yield in response to K-fertilizer application was observed in all the provinces. The average yield with K treatments was 2.50 t ha^{-1}, which was much higher than that without K treatment (2.11 t ha^{-1}; Tab. 4). The increase in seed yield averaged 18.5% and ranged from 9.4% to 26.8% indicating that the seed-yield potential of winter oilseed rape was greater with optimal K fertilization. However, it should also be noted that in 13.7% of the experiments, the yield increase with the potassium fertilizer application was still less than 5%. The seed yield and the available soil K content were the major factors influencing yield responses to K fertilizer in the different provinces. The discrepancy between high seed yield and low available soil K content led to the highest seed yield increase, due to the additional K-fertilizer input in the Anhui province, which was lowest in soil K content. In contrast, in Yunnan province with a high soil K content, the yield increase of 67.9% of the fields was less than 10%. Thus, optimal fertilization based on the soil K fertility and seed yield in the different regions cannot only ensure high seed yield but also economize on resources and reduce agricultural costs.

Table 4 The average yield for different K treatments and the frequency distributions of yield increase rate in the major winter oilseed-rape production regions in China.

Province	n	Optimum K fertilizer application rate/kg K ha^{-1}	Yield /t ha^{-1}		Frequency distribution of the increased rate in seed yield /%					
			−K[a]	+K[a]	<5	5 - 10	10 - 15	15 - 20	20 - 30	>30
Guizhou	70	105	1.84±0.49[b]	2.25±0.53	17.14	14.29	7.14	5.71	17.14	38.57
Yunnan	28	76	2.54±0.67	2.78±0.67	39.29	28.57	7.14	7.14	10.71	7.14
Chongqing	26	76	2.09±0.50	2.61±0.52	3.85	15.38	11.54	15.38	15.38	38.46
Sichuan	111	70	2.25±0.46	2.56±0.47	18.92	22.52	18.92	12.61	12.61	14.41
Hubei	154	71	2.02±0.56	2.43±0.57	11.04	15.58	17.53	9.09	20.13	26.62
Hunan	114	101	1.95±0.51	2.26±0.53	7.02	24.56	24.56	17.54	10.53	15.79
Jiangxi	21	95	1.82±0.59	2.03±0.68	42.86	9.52	9.52	9.52	23.81	4.76
Anhui	91	117	2.20±0.41	2.79±0.44	3.30	13.19	12.09	9.89	17.58	43.96
Jiangsu	58	117	2.39±0.60	2.77±0.68	13.79	13.79	17.24	20.69	27.59	6.90
Zhejiang	30	71	2.37±0.56	2.63±0.55	26.67	26.67	13.33	13.33	6.67	13.33
Shanxi	29	57	2.16±0.32	2.56±0.31	6.90	10.34	13.79	27.59	34.48	6.90
Winter oilseed rape regions	732	89	2.11±0.55	2.50±0.58	13.66	18.03	15.98	12.70	17.08	22.54

[a] "−K" indicates without potassium fertilizer treatment; "+K" indicates with local potassium fertilizer recommendations treatment.

[b] mean±standard deviation.

4.2 Potassium fertilizer use efficiency

Fertilizer-use efficiency is an important index for estimating whether a fertilizer has been rationally applied and for forecasting fertilizer demand at regional and national scales (*Zhang* et al., 2008). The distribution of KUE of optimal K-fertilizer management in the winter oilseed-rape cropping system from the results of 722 fields of our experiments as shown in Fig. 3 indicates an increase in mean value of all the experiments of 36.1% by local K-fertilizer recommendations. This is a much higher increase than only 13.8% reported by *Zou* (2010). Nevertheless, from our findings there were still approximately 45.8% of the fields for which KUE was less than 30%. Further improving K fertilizer-use efficiency thus still remains a great challenge.

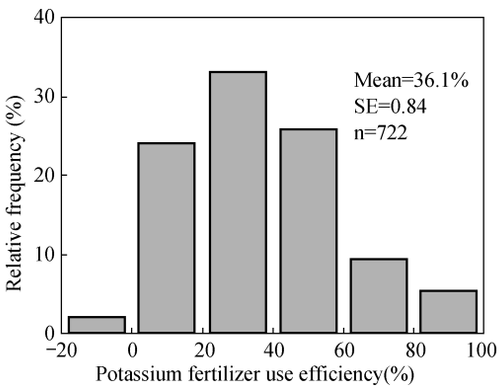

Figure 3 Frequency distribution of K fertilizer use-efficiency under local K-fertilizer recommendations for winter oilseed rape cropping system in China. There were ten experiments without measuring K uptake of winter oilseed rape.

4.3 Winter oilseed rape quality

The responses of seed quality to K-fertilizer application in the Yangtze River Basin from 2005 to 2007 were also studied (*Zou* et al., 2008). Optimal K fertilization was compared with no K fertilizer, both treatments receiving adequate N and P supply (180 kg N ha^{-1} and 39 kg P ha^{-1}). Potassium fertilization was without effect on seed quality, with no significant differences in the concentrations of quality constituents observed between the two K-fertilizer treatments. For the two treatments average oil, protein, glucosinolate, and erucic acid concentrations were 40.9%, 19.3%, 24.4 μmol g^{-1}, and 1.1%, respectively (Tab. 5).

Table 5 Effects of K-fertilizer addition on the quality of winter oilseed rape in the Yangtze River Basin (data from *Zou* et al., 2008).

Seed quality	Treatments	
	−K[a]	+K[a]
Oil content /%	40.9±3.4[b]	41.3±3.6
Protein content /%	19.3±1.8	19.0±2.1
Glucosinolate /μmol	24.4±11.5	27.8±12.1
Erucic acid content /%	1.1±1.7	1.4±1.8
Oleic acid content /%	61.5±5.7	60.4±5.9
Linoleic acid content /%	21.4±1.4	21.3±1.5
Linolenic acid content /%	8.5±0.6	8.5±0.5
Stearic acid content /%	0.8±0.5	0.8±0.5
Palmitic acid content /%	4.4±0.5	4.4±0.6

[a] "−K" indicates without K-fertilizer treatment; "+K" indicates an application rate of 100 kg K ha^{-1} of mineral fertilizer K.

[b] mean±standard deviation.

5 Soil K test index and potassium fertilization recommendation

The relationship between available soil K content and yield response to K fertilization has been reported for many crops (*MAFF*, 2000; *Mallarino* et al., 2003; *Brennan* and *Bolland*, 2006). Crop yields benefit from K-fertilizer application when the available soil K content is less than the critical value. Both the M3 and ASI extraction methods, which are similar to the NH_4OAc method, have been more readily accepted in recent years as a measure of available soil K because they are convenient in permitting the extraction of other mineral nutrients in one procedure and improve laboratory efficiency. Many studies have shown that available soil K as determined using the ASI and M3 methods is significantly positively correlated to that using the NH_4OAc method (*Loide* et al., 2005; *Xiong* et al., 2007; *Slaton* et al., 2010). Positive correlations between soil NH_4OAc-K and ASI-K and M3-K were also observed in our studies (data not shown). However, relatively little is known as to how these two soil extraction methods can be applied to K-fertilizer recommendations especially for winter oilseed rape. This was investigated using data from 74 winter oilseed-rape field experiments conducted in the Yangtze River Basin in recent years in which the relationships between available-soil-K determinations from the different test methods and relative yield were analyzed to establish new soil-K-test indices (*Zou*, 2010). All three methods were similar in ability to predict winter oilseed-rape response to K fertilization (Fig. 4). From the logarithmic equation, the threshold values of soil NH_4OAc-K, ASI-K, and M3-K contents when the relative yield was 90% were 135 mg kg^{-1}, 75 mg L^{-1}, and 135 mg kg^{-1}, respectively.

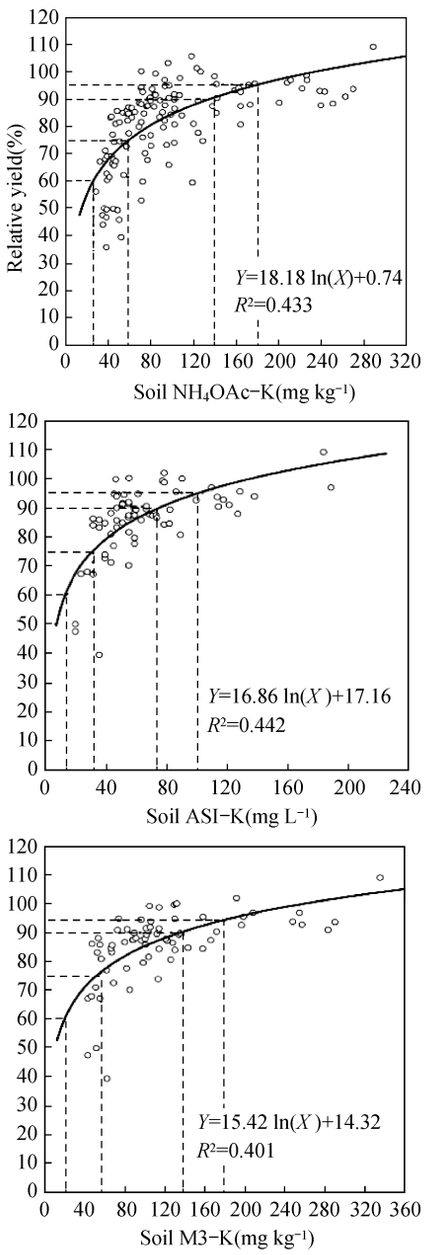

Figure 4 The relationship between the relative yield of winter oilseed rape and different available K contents in 0 - 20 cm soil layer (data from *Zou*, 2010). The four lines in each figure represent the different threshold values of soil available K content and relative yield at different levels.

The seed yield in the winter oilseed-rape production regions in 2010 averaged 1.74 t ha^{-1} and ranged from 0.96 t ha^{-1} to 2.44 t ha^{-1} (*China Statistical Yearbook*, 2011). Recommended K fertilization based on yield could therefore be established by combined use of various data namely, the available soil K-content levels and the current K fertilizer-use efficiency, the average K uptake of winter oilseed rape, and the soil—K-test indices (Tab. 6). When the available soil K content is high (relative yield > 95%), high yield can be achieved even without the K-fertilizer application, and only a small amount of K fertilizer should be applied as basal fertilizer to meet the demands of seedlings. In contrast, the input of K fertilizer should be increased at a low K content according to the soil—K-test index and yield level to achieve the maximum seed yield.

Table 6 Mineral K-fertilizer recommendation rate based on different seed yield levels and available soil K content in winter oilseed-rape cropping systems (data from *Zou*, 2010).

level	Relative yield /%	Available soil K content			Mineral fertilizer recommendation rate /kg K ha^{-1} [a]			
		NH_4OAc-K /mg kg^{-1}	M3-K /mg kg^{-1}	ASI-K /mg L^{-1}	1.50 /t ha^{-1}	2.25 /t ha^{-1}	3.00 /t ha^{-1}	3.75 /t ha^{-1}
1	< 60%	< 25	< 20	< 13	100	—	—	—
2	60 – 75%	25 – 60	20 – 50	13 – 30	83	124	174	232
3	75 – 90%	60 – 135	50 – 135	30 – 75	50	75	100	141
4	90 – 95%	135 – 180	135 – 185	75 – 100	33	50	66	91
5	> 95%	> 180	> 185	> 100	17	25	33	50

[a] K fertilizer application rate = (Crop K uptake$_{\text{target yield}}$ — soil nutrient supply) / K fertilizer use efficiency, Crop K uptake $_{\text{target yield}}$ = target crop yield × crop K demand for 100 kg seed, Soil nutrient supply = crop yield $_{\text{without K fertilizer}}$ × crop K demand for 100 kg seed. The average crop K demand for 100 kg of seed is 4.94 kg K and 4.54 kg K for K fertilization treatment and without K fertilization treatment, respectively (*Li* et al., unpublished data). The average K-fertilizer use-efficiency is 36.1%. For example, the target seed yield is 3.00 t ha^{-1} and the crop K uptake is 148.2 kg. The soil NH_4OAc-K content is 80 mg kg^{-1}, which constitutes a "slight deficiency." Without K fertilizer application, only 75 – 90% of the target yield can be achieved. The seed yield without K fertilization varies from 2.25 t ha^{-1} to 2.70 t ha^{-1}. The corresponding K uptake varies from 102.2 kg K ha^{-1} to 122.6 kg K ha^{-1}. According to the equation, the K-fertilizer application rate varies from 71 kg K ha^{-1} to 127 kg K ha^{-1}. The recommended K-fertilizer application rate is 100 kg K ha^{-1}.

6 Discussion

6.1 Dry matter accumulation and K uptake of winter oilseed rape

Lower growth rate, dry-matter accumulation, and distribution characteristics observed in winter oilseed rape were similar to those reported at Rothamsted Experimental station (*Barraclough*, 1989), Germany (*Diepenbrock*, 2000) and other sites in the Yangtze River Basin (*Liu* et al., 2001; *Liao* and *Guan*, 2002). Until the onset of stem elongation in March, dry-matter accumulation accounted for only about 30% of the total crop grown in the Yangtze River Basin (*Liao* and *Guan*, 2002). In Europe, even with a longer growth period, the corresponding value was approximately 20% which might be associated with the lower European winter temperatures. As the temperature rose in early spring, the crop entered a fast-growth period, and total dry-matter accumulation increased sharply with average daily rates of 151.2 kg DM ha^{-1} d^{-1} and 179.0 kg DM ha^{-1} d^{-1} for the two varieties, HS and XYZ, respectively. These are similar to the rates reported by *Liao* and *Guan* (2002), *i.e.*, 154.5 kg DM ha^{-1} d^{-1} to 213.0 kg DM ha^{-1} d^{-1}, depending on the sowing date. However, the values in the Yangtze River Basin (YRB) were lower than in Germany (*Diepenbrock*, 2000), which may be due to differences in cultivation and climate characteristics between these two regions.

At harvest, the accumulated dry matter, including dead leaves, was approximately 16.3 t ha^{-1} and 20.7 t ha^{-1} for HS and ZYZ, respectively. Because of the high dry-matter accumulation, the average seed yield in our uptake experiment was higher than the average values in the YRB (Tab. 4). Nevertheless, the harvest-index values were 0.26 and 0.28 for HS and ZYZ, respectively (data not shown), which are close to the values reported in many studies (*Hühn* et al., 1991; *Diepenbrock*, 2000; *Zou* et al., 2011b), indicating that high dry-matter accumulation is crucial for achieving higher seed yield.

In our experiment, the average K uptake for 100 kg seed was 5.12 kg K and 5.82 kg K for HS and ZYZ, respectively. Based on 722 field experiments in the YRB, the comparative value was 4.94 kg K. Obviously, K uptake measured at harvest underestimates total demand because maximum K uptake occurs during the flowering period. In our experiments, the differences in K uptake between the flowering period and the harvest period were 50.9 kg K ha^{-1} and 87.5 kg K ha^{-1} for HS and ZYZ, respectively. From data based only on these two varieties, it is difficult to estimate the average

difference in K uptake between the flowering period and the harvest period. Nevertheless, K uptake measured at harvest underestimates crop K demand and K-use efficiency.

6.2 Effects of potassium fertilizer application on yield and quality

Optimal K fertilization significantly enhances winter oilseed rape yield, largely due to increases in the yield components. The number of branches and pods per plant and the 1 000-seed weight increase with K-fertilizer addition (*Sharma* and *Kolte*, 1994; *Khan* et al., 2004). Furthermore, K fertilization can enhance seed germination and vigorous seedling growth, which increases resistance to lodging and seed infection (*Sharma* and *Kolte*, 1994) and favors high yield. In our experiments, the average increase with adequate K fertilization was 18.5%, with a range from 9.4% to 26.8% in winter oilseed rape production regions in China, which is slightly higher than that reported in Germany (*Orlovius*, 2003). In Pakistan, the seed-yield increase with adequate K fertilization is reported to reach 34.3% (*Khan* et al., 2004), the lower available soil K content in China possibly being the main reason for the difference. The value determined in this study was also higher than that reported by *Liu* and *Tu* (1989) who observed an average seed-yield increase of 14.2% with K-fertilizer application in the early 1980s. With the increase of the average seed yield from 0.84 t ha^{-1} in 1980 to 1.74 t ha^{-1} by 2010, (*China Statistical Yearbook*, 2011), the K requirements of oilseed rape have also risen. However, insufficient K-fertilizer input is still widespread, and the average mineral application rate for local farmers is only 35 kg K ha^{-1}. The discrepancy between the high K demand observed in the uptake experiments and insufficient K input for winter oilseed rape in different provinces (Tab. 2) is responsible for the high yield increases observed in the K-fertilizer trials. There is thus an enormous potential in the major production regions to increase seed yield by adequate K-fertilizer management.

Potassium plays an important role in plant enzyme systems, controlling photosynthesis and the conversion of oil within fat metabolism (*Orlovius*, 2003). Supplemental K fertilizer has been reported to produce a significant increase (4.1%) in the seed oil (*Singh* et al., 1997). In contrast, some experiments have shown that the oil concentration is not consistently influenced by the K addition (*Tang* and *Guan*, 2001; *Govahi* and *Saffari*, 2006; *Brennan* and *Bolland*, 2009). Even in Khan's study (*Khan* et al., 2004), the oil concentration decreased with increasing K levels. In our experiments, no significant differences in seed qualities between the two K-fertilizer treatments were detected. This is possibly because all the K experiments were carried out under adequate N supply, which is known play a dominant role in oilseed-rape quality in maintaining metabolic processes in the seeds ensuring oil and protein production (*Brennan* et al., 2000; *Rathke* et al., 2006).

6.3 Evaluation of available soil K

Soil extraction methods such as the NH_4OAc, Mehlich-3, and ASI solution methods are usually employed to estimate the soil K supply. The NH_4OAc-extraction method in particular is widely used, and the K-fertilization recommendation strategy based on soil NH_4OAc-K content has been successfully applied to many crops (*MAFF*, 2000; *Mallarino* et al., 2003). In our study, the threshold value of soil NH_4OAc-K for winter oilseed rape indicative of yield increases due to K fertilization was 135 mg kg^{-1}, which is higher than that in the previous study in the 1980s (*Liu* and *Tu*, 1989). The general seed-yield increase that resulted from improved cultivation practices might be an important reason for this difference. In the USA and UK, 150 mg kg^{-1} of NH_4OAc-K has been recommended as an adequate level (*MAFF*, 2000; *Gerwing* et al., 2001). Also *Govahi* and *Saffari* (2006) reported an absence of seed yield increase with K-fertilizer addition when the soil NH_4OAc-K content was higher than 209 mg kg^{-1}. Differences in soil texture, climate, yield levels, varieties, and other cultural management practices may be responsible for the different critical levels for available soil K content. In addition, the soil-testing method influences the threshold values. In our study, the threshold values for the NH_4OAc and M3 extractants were the same, as also observed in Barbagelata's similar study of corn and soybean yields (*Barbagelata*, 2006). Several other authors have also reported similar findings relating to the

effects of these extractants on soil K (*Gartley* et al., 2002; *Wang* et al., 2004). On the other hand, *Mallarino et al.* (2003) *found that the threshold value of the available soil* K *as determined with the* M3 method is higher than that for NH_4OAc.

Accurately predicting soil K availability for crops is the decisive factor in developing K-fertilization recommendations. In general, the NH_4OAc method only extracts the soluble and exchangeable K in soils (*Cox* et al., 1999), which is an inadequate basis for fertilization recommendation under conditions when non exchangeable K contributes significantly to crop yield (*Cox* et al., 1999; *Prasad*, 2009; *Wang* et al., 2010). It is therefore very important to select suitable chemical extraction methods to estimate the soil K supply in relation to specific soils. *Bao* and *Shi* (1984) found that extraction with 2 M cold HNO_3 could be used to determine the soil K supply for paddy soils. Furthermore, both *Cox* et al. (1999) and *Wang* et al. (2010) demonstrated that the sodium tetraphenylboron ($NaBPh_4$) method was more capable of extracting both exchangeable and non exchangeable K in soils than the NH_4OAc method. In our experiments, using the soil-K-test index based on the NH_4OAc method in winter oilseed rape although predictable results were mainly obtained, in some field experiments, the yield response to K fertilization was low despite low soil NH_4OAc-K contents. This finding might possibly relate to a contribution of non exchangeable K in the soil. It is thus necessary to estimate soil—K availability for crops considering both exchangeable K and non exchangeable K and develop guidelines on better soil—K management in winter oilseed rape production to optimize the farmers' K-fertilizer input.

6.4 K management of the whole crop rotation

In contrast to previous studies on K-fertilization recommendations for winter oilseed rape, other factors than available soil K were considered for K recommendation (Tab. 6). These factors included seed-yield level, K uptake, and K fertilizer-use efficiency, which together with the available soil—K data could be used as a guide for K fertilization for specific conditions to improve fertilizer-use efficiency. In our studies on K fertilizer use efficiency of winter oilseed rape, the optimal K fertilizer application rates were based on local soil and fertilizer work stations' recommendations. These rates were conducive to achieving high seed yield in most cases in these regions. The average KUE was 36.1%, which was higher than the average K fertilizer use efficiency in China (*Zhang* et al., 2008). However, the occurrences of some sites with low KUEs indicate that these rates might not be optimal because of specific site conditions that have not been taken into account. Using the new K recommendations, the optimal K fertilizer-application rate can be determined, depending on the available soil K content and the seed-yield level of each site.

It should be noted that at harvest, approximately 81.2% of the K uptake by oilseed-rape crop was stored in pods and stems, which provide an important supplemental source of K for the next crop when crop residues are returned to the field. In the case of the rice crop, *Hemalatha* et al. (2008) noted that 25% of the recommended K fertilizer could be saved through optimal straw management. In general, more than 90% of the crop-residue K can be released within one year, which increases soil water-soluble K and non exchangeable K, enhances soil K supply, and improves soil fertility and crop yield (*Singh* et al., 2002; *Sheldrick* et al., 2003; *Lupwayi* et al., 2005; *Kaur* and *Benipal*, 2006). Nevertheless, many field experiments have shown that crop yields for straw treatment are lower than those for mineral K fertilizer treatment even when the amount of K input is the same for the two treatments (*Liu* et al., 2000; *Ranamukhaarachchi* and *Ratnayake*, 2006; *Tan* et al., 2007). Thus, K from crop residues effectively complements K input but cannot entirely replace mineral fertilizer. Therefore, estimating the potential savings in reduced mineral K fertilizer with straw returned to the field is essential to the K management of the whole rotation system.

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中国冬油菜钾肥管理

摘　要：合理施用钾肥能明显提高油菜的产量和品质，但是油菜的高钾素需求与低土壤钾素肥力以及钾肥投入不足之间的矛盾严重限制了油菜产业的可持续发展。因此本文汇总 2004—2010 年在中国冬油菜主产区开展的油菜钾肥试验，以期为油菜钾肥管理提供理论依据。结果表明，目前中国冬油菜主产区油菜种植土中 0～20 cm 土壤平均 NH_4OAc-K 含量为89.1 mg/kg，属于“轻度缺乏”。2010 年冬油菜生产中农民平均钾肥投入为 35 kg/hm^2，远低于推荐的钾肥用量。充足的钾肥投入能明显提高油菜的产量，冬油菜施钾的平均增产率为 18.5%，钾肥利用率为 36.1%。根据土壤速效钾含量和施钾后油菜产量之间的关系，我们建立基于土壤测试的冬油菜钾肥管理指标体系，临界的 NH_4OAc-K 含量为 135 mg/kg。当土壤速效钾含量低于临界值时，适当增加钾肥投入有利于提高油菜的产量和维持土壤钾素肥力。总体来看，目前中国冬油菜钾肥管理中最大的挑战是如何根据土壤测试的结果来指导不同区域农户合理施用钾肥以维持高的油菜产量和土壤肥力。

关键词：钾；肥料；土壤；冬油菜；中国

Potassium management in tea plantations: its uptake by field plants, status in soils and efficacy on yields and quality of teas in China §

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Abstract: Tea is one of the major cash crops in the tropical and subtropical areas of China. Insufficient potassium (K) supply was an important limiting factor to the productivity as the soils are highly leached and strongly acidic. However, information about effects of K fertilization and application techniques was very limited. This manuscript summarizes results of field experiments investigating K uptake, soil K status, effects and methods of K fertilization in China during the past two decades. The K stocks and uptake were investigated by sampling commercial plantations aged 1, 2, 3, 5 and 10 years. There was no harvest of young shoots and most K was assigned to frame growth accounting for 59 - 61% of the total uptake in the aboveground for young plantations aged 1 - 3 years. In production plantations (age ≥ 5) such assignment to frame growth became relatively small (7.6 - 11.9%) and a major proportion was assigned to young shoots production accounting for up to 78% of the total. Analysis of 3 396 soil samples taken in 2009—2010 from 54 counties of 16 main tea producing provinces showed that the exchangeable K (extracted by Mehlich III) in soils averaged 81 mg kg^{-1} and in about 74% samples were below critical deficient level (100 mg kg^{-1}). The low activity ratio at equilibrium (AR_e^k) and non-specific absorbed K (ΔK_0) values of Quantity/Intensity (Q/I) curves also indicated low status of labile K pools of tea soils. Field experiments at 16 of total 18 sites with black, green and oolong teas during 1992 to 2002 showed significantly increase of yield by K fertilization either as potassium sulfate (K_2SO_4) or potassium chloride (KCl) despite of the largely different initial soil exchangeable K contents, plucking standards and yield levels among the tea types. The agronomical efficiency of K fertilizers was averaged at 8.8 kg fresh shoots or 1.71 kg made tea per kg K-fertilizer (K). The quality of harvested shoots were improved by K fertilization as revealed by increased concentrations of free amino acids, water extractable dry matter and total polyphenols. There was little difference in the effects of K as K_2SO_4 and KCl on yield and quality. Field experiments at 6 sites evaluating variable K amounts demonstrated that the optimal K doses ranged from 124 to 160 kg (K) ha^{-1} a^{-1} for both K_2SO_4 and KCl and were little affected by initial soil K contents, tea types and the yield levels. No privilege of K applications split into 3 times in tea seasons was observed concerning the risk of leaching in the soils of low cation exchange capacity and abundant rainfall in the production areas. A single K application as base fertilizer in the autumn had similar or better effect. The present studies showed low soil labile K pools, incapable to meet plant K demand for quality tea production, therefore highlighting importance of K fertilization. The overall results provide general supporting information for rational K management in plantations of producing main tea types in China.

Key words: agronomical efficiency, soil K availability, optimal dose, application method, potassium source, quantity/intensity curve

1 Introduction

Tea yield increases due to potassium (K) application have been reported from various countries (*Malenga and Grice*, 1991; *Rahmanand and Jain*, 1985; *Krishnapillai and Ediriweera*, 1986; *Godziashvili and Peterburgsky*, 1985; *Sharma and Sharma*, 1995; *Venkatesan and Ganapathy*, 2004; *Venkatesan* et al., 2005). The positive response to K has been explained by the fact that most of the

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soils in which tea is grown contain small amounts of exchangeable K. On the other hand, there are also examples where no response to K fertilization was observed (*Kamau* et al., 1999), obviously caused by a high K supplying capacity of the studied soil. In China, tea is one of the major cash crops, grown in the tropical and subtropical areas, where soils are highly leached and strongly acidic. The majority of soils are classified as red soils (Ferrosols, Luvisols, Ferralisols) with low inherent fertility (*Han* et al., 2002). Analysis of soil samples taken from typical tea fields revealed that more than 50% were classified as K deficient (*Ruan and Wu*, 2001), indicating that insufficient K supply became a widespread limiting factor for tea productivity. The situation of poor K supply to tea was aggravated by a generally practiced imbalanced fertilization, characterized by increasing nitrogen (N) application without or with insufficient supply of other nutrients, particularly K (*Ruan and Wu*, 2001). As tea plants grow on the same site for more than 30 years, such a continuous K deficit is likely to cause a substantial cumulative K mining of the soils over the years. Therefore, focus has to be laid on an improved K application by better adjusting the K supply to the needs of the plants, towards a sustainable tea production. Although the K uptake by tea plants under controlled conditions such as pot and nutrient solution experiments was well-known, data on K stocks, uptake and distribution in tea plants in the fields have been very limited, except a recent study performed in Kenyan tea plantations (*Kamau* et al., 2008). Such information may not be extrapolated to China because of rather greatly different conditions such as in climate, varieties and field management. It has been shown that K application improved yields, quality, and tolerance to drought in China (*Ruan and Wu*, 2001; *Ruan* et al., 1997; 1998; 1999). Potassium sulfate (K_2SO_4) and potassium chloride (KCl) are two main sources of K fertilizers. The negative effect of Cl^- on N uptake and concentration of theanine, a unique amino acid important for the flavour characteristics of green tea in pot experiments raised concerns of KCl application under field conditions (*Ruan* et al., 2007). However, limited information can be found regarding long-term effects of K fertilization in the fields, as influenced by K application rates, sources and the employed application techniques. These latter might be essential for tea productivity, especially on the widely observed low CEC soils, often characterized by low base and high Al saturation, leading to risk of K loss by leaching.

In the past two decades, a number of field experiments have been conducted in producing plantations in China to evaluate the effects of K fertilizers as K_2SO_4 and KCl on teas of different types (green, black and oolong teas) and application techniques. In the meantime, soil samples from typical areas were analyzed for labile K pools to evaluate its status and availability. The results were summarized and reported in the present paper.

2 Materials and Methods

2.1 Stock and uptake of K under field conditions

To investigate K stock and uptake by tea plants of different ages, plant samples were taken from 5 commercial plantations aged 1, 2, 3, 5 and 10 years in Shaoxing, Zhejiang province. The bushes (clone Longjing 43 for green tea) were planted in double rows with inner row distance of 40 cm, outer row distance 140 cm and 33 cm space between bushes within a row. The plants were fertilized with standard levels of N, P and K (140 - 900, 30 - 170 and 30 - 300 kg ha^{-1} a^{-1}, respectively) to provide adequate nutrients for defined ages by the owner of plantations. Each of 5 plants were randomly selected and cut from the base, separated, and dried to constant weight in electrical ovens in October after tea harvest finished or plants turned into dormancy. Fallen leaves were collected from the plantations afterwards until the next autumn lasting for one year. Pruning for frame formation was performed by cutting the stems at heights of 15, 30 and 45 cm above the ground for plantations aged 1, 2, and 3 years, respectively in late March. Maintenance pruning was performed to harvesting plantations aged 5 and 10 years. Prunings were collected in four randomly selected sections of 1 meter long for each plantation of

different ages and oven-dried. Young shoots were sampled from 5 and 10 year-old tea plantations when regular mechanical harvestings were done in April, May, July and September. There were 4 replications for collection of fallen leaves, prunings and young shoots. Potassium concentrations in plant samples were analyzed by inductively-coupled plasma atomic emission spectrophotometer after digestion with concentrated nitric acid and perchloric acid. The amounts of K in young shoots, fallen leaves and prunings were obtained by multiplying K concentrations and dry weights. The increase of K amounts in woody frames within one year (frame growth) were estimated from the slopes of regression lines in plantations of ages 1 - 5 and ages 5 and 10, respectively (as shown in Fig. 1a). The total aboveground K uptake was sum of the amounts of K in young shoots, fallen leaves, prunings and frame growth.

2.2 K status in soils of tea plantations in China

To gain information of K status in soils, a total of 3 396 soil samples were taken from 54 counties of 16 main tea producing provinces during years 2009 to 2010. Soil samples were taken in September and October and air dried. Exchangeable K contents in the soil samples were extracted by Mehlich III soil extractant (*Mehlich*, 1984) and analyzed by inductively-coupled plasma atomic emission spectrophotometer.

Sixteen soil samples were further tested for quantity/intensity (Q/I) curves (*Sparks and Liebhardt*, 1981). Soil samples (2.5 g) were added to 25-ml portions of each of 0, 0.2, 0.5, 1.0, 2.5 and 5.0 mmol L^{-1} KCl in 0.01 mol L^{-1} $CaCl_2$. Suspensions were shaken for one hour at 298 K followed by standing for additional 23 hours in an incubator at 25℃. The suspensions then were centrifuged and the supernatants analyzed for K, Ca and Mg by an atomic absorption spectrophotometer. Two replications were made for each suspension. The activity ratio, AR was calculated for each equilibrated suspension from the equation: $AR = aK^{+}/\sqrt{(aCa^{2+} + aMg^{2+})}$. The change in K quantity (ΔK) of the soil in each suspension was calculated from the difference between the initial and final K concentrations in the solution and expressed as $cmol_c\ kg^{-1}$ oven-dry soil. The parameters of activity ratio at equilibrium ($AR^k e$), equilibrium potential buffering capacity (PBC^K) and non-specific K (ΔK_0) were estimated form Q/I plots constructed from the measured ΔK (as *y*-axis) and AR (as *x*-axis). The AR^k_e was calculated from the intersection of the Q/I curve with the *x*-axis ($\Delta K = 0$). The PBC^K was determined as the slope of the linear section of the Q/I curve. The ΔK_0 was obtained by extending the linear part of the curve to the *y*-axis (AR = 0). The exchangeable (exch-) and slowly exchangeable (sl-exch) K of the soil samples were extracted by neutral NH_4OAC (pH 7.0) and boiling 1 mol L^{-1} HNO_3 (*Pope and Cheney*, 1957), respectively. For measurement of total K soil was digested with NaOH at 720℃ in silver crucibles in a muffle furnace (*Fu* et al., 1989). The K in extracts or digestions was measured by an atomic absorption spectrophotometer.

2.3 Field experiments evaluating effect of K fertilization

Field experiments evaluating effect of K fertilization as K_2SO_4 and KCl were conducted in total of 18 commercial clonal plantations during 1992 to 2002. Information of experimental sites, durations, exchangeable K levels in soils at initiation of experiments and K doses applied is given in Tab. 3. Within each experiment, identical amounts of N and P, as urea and single superphosphate or diammonium phosphate were applied for all treatments either with or without K fertilizer. The quantities of nutrients varied among different experiments while the N: P: K ratio was maintained at about 1 : 0.22 : 0.42. In experiments comparing K_2SO_4 and KCl, equal doses of K were applied to treatments with K fertilizer. The fertilizers including N, P and K were continuously applied for every year at constant amounts within the experimental periods. There were 3 - 4 replications for treatments in each experiment and the plots were randomly arranged in the fields. All other field management practices including harvest, plant protection, pruning, etc. were according to the local practices at experimental sites. Samples of a bud and two adjacent expanding leaves were collected in spring and autumn tea seasons, treated by steam for 3 min, and then oven-dried at 65 ℃ for 48 h. Chemical compositions (total free amino acid,

polyphenols, caffeine and water extractable dry matter) were analyzed according to standard methods described earlier (*Ruan* et al., 1998; 1999). The contents of K in samples of regularly harvested young shoots for commercial products were analyzed by atomic spectrophotometer or inductively-coupled plasma atomic emission spectrophotometer after ashed in furnace at 550 ℃ and dissolved in HCl (0.1 mol L^{-1}). The agronomical efficiency (AE) of K was calculated as (Yield of young shoots in NPK—yield in NP)/fertilizer K input.

2.4 Field experiments evaluating the effects of K application amounts

The effects of K application amounts were investigated in field experiments at 7 sites. During 1992—1996, two field experiments with two doses of K fertilizers at 124 and 248 kg (K) ha^{-1} a^{-1} as K_2SO_4 and a control (NP) without K were conducted in plantations located in Zhejiang and Guangdong province. Soil samples were taken from the plots for analysis of Q/I parameters three years after continuous K fertilization. During 1999 to 2002, four other field experiments were conducted in plantations located in Zhejiang, Hubei, Hunan, and Guangdong provinces. There were two doses of K fertilizers at 156 and 311 kg (K) ha^{-1} a^{-1} as K_2SO_4 together with a control treatment (NP) without K. During 1999 to 2001, another field experiment with four doses of K at 83, 166, 249, and 373 kg (K) ha^{-1} a^{-1} as KCl together with a control without K was conducted in Guangdong province. The contents of exchangeable K in soils were variable from 44 to 108 mg kg^{-1} (extracted by 1 mol L^{-1} NH_4OAC, pH =7.0). There were 3-4 replications for treatments and the plots were randomly arranged in the fields. Except K treatments, other nutrients including N and P and other practices were the same among treatments of individual experiment.

2.5 Field experiments evaluating the effects of K timing

Three field experiments were conducted at Shengxian and Hangzhou in Zhejiang province during 1995—1997 and at Yingde in Guangdong province during 1999—2001. The treatments consisted of a control (NP) without K, one basal application in autumn (NPK_b) and three split applications (NPK_s) around late February, early May and late July. Equal dose of K was applied for the latter two K treatments. The treatments of individual experiment received identical amounts of N as urea and P in form of diammonphosphate or single superphosphate in three rounds (around late February, early May and late July). Each treatment was replicated four times and the plots were randomly arranged in the fields.

2.6 Statistical analysis

Data of yields during the experimental periods were pooled on the basis of individual plots within defined field experiments and subjected to analysis of variance and LSD test if initial F test is significant ($p < 0.05$).

3 Results

3.1 K stocks and annual uptake in tea plants under field conditions

The K stocks in above-ground parts increased with increasing ages until 5 years (Fig. 1a). Before age 5, rapid accumulation of biomass and nutrient stocks was expected because stem frames were built up to establish harvest tables. After age 5, the accumulation of biomass and nutrient stocks, though still increasing with ages, became slower when the plantation was turn to tea production. The fractions of K stocks in stems were 22.3%, 32.1%, 37.8%, 46.5%, and 55.2% for plantations aged 1, 2, 3, 5, and 10, respectively, showing increasing values with increasing ages.

The annual uptake of K by plants also increased with ages (Fig. 1b). Such increase was largely explained by assignment to frame growth and young shoots production. For young plantations (ages 1-3), there was yet no harvest of young shoots and most K uptake was assigned to frame growth accounting for 59-61% of the total uptake in the above-ground parts. In production plantations such

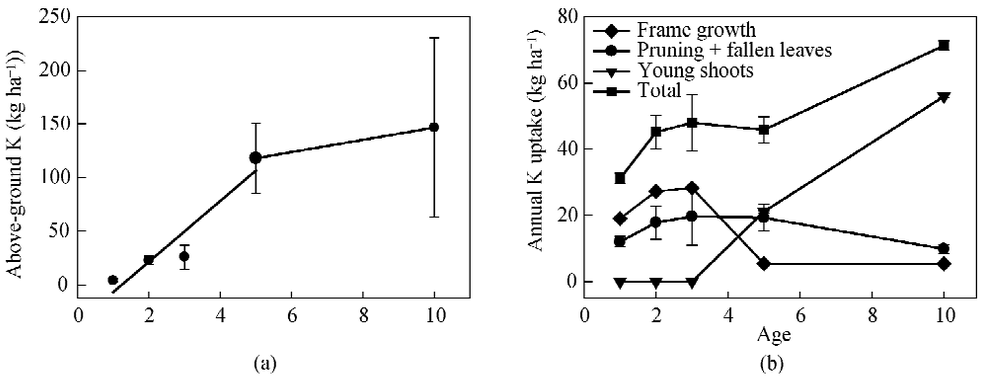

Figure 1 Stock (a) and annual uptake (b) of K in aboveground by tea plants of different ages under field conditions. Bars are standard deviations of replicates (n=4-5). The slope of the two regression lines were used to estimate the annual K uptake of frame growth

assignment became relatively small (7.6-11.9%). The proportions assigned to young shoots accounted for 46% and 78% of the total uptake for 5 and 10 year-old plantations, respectively. Assignment of K to prunings increased slightly with age until 3 years while their fractions were relatively constant (36-39%) for ages of 1 to 5 years. Fallen leaves generally accounted for below 3% of the total K uptake. The total annual K uptake in the above ground for plantations of age 10 was 71.3 kg ha^{-1} or 1.86 kg per 100 kg made tea based on the yield.

3.2 Soil K status and Q/I parameters

To gain information of K status in soils of tea plantations, a total of 3 396 soil samples were taken from 54 counties of 16 main tea producing provinces during years 2009 to 2010. There were about 580 000 ha tea plantations in these counties accounting for nearly one forth of total area in China. The exchangeable K in soils of tea plantations averaged 81 mg kg^{-1} and about 74% samples contained less than 100 mg kg^{-1}, the assumed critical level (Tab. 1).

Table 1 Information of sampling and exchangeable K status in soil samples of tea plantations in China taken at different periods

Period	Number of samples	Soil depth (cm)	Number and frequency of deficient samples
1988—1990	188	0-45	111 (59.1%)*
1998—2002	568	0-20 (15)	368 (64.3%)*
		20-40 (15-30)	449 (79.0%)*
2009—2010	3 396	0-40	2 528 (74.4%)**

The deficient critical levels of soil exchangeable K were 80 and 100 mg kg^{-1} for extracted by NH_4OAC (1 mol L^{-1}, pH=7) (*) and Mehlich III (**), respectively.

The Q/I plots showed the common shapes described in the literature (*Sparks and Liebhardt*, 1981). Most of them have a linear part at high activity ratios (Fig. 2). However, to a majority of the soils, the curves showed a gentle convex curvature at the low activity ratios. The values of PBC^K ranged from 17.4 to 37.3 (mol kg^{-1})/(mol L^{-1})$^{1/2}$ and did not correlated significantly with total K, slowly-exchangeable K or exchangeable K (Tab. 2). The AR_c^k values ranged from 1.21×10^{-3} to 12.27×10^{-3} (mol L^{-1})$^{1/2}$. The values of AR_c^k correlated significantly with the contents of total K (r=0.74, $p<0.01$), slowly-exchangeable K (r=

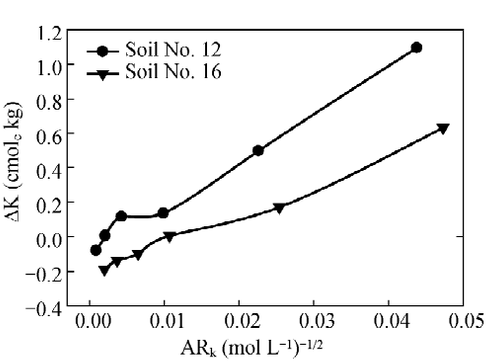

Figure 2 Quantity/intensity (Q/I) relationship of typical tea soil samples

0.62, $p < 0.01$) and exchangeable K ($r = 0.58$, $p < 0.05$). In the majority (11 out total 16 samples) of the tea soil samples tested, ΔK_0 generally were positive (0.01 - 0.18 $cmol_c\ kg^{-1}$) and only a few had negative values (−0.01 −−0.21 $cmol_c\ kg^{-1}$). The ΔK_0 correlated significantly but negatively with total K ($r = -0.57$, $p < 0.05$), slowly-exchangeable K ($r = -0.70$, $p < 0.01$) whereas correlated insignificantly with exchangeable K ($r = -0.45$, $p = 0.08$).

Table 2 Selected properties and Q/I parameters of soil samples

No.	Soil type*	Sampling site	pH (H_2O)	OM (mg g^{-1})	Total K (mg g^{-1})	Exch- K (mg kg^{-1})	Sl-exch-K (mg kg^{-1})	PBC^k ($cmol_c\ kg^{-1}$)	ΔK_0 ($cmol_c\ kg^{-1}$)	AR^ke ($\times 10^{-3}$) (mol $L^{-1})^{-1/2}$
1	Rhodi-Udic Ferralisol	Yinde, Guangdong	4.5	24.5	10.4	45	101	23.1	0.12	1.56
2	Haplic-Udic Ferralisol	Guiling, Guangxi	4.6	10.7	10.7	94	216	21.4	0.04	3.73
3	Haplic-Udic Ferralisol	Guiling, Guangxi	4.3	12.7	10.7	61	146	25.8	0.08	1.94
4	Argic-Udic Ferrosols	Qiyang, Hunan	4.9	11.4	13.5	66	227	18.4	0.18	2.46
5	Argic-Udic Ferrosols	Hengshan, Hunan	4.8	21.9	15.2	65	252	20.9	0.08	2.27
6	Haplic-Udic Ferrosols	Shangrao, Jiangxi	4.8	10.4	12.5	68	300	20.7	0.15	3.16
7	Ali-Perudic Luvisols	Songtao, Guizhou	5.0	17.9	14.5	75	312	28.7	0.10	2.02
8	Argic-Udic Ferrosols	Lanqi, Zhejiang	4.8	10.6	11.4	76	220	25.9	−0.06	2.24
9	Haplic-Udic Ferrosols	Shengxian, Zhejiang	4.9	14.1	9.0	31	109	27.4	0.07	1.21
10	Haplic-Udic Ferrosols	Langqi, Anhui	5.0	15.7	11.8	168	452	24.1	0.01	6.45
11	Ferri-Udic Luvisols	Jingtan, Jiangsu	5.2	18.0	12.4	70	420	32.6	0.15	1.79
12	Ferri-Udic Luvisols	Liyang, Jiangsu	5.2	10.8	12.4	69	412	24.0	−0.01	2.4
13	Ferri-Udic Luvisols	Xuanzhou, Anhui	5.1	16.1	13.7	54	367	24.7	0.08	1.57
14	Clay pani-Udic Luvisols	Zhaoyang, Hubei	5.0	24.3	12.4	69	400	37.3	−0.12	3.07
15	Clay pani-Udic Luvisols	Baokang, Hubei	5.0	10.3	17.3	135	821	34.2	−0.20	5.75
16	Haplic-Udic Luvisols	Rizhao, Shandong	5.2	17.8	20.8	89	613	17.4	−0.21	12.27

* Soil types were classified according to *Gong and Chen* (1999).

3.3 Effect of K fertilizers on yield and quality and balance of K in plantations

The yield levels of the field experiments (Tab. 3) were highly variable largely due to diversity plucking standards of tea types, clones and climatic conditions. Despite of the largely different initial soil K status, plucking systems and yield levels, the 16 of 18 field experiments during 1992 to 2002 showed significantly increase of yield by K fertilization either as K_2SO_4 or KCl (Tab. 3). For example, the green tea yield was increased by K application by 9.9 - 25.6% (mean 16.6%) at Hangzhou (Expt. No. 1) for 7 years and by 4.7 - 12.8% (mean 10.2%) at Yingde (Expt No. 2) for 5 years. Yields of seasons (spring, summer and autumn tea) were increased by K application at similar magnitude (data not shown). On average, fresh yield was increased by 11.7%, corresponding to an increase of 233 kg ha^{-1} made tea by K fertilization. The agronomical efficiency (AE) of K fertilizers was largely variable, depending on the yield levels of the experimental sites. On average, the AE was about 8.8 kg fresh leaves or 1.71 kg made tea per kg K-fertilizer (K). We found no significant differences in yield increase and agronomical K efficiency between the two K fertilizers K_2SO_4 vs KCl.

Table 3 Fresh yields and agronomical efficiency (AE) as affected by K fertilization of potassium sulfate (K_2SO_4) and potassium chloride (KCl) in field experiments

Expt. No.	Site	Duration	Exch-K (mg kg^{-1})	Averaged yield (t ha^{-1} a^{-1})			AE (kg kg^{-1})		K dose (kg K ha^{-1} a^{-1})
				NP	NPK (K_2SO_4)	NPK (KCl)	K_2SO_4	KCl	
1	Hangzhou, Zhejiang	1992—1998	106	9.7 a§	11.3 b	—	6.6 - 23.4	—	124
2	Yingde, Guangodng	1992—1996	58	19.3 a	21.2 b	—	7.1 - 19.3	—	124
3	Anqi, Fujian	1993—1994	50	6.6 a	7.9 b	—	0.6 - 17.2	—	124
4	Shengzhou, Zhejiang	1995—1996	31*	24.3 a	26.3 b	—	11.8 - 17.5	—	139

续 表

Expt. No.	Site	Duration	Exch-K (mg kg^{-1})	Averaged yield (t ha^{-1} a^{-1})			AE (kg kg^{-1})		K dose (kg K ha^{-1} a^{-1})
				NP	NPK (K_2SO_4)	NPK (KCl)	K_2SO_4	KCl	
5	Hangzhou, Zhejiang	1995—1996	91	7.3 a	8.4 b	—	3.3－11.0	—	139
6	Shanming, Fujian	1995—1997	58	5.9 a	7.1 b	—	16.0－26.3	—	80
7	Yingde, Guangodng	1995—1997	43*	20.6 a	23.0 b	22.3 b	11.8－14.0	5.3－11.8	187
8	Hangzhou, Zhejiang	1995—1997	160*	6.8 a	7.8 b	7.8 b	6.9－13.6	7.2－12.1	93
9	Shangrao, Jiangxi	1995—1997	61*	2.9 a	3.4 b	3.3 b	7.4－9.0	6.9－7.2	62
10	Shaoxing, Zhejiang	1995—1997	74*	16.6 a	18.2 b	18.1 b	8.1－8.6	6.4－9.2	187
11	Hangzhou, Zhejiang	1999—2000	86*	8.2 a	—	9.0 b	—	4.6－13.3	166
12	Yingde, Guangodng	1999—2001	31*	11.8 a	—	12.9 b	—	6.0－7.0	166
13	Yingde, Guangodng	1999—2002	44	11.7 a	13.3 b	12.7 b	8.3－11.3	5.1－7.0	156
14	Changsha, Hunan	1999—2002	79	11.3 a	12.5 b	12.2 b	1.6－9.4	4.3－8.0	156
15	Wuhan, Hubei	1999—2002	66	3.1 a	3.9 b	3.4 ab	1.4－11.1	0.7－3.1	156
16	Hangzhou, Zhejiang	1999—2002	68	3.8 a	4.2 b	4.4 b	0.6－5.5	0.5－9.3	156
17	Guilin, Guangxi	1999—2002	108	9.7^{NS}	10.1	10.1	－0.4－7.0	－0.5－5.2	156
18	Nanchang, Jiangxi	2000—2002	85	11.0^{NS}	11.0	10.5	－5.2－0.4	－8.6－0.1	156

* by weight of volume, kg L^{-1}.

§ Different letters following data within the same line indicate significant differences at $p < 0.05$. ^{NS}: insignificant.

The concentrations of total free amino acid and water extractable dry matter were increased significantly by K fertilization (Tab. 4). The contents of caffeine were unaffected and those of polyphenols of autumn tea were increased significantly by K fertilization. We observed similar effect of K fertilization as K_2SO_4 and KCl on total free amino acid.

Table 4 Chemical composition (mg g^{-1}) in young shoots as affected by K-fertilization as potassium sulfate (K_2SO_4) and potassium chloride (KCl) pooled from 4 field experiments during year 1995—1997.

Treatment	Free amino acid	Caffeine	Polyphenols	Water extractable dry matter
Spring tea				
Control (NP)	37.6 a§	27.2^{NS}	278.0^{NS}	335.6 a
NPK (KCl)	40.5 b	28.3	288.6	352.7 b
NPK (K_2SO_4)	40.9 b	28.4	291.9	353.8 b
Autumn tea				
Control (NP)	28.3 a	21.3^{NS}	228.7 a	360.0 a
NPK (KCl)	30.8 b	22.4	244.6 b	379.0 b
NPK (K_2SO_4)	31.0 b	22.6	247.2 b	378.1 b

§ Different letters following data within the same column of tea seasons indicate significant differences at $p < 0.05$. ^{NS}: insignificant.

Apparent K balances were estimated in 2 experiments (No 1 and 2 of Tab. 3) taken as examples, using dry yields at 75% moisture and nutrient contents in the shoots as removal (output) and K application by mineral fertilizer input (Tab. 5). Potassium loss by leaching and treatment related changes in nutrient accumulation in frames (trunk, branches) and rest of the canopy were not accounted for, as the fraction in frames was relatively smaller than in the young shoots for a producing plantation (Fig. 1). The K in the maintenance pruning was not included since the prunings were kept in the plantations. The difference between input and output revealed positive balances at both sites, which were reflected by significant accumulations of exchangeable K in the soils. As indicated by the soil analysis in 1996, a considerable available K pools were built up in the inter-row after 5 years of continuous K application at both sites. The contents of available K in the soils (depth 0－40 cm) were 226 and 55 mg kg^{-1} in the treatment (NPK) receiving K fertilization in contrast to 73 and 33 mg kg^{-1} in the control (NP) at Hangzhou and Yingde, respectively. The negative balances of K in the NP

treatments led to a serious depletion of soil K pools. The contents of exchangeable K in the surface soils were reduced by 28% at Hangzhou and 44% at Yingde, at rates of 6.0 and 5.2 mg kg^{-1} a^{-1}, respectively, during the study period of five years.

Table 5 Apparent K balance (kg K ha^{-1} a^{-1}) in some representative field experiments

Expt No.	Site	Duration	Treatment	Input	Removal	Balance
1	Hangzhou, Zhejiang	1992—1998	Control (NP)	0	35.7	−35.7
			NPK	124	41.3	82.7
2	Yingde, Guangdong	1992—1996	Control (NP)	0	94.7	−94.7
			NPK	124	104.8	19.2
12	Yingde, Guangdong	1999—2001	Control (NP)	0	113.9	−113.9
			NPK_1	83	115.5	−32.5
			NPK_2	166	125.2	40.7
			NPK_3	249	130.2	118.8
			NPK_4	373	129.8	243.6

The bioavailability of such accumulated K pool was further tested in Hangzhou (Expt. No. 1) during 1997—1998. The previous K plots were split into two equal plots of which one part received no K over a period of two years (NPK_R) and the other part continued to receive the same amounts as in the preceding five years (NPK). In both years, the yields in treatments of NPK_R (10.9 t ha^{-1} a^{-1}) and NPK (11.4 t ha^{-1} a^{-1}) were significantly larger than that of the control (9.1 t ha^{-1} a^{-1}) without K application.

3.4 Effects of K application rates

Due to large diversity of harvest practices in the experimental sites and yield variability among years, relative yields to those of the control (NP) treatments without K instead of absolute yields were used to collectively assess the effects of K doses in sites. The combined data showed rather uniform responding pattern (Fig. 3, a; b). The yield increased significantly by the lower K application rates (at 124 or 156 kg ha^{-1} a^{-1}) and was benefited from higher rates (248 or 312 kg ha^{-1} a^{-1}) (Fig. 2a; b). However, the average agronomical K efficiencies decreased with increasing K rates, from 14.5 for low (124 ha^{-1} a^{-1}) to 9.8 kg kg^{-1} at high K rate (248 kg ha^{-1} a^{-1}) (Fig. 3a). The corresponding values were 6.4 and 5.2 for low and high K rates (156 and 312 kg ha^{-1} a^{-1}) in the 4 experiments during 1999—2002, respectively (Fig. 3b). The K was negatively balanced in NP treatments at all sites with deficits of −11.4 to −104.8 kg ha^{-1} a^{-1}. Application of K fertilizers at all 4 levels resulted in positive annual K balance ranging from 19.7 to 297 kg ha^{-1} a^{-1}. The Q/I analysis of soil samples taken 3 years after continuous K applications from Expt. 1 and 2 showed that the AR_e^k values were increased by both K rates at Hangzhou and by high K rates at Yingde (Tab. 6), suggesting higher intensity of K in soil solution after K fertilization. The ΔK_0 were generally negative and became more negative in the treatments supplied with K fertilizers. The PBC^k value was not consistently affected by K fertilization, increasing at Hangzhou while decreasing at Yingde with K rates.

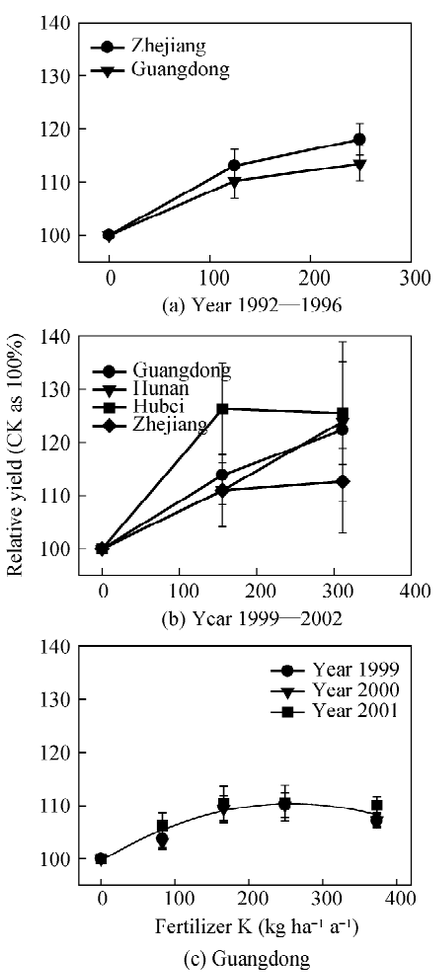

Figure 3 Response of fresh tea yields relative to those of the control treatment without K application to doses of K fertilizers as potassium sulfate (a, b) and potassium chloride (c) at 7 sites (provinces). Bars are standard deviations of replicates.

Table 6 Parameters (ΔK_0、AR_e^k and PBC^k) of soil K Q/I curves as affected by continuous K applications at two sites for 3 years

Site	K treatment (kg K ha^{-1} a^{-1})	PBC^k ($cmol_c$ kg^{-1})	ΔK_0 ($cmol_c$ kg^{-1})	AR_e^k ($\times 10^{-3}$) (mol $L^1)^{-1/2}$
Hangzhou, Zhejiang	0	21.55	−0.163	6.5
	124	25.81	−0.319	12.5
	248	24.38	−0.378	15.5
Yingde, Guangdong	0	18.66	−0.137	7.3
	124	13.85	−0.046	5.2
	248	15.26	−0.200	13.1

For the experiment investigating KCl in Guangdong during 1999—2001, the maximum yield increase was achieved by applying K fertilizers at 166 and 249 kg (K) ha^{-1} a^{-1} (Fig. 3c). The agronomical efficiencies of K fertilizer as KCl averaged 6.0, 6.7, 4.7, and 2.5 kg kg^{-1} for the treatments receiving K rates at 83, 166, 249, and 373 kg ha^{-1} a^{-1}, respectively. The balances of K were negative in the control treatment and the treatment receiving low K (K_1) and turned to positive in the treatments with higher K applications (Tab. 5). We observed that yield was slightly declined by the highest KCl application (373 kg ha^{-1} a^{-1}), showing different responding patterns of yields to applications of KCl and K_2SO_4. Despite of largely different initial soil exchangeable K contents and yield levels among the sites, there appeared rather similar levels of optimal application doses of K, ranging from 124 to 166 kg ha^{-1} a^{-1} for both K_2SO_4 and KCl. These K doses provided sufficient supply of K nutrient, achieved relatively high agronomical efficiency and maintained a positive K balance for tea plantations of different tea types (Tab. 5).

3.5 Effects of K timing

The effect of K application timing was evaluated in three other field experiments as well. There was no significantly difference of yield between one single in autumn and 3 split applications in tea seasons of K fertilizer in two field experiments conducted in 1995—1997. On the contrary, in the experiment during 1999—2001 one single application in the autumn had better effect than 3 split applications in tea seasons (Tab. 7).

Table 7 Effect on yield (t ha^{-1} a^{-1}) of K fertilizer as one base application after autumn tea (K_b) and three split applications (K_s) each before spring, summer and autumn tea seasons

Site	Duration	Initial soil exch-K (mg kg^{-1})	Treatment			K dose (kg K ha^{-1} a^{-1})
			NP	NPK_b	NPK_s	
Shenzhou, Zhejiang	1995—1997	31	24.25 a§	26.33 b	26.50 b	139
Hangzhou, Zhejiang	1995—1997	91	7.30 a	8.42 b	7.91 b	139
Yingde, Guangdong	1999—2001	33	10.93 a	12.54 c	11.81 b	249

§ Different letters following data within the same line indicate significant differences at $p < 0.05$.

4 Discussion

Potassium fertilization is essential when K pools in soil cannot sufficiently meet the demand of tea plants. In the present study, the K status in tea soils of main tea producing provinces was evaluated by soil testing and analysis of Q/I relationship. Analysis of soil samples showed that the contents of exchangeable K in about 74% samples were below critical deficient levels. The proportion of deficient samples was comparable to but slightly larger than those surveyed during 1988—1990 and 1998—2002 (Tab. 1). The exchangeable K in the earlier soil samples were extracted by 1 mol L^{-1} neutral NH_4OAC while a more universal extractant Mehlich III was adopted for the most recent samples taking its advantage of analysis for multi-nutrients by ICP-AES. The Mehlich III showed stronger extracting

ability and larger values than NH_4OAC (*Ma* et al., 2007). The critical level for Mehlich III was set at 100 mg kg^{-1}, calculating from that of NH_4OAC (80 mg kg^{-1}) as reference as there was close linear correlation between the two methods ($r=0.985$, $p<0.001$) (*Ma* et al., 2007).

Availability of soil K to plants depends on its intensity, quantity and renewal rate in the soil. Previous researches pointed out that analysis of Q/I curves therefore gave a more complete information about the soil K status than testing of exchangeable K by extractant such as NH_4OAC or Mehlich III (*Rupa* et al., 2001; *Sparks and Liebhardt*, 1981). ΔK_0 has been thought a better estimate of soil labile K than normal exchangeable K. A negative ΔK_0 value indicates a K release into soil solution and the more negative ΔK_0 the larger in the labile K pool. The positive ΔK_0 of most of the tested samples (11 out total 16 samples) suggested that the solid phase of soils tended to adsorb some K^+ from the solution when the activity ratio was low. The values of AR_e^k ranged from 1.21×10^{-3} to 12.27×10^{-3} (mol $L^{-1})^{1/2}$, which was similar to those of non-tea soils of the same soil types reported by other authors (*Zheng* et al. 1996). In soils Ferralisol and Ferrosols were dominated by 1∶1 mineral clays (kaolinite) and sesquioxide while in Luvisols mainly by 2∶1 (vermiculite, illite, chlorite) and some 1∶1 clays (e. g. kaolinite). As proposed by previous studies (*Sparks and Liebhardt*, 1981), the magnitude of AR_e^k was indicative of K absorbing position in clay mineral of soil. It would appear that K^+ was held at planar positions for AR_e^k value $>$ 0.01 (mol $L^{-1})^{1/2}$ in only one soil sample (No. 16 from Shangdong province), exhibiting high availability. The adsorbed K^+ in the most tested tea soils was likely held at edge positions of moderate availability since the AR_e^k was $<$ 0.01 (mol $L^{-1})^{1/2}$. The positive values of ΔK_0 and relative low levels of AR_e^k possibly suggested that the labile K pools were exhausted in most tested tea soils without replenishment from fertilization. Under the conditions of K fertilization, the AR_e^k values were increased by both K rates at Hangzhou and by high K rates at Yingde (Tab. 6), suggesting higher intensity of K in soil solution after K fertilization. The ΔK_0 were generally negative and became more negative in the treatments supplied with K fertilizers, indicating a greater release of K into soil solution and a larger pool of labile K (*Sparks and Liebhardt*, 1981). A number of other studies also showed that the AR_e^k values were considerably increased and ΔK_0 became more negative by K application (e. g. *de la Horra* et al., 1998; *Rupa* et al., 2001).

In the present work, the effect of K fertilization was evaluated in commercial plantations of variable tea types and soil K availability. The tea types at experimental sites covered three main teas including oolong tea (located in Fujian province), black tea (located in Guangdong province) and green tea (other sites). The plucking standards were considerably different among these teas. Generally semi-matured shoots of 4 young leaves with a dormant bud were harvested for oolong tea while one bud with 1 - 3 leaves used for black tea. The standards for green tea were quite variable, from very young shoots (one bud and one leaf) for most spring tea and young shoots of one bud and 2 leaves for summer and autumn green teas. In some experiments (Expt. No. 9, 15 and 16), little summer and autumn teas were harvested because of bad price during the experimental periods, resulting in comparable lower yields. In experiments (Expt. No. 4 and 10) at Shaoxing and Shenxian of Zhejiang province, older young shoots of one bud with 3 to 4 leaves were plucked for the production of steamed green tea and gunpowder green teas. Despite the large difference of yield levels resulting from plucking standards, significantly increase of yield by K fertilization either as K_2SO_4 or KCl was observed from the 16 of 18 field experiments. The effect of K fertilization appeared to be predicted by the assumed level of critical soil K content (NH_4OAC-extracted K, 80 mg kg^{-1}) to certain extent. Significant yield increase was observed in the 13 experiments when their initial soil exchangeable K levels were below 80 mg kg^{-1}(assuming 1.2 kg L^-). In the other 5 experiments with levels above 80 mg kg^{-1}, significant yield increase was observed in 3 experiments while no effect was found in 2 experiments. The averaged AE (1.71 kg made tea per kg K) was relatively low as compared to field crops (i. e. rice,) in China (7.4±2.5 kg kg^{-1} from *Zhang* et al., 2010; *Zhang* et al., 2011). However, we were unable to relate yield increment (relative to the

control without K, data not shown) with the initial soil exchangeable K levels. A recent meta-analysis suggested that soil test data were not the sole factor governing yield response (*Kuchenbuch and Buczko*, 2011).

Analysis of chemical components indicated that the quality of young shoots was improved by K fertilization. These findings were in line with previous studies showing positive effect of K fertilization on quality from the pot and field experiments (*Ruan* et al., 1999; *Ruan* et al., 2007; *Venkatesan and Ganapathy*, 2004; *Venkatesan* et al., 2005). However, we observed similar effect of K as K_2SO_4 or KCl on total free amino acid under field conditions. This is different from previous findings that chloride reduced the content of total free amino acids in young shoots in pot experiments (*Ruan* et al., 1998; *Ruan* et al., 2007). This might be explained by the fact that the mobile Cl^- was easily leached out root zone and only a limited part of root system was exposed to Cl^- under field conditions (*Ruan* et al., 2007). However, the different responding patterns of yields between to highest K applications as KCl (Fig. 3c) and K_2SO_4 (Fig. 3a; b) might reflect the negative effect of accumulated Cl from high application of KCl as previously reported from pot experiments (*Ruan* et al., 2007).

Right amount and timing are both essential for efficient application of K fertilizers. To develop rational fertilization strategy, the annual quantity of nutrients that tea plants need to take up is a fundamental step. During the year, tea plants produce young shoots and increase sizes and mass by primary and secondary growth. The nutrients taken up are partitioned to young shoots, new maintenance leaves, and woody organs (roots and woody frames including stems, branches, twigs). The biomass and nutrients in the harvested young shoots are easily and precisely measured whereas those in woody organs and leaves cannot be directly determined. In the present work, the cumulative amounts of K in woody frames in one year were estimated from annual increase rates by extrapolating stocks in plantations of known ages. The results showed that a majority of absorbed K was assigned to young shoots in production plantations. This indicated that the amount of K fertilizer to be applied can be largely determined from the removal of young shoots. Based on yield level of sampled plantations (age 10), it was estimated that approximate 1.86 kg K in aboveground was required to produce 100 kg dried made tea without considering any loss of leaching and fixation in the soils. The value was much lower than the reported value of 3.7 kg K uptake per 100 kg made tea in Indian (*Ranganathan and Natesan*, 1985). However, in their work the K concentration in the harvested young shoots was assumed to be 2.0 g kg^{-1}, which was much higher than the measured (1.2 - 1.8 g kg^{-1}) in the present study. Furthermore, our data on K stocks in the aboveground were much smaller than those reported (579 - 919 kg ha^{-1}) from Kenyan tea plantations (*Kamau* et al., 2008). The reason for such difference was unknown, but possibly due to differences in climatic conditions, variety, spacing, and field management. Due to methodology limitation, the uptake by roots was not measured, making it difficult to give estimation of whole plants.

In the present work, the optimal dose of K application was evaluated in the field experiments. Despite of largely different initial soil exchangeable K contents and yield levels among the sites, there appeared rather similar levels of optimal application doses of K, ranging from 124 to 160 kg (K) ha^{-1} a^{-1} for both K_2SO_4 and KCl. These K doses provided sufficient supply of K nutrient, achieved relatively high agronomical efficiency and maintained a positive K balance in tea plantations (Tab. 5). Due to lack of the amount of K uptake, the information of K fertilizer use efficiency in tea plants under field conditions was very limited. The averaged K fertilizer use efficiency for field crops (wheat, rice and maize) was 35 - 50% (*Zhu*, 1998). Taken these values as reference and annual K uptake (61 kg ha^{-1}, excluding fallen leaves and pruning for recycling to fields, Fig. 1b) from the production plantation (age 10), the rational amount of K fertilizer was roughly estimated to be 122 - 174 kg ha^{-1}, which was close to the above mentioned range. The present work showed residual effect in the following years of accumulated K in the soils resulting from continuous K applications. Residual effects of K application

have been reported in other field crops such as cotton and soybean (*Cassman* et al., 1992; *Rosolem and Nakagawa*, 2001). Under such conditions, the amount of K fertilizer should be adjusted to avoid unnecessary and unproductive surplus in the long run.

Tea soils are usually characterized by low cation exchange capacity, strong acidity and rich exchangeable Al. These soil properties together with relatively abundant rainfall in most of the tea production areas create favorable conditions for the leaching of K and other cations. In the meantime, harvest of young shoots starts in spring (usually late Feb and March) and last for 7－8 months until late autumn (September and October) in most producing areas of China. Thus, the demand for K need to be met yearly round. In south India, *Ranganathan and Natesan* (1985) showed that split application of same K fertilizer amount into 4－6 times significantly increased yield (by 6－10%) compared to in single or into 2 applications, and therefore suggested split K applications during tea seasons. The results of the present work however indicated no privilege of splitting applications while single application as base fertilizer in the autumn had similar or even better effect, and consequently was more profitable for saving of labor cost.

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茶树钾素营养管理:田间条件下钾的吸收、土壤供钾能力和钾肥施用效果和施用技术研究

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摘　要:茶是中国热带和亚热带地区的主要经济作物。酸性茶园土壤钾供给不足是限制茶树产量和品质的一个重要因素,但我国对茶园钾肥效应和施用技术研究还比较少。本文总结了过去 20 年我们对茶树钾吸收、土壤钾素状况、钾肥施用效果和施用方法方面的研究结果。对不同年龄(1～10 年)茶树钾的吸收和树体钾储量的研究表明,幼龄茶园(1～3 年)吸收的钾主要用于骨架枝条生长,约占地上部钾总量的 59%～61%;成龄采摘茶园(5 年和 10 年)大部分钾(78%)用于新梢生长,用于枝条生长的钾仅占地上部总量的 7.6%～11.9%。2009—2010 年,我们从 16 个主要产茶省的 54 个主产县的代表性茶园中选取了 3 396 个土壤样进行了试验,分析表明土壤有效钾(Mehlich III 提取)平均为 81 mg/kg,但约 74%样品中的有效钾含量低于临界缺乏水平(100 mg/kg),容量/强度(Q/I)分析也表明茶园土壤钾活性(AR_e^k)和容量(ΔK_0)均较低。1992—2002 年间,我们在绿茶、红茶和乌龙茶主产区选择有效钾含量不同的茶园进行田间试验,试验时间2～7年,多数田间试验 3～4 年,试验得到的土壤有效钾含量、各茶类的采摘标准和产量水平也有较大差异,在 16 个试验(总共 18 个)中施用硫酸钾或氯化钾都具有显著的增产作用。钾肥的农学效率平均为每公斤钾(K)增产 8.8 kg 鲜叶或 1.71 kg 成茶,施钾肥能提高茶叶的品质,增加茶叶游离氨基酸、茶多酚和水浸出物的浓度,硫酸钾和氯化钾对产量和品质的影响差别不大。同时我们还进行了不同钾肥用量田间试验(共 6 个),最适施钾量范围为 124～160 kg/hm^2,茶类、产量水平和初始土壤速效钾含量对最适用量范围无明显影响。虽然茶园土壤阳离子交换量低且处于降雨丰富地区,分次(3 次)施用并没有显示出特别效果,相反在秋季基肥时一次性施钾有相近或更好的效果。上述研究结果表明,由于茶园土壤供钾能力低而不能满足茶树对钾的需求,因此通过施肥满足茶树钾营养具有重要意义。

关键词:钾肥农学效率;土壤有效钾;钾肥适宜用量;钾肥种类;土壤钾 Q/I 曲线分析

钾氮配施对湖南丘陵双季稻区钾肥效应及钾素平衡的影响①②

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摘　要：采用大田试验，研究了丘陵双季稻区2种土壤上不同钾肥用量及2种氮肥用量配施钾肥对早、晚稻产量、钾素吸收利用、钾素平衡、土壤钾素含量和钾肥经济效益的影响。结果表明：施钾能显著提高早、晚稻产量；在中量氮肥条件下，晚稻产量在一定施钾（K_2O）量范围内（0～195 kg/hm²）随施钾量增加而提高；早稻黄泥田产量随施钾量增加而提高；不施钾或配施高量钾肥，早晚稻产量均随氮肥用量增加而提高。施用氮、钾肥促进早晚稻植株对钾素的吸收积累，在中量氮肥条件下植株吸钾量随钾肥用量增加而提高，不施钾或配施高量钾肥，早晚稻植株吸钾量均随氮肥施用量增加而提高。在中量氮肥条件下，早稻施 K_2O 0～105 kg/hm²时钾素亏缺，亏缺量随施钾量的增加而降低；施 K_2O 150～195 kg/hm²时钾素盈余，盈余量随施钾量的增加而增加，晚稻施 K_2O 0～195 kg/hm²时钾素亏缺，亏缺量随施钾量的增加而降低；施 K_2O 253.5 kg/hm²时钾素盈余；高量钾配施高量氮时钾素盈余量低于配施中量氮处理。不同施钾量对土壤钾素含量有明显影响，同一施氮水平下土壤速效钾和缓效钾含量均随施钾量的增加而增加，施高量钾肥时土壤速效钾和缓效钾含量随氮肥用量增加而提高；在经济效益上，早晚稻黄泥田上施钾处理下产投比大于红黄泥田，且均大于1.0，能获得较高经济效益。

关键词：湖南丘陵双季稻区；钾肥；钾肥效应；钾素平衡

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湖南省地处中亚热带地区，属季风性湿润气候，光照充足，热量丰富，雨水充沛。其中丘陵地区约占全省总面积的28.79%[1]，具有较优越的水稻种植自然条件，是湖南省主要的粮食生产基地，且以栽培双季水稻为主。随着水稻生产集约化程度的提高，水稻品种质量的改善，水稻单产和复种指数的提高，有机肥用量锐减，氮、磷肥用量的加大以及农民将稻草作为燃料和家畜饲草或为方便耕地而将其燃烧，导致稻田土壤钾素消耗越来越严重[2,3]；同时由于南方地区高温多雨，雨水充沛而集中，土壤养分淋失严重，特别是钾素，近30年来农田养分产出与投入严重失去平衡[4]。因此，大多数稻-稻生产体系处于负钾素平衡[4]。在习惯种植模式中，农民多采用重施氮肥，轻施钾、磷肥及减少含钾有机肥投入的施肥方式，导致养分失衡，土壤钾素下降，不能满足水稻正常生长发育的需要，严重影响了水稻产量。因此，合理施用钾肥仍是维持稻-稻生产体系中水稻产量的一种重要措施[3]。本文为探讨湖南省丘陵地区钾肥优化施用技术，提高作物产量和土壤供钾能力，研究了施钾对湖南丘陵双季稻区钾肥效应及土壤钾素平衡的影响，旨在为湖南丘陵双季稻区水稻土的合理配施钾肥提供科学依据。

1　材料与方法

1.1　试验地点及土壤基本性状

试验在湖南省长沙县和衡山县进行。长沙县试验点土壤为第四纪红土发育的红黄泥田，衡山县试验点土壤为板页岩发育的黄泥田，试验前0～20 cm土壤的基本性状和钾素状况见表1。

表1　供试土壤基本理化性状

Table 1　The physical and chemical properties of two paddy soils used in experiments

土壤名称	pH（水）	有机质/(g/kg)	全氮/(g/kg)	碱解氮/(mg/kg)	速效磷/(mg/kg)	全钾/(g/kg)	速效钾/(mg/kg)	缓效钾/(mg/kg)
红黄泥田	5.3	32.9	12.5	298.1	6.4	9.2	54.2	103.5
黄泥田	5.8	38.3	13.4	191.2	4.9	9.9	74.3	94.4

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1.2 试验设计

试验于2012年种植早、晚稻。设6个处理，即N_1K_0、N_1K_1、N_1K_2、N_1K_3、N_2K_0、N_2K_3。按处理要求，早稻N_1（中量氮肥）和N_2（高量氮肥）分别施N 150 kg/hm²和195 kg/hm²，晚稻施N 180 kg/hm²和234 kg/hm²；早稻K_0、K_1、K_2、K_3分别施K_2O 0、105、150、195 kg/hm²，晚稻施K_2O 0、136.5、195、253.5 kg/hm²；磷肥施用各处理均一致，早、晚稻分别施P_2O_5 75 kg/hm²和45 kg/hm²。氮肥为尿素；磷肥为过磷酸钙；钾肥为氯化钾。早稻氮肥的70%作基肥、30%作分蘖肥，晚稻60%作基肥、40%作分蘖肥，磷、钾肥均100%作基肥。

供试水稻品种（组合）：早稻分别为“浙辐7号”（长沙县试验点）和“威优402”（衡山县试验点），晚稻分别为“丰源优272”（长沙县试验点）和“玉香88”（衡山县试验点）。早稻于4月下旬移栽，7月上旬收获，株行距13.3 cm×20.0 cm。晚稻于7月中下旬移栽，10月中下旬收获，株行距为20.0 cm×20.0 cm。小区面积20 m²，重复4次，随机区组排列。

1.3 样品采集和测定方法

每季水稻成熟期采集植株样品用于钾养分测定，各小区单打单晒，单独计产。试验前采集0～20 cm耕层基础土壤样品，用于基本理化性状测定；早、晚稻收获后采集0～20 cm耕层土壤样品，风干磨碎后用于测定速效钾、缓效钾含量。土壤有机质、全氮、碱解氮、速效磷、全钾、速效钾、缓效钾的含量和植株中钾含量及土壤pH采用常规分析法测定[8]。

1.4 计算与统计方法

钾肥利用率（K use efficiency，%）=（施肥区植株吸钾量－对照区植株吸钾量）/施钾量×100

钾肥农学效率（Agronomy efficiency，AE，kg/kg）=（施肥区子粒产量－对照区子粒产量）/施钾量

土壤钾素表观平衡按下式计算：

钾素（K_2O）盈亏量（kg/hm²）=肥料投入钾素量－植株吸收钾素量

所有数据均采用SPSS系统软件进行统计检验，用Excel软件进行图形绘制。

2 结果与分析

2.1 氮钾配施对水稻产量的影响

不同施钾处理对水稻产量有较大影响，如表2所示。早稻在中量施氮水平下（N_1），红黄泥田每公顷施K_2O 105～195 kg比不施钾肥增产2.4%～5.1%，其中以K_1水平产量最高，与不施钾产量间的差异达到5%的显著水平；黄泥田每公顷施K_2O 105～195 kg比不施钾肥增产10.3%～12.9%，与不施钾产量间的差异达到1%的显著水平，且产量随施钾量的增加而提高；黄泥田早稻施钾增产效果高于红黄泥田。晚稻在中量施氮水平下（N_1），红黄泥田和黄泥田钾肥施用量在136.5～253.5 kg/hm²的各处理均比不施钾处理增产，差异达极显著水平（$p<0.01$），且最高产量均出现在K_2水平；红黄泥田增产幅度为9.0%～13.9%，黄泥田增产幅度为12.9%～17.7%，黄泥田晚稻施钾增产效果也好于红黄泥田。

表2 丘陵区2种土壤上氮钾配施的水稻产量情况

Table 2 The rice yield of potassium application combined with nitrogen in two paddy soils in hilly regions

土壤名称	处理	早稻产量（kg/hm²）	增产率（%）	晚稻产量（kg/hm²）	增产率（%）
红黄泥田	N_1K_0	5 396 cB	—	5 663 cB	—
	N_1K_1	5 676 bB	5.1	6 175 bAB	9.0
	N_1K_2	5 528 bcB	2.4	6 450 abA	13.9
	N_1K_3	5 594 bcB	3.7	6 238 abAB	10.2
	N_2K_0	5 412 cB	—	6 200 abAB	—
	N_2K_3	6 155 aA	13.7	6 650 aA	7.3
黄泥田	N_1K_0	5 663 dD	—	6 218 bB	—
	N_1K_1	6 244 bBC	10.3	7 229 aA	16.3
	N_1K_2	6 363 bB	12.4	7 318 aA	17.7
	N_1K_3	6 394 bB	12.9	7 020 aA	12.9
	N_2K_0	6 088 cC	—	6 390 bB	—
	N_2K_3	6 994 aA	14.9	7 103 aA	11.2

注：小写字母表示处理间差异达5%的显著水平；大写字母表示处理间差异达1%显著水平，下同。

比较高量氮肥(N_2)与中量氮肥(N_1)水平下的施钾效应发现,早稻高量氮配施高量钾(N_2K_3)产量显著高于中量氮配施高量钾(N_1K_3)($p<0.01$),也显著高于其他处理($p<0.01$);其中红黄泥田高量氮配施高量钾(N_2K_3)比中量氮配施高量钾(N_1K_3)增产 10.0%,黄泥田增产 9.4%;说明早稻高钾配施高氮可进一步发挥钾肥效应。晚稻红黄泥田高量氮配施高量钾(N_2K_3)比中量氮配施高量钾(N_1K_3)增产 6.6%,黄泥田增产 1.2%,但差异不显著($p>0.05$)。

2.2 氮钾配施对水稻钾素吸收利用及钾素平衡的影响

在中量氮肥(N_1)施用条件下,2 种土壤早、晚稻的植株总吸钾量呈现随钾肥用量增加而增加的趋势(见表 3),仅红黄泥田晚稻在 K_2 水平下植株总吸钾量最高。比较不同施氮水平、相同施钾量的植株钾素吸收量发现,无论施钾或不施钾,2 种土壤早、晚稻的植株总吸钾量随氮施用量增加而提高,即 N_2K_0 处理的植株总吸钾量大于 N_1K_0 处理的植株总吸钾量,N_2K_3 处理植株总吸钾量大于 N_1K_3 处理的植株总吸钾量。

表 3 丘陵区 2 种土壤不同施钾处理的水稻钾素吸收利用及钾素平衡情况

Table 3 potassium uptake and potassium balance of potassium application combined with nitrogen in two paddy soils in hilly regions

土壤名称	处理	早稻季				晚稻季			
		吸 K_2O 总量/(kg·hm^{-2})	钾盈亏量/(kg K_2O·hm^{-2})	钾肥利用率/(%)	农学效率/(kg 稻谷·kg^{-1} K_2O)	吸 K_2O 总量/(kg·hm^{-2})	钾盈亏量/(kg·hm^{-2})	钾肥利用率/(%)	农学效率/(kg 稻谷·kg^{-1} K_2O)
红黄泥田	N_1K_0	87.3	−87.3	—	—	108.2	−108.2	—	—
	N_1K_1	120.4	−15.4	31.5	2.00	197.6	−61.1	65.5	3.75
	N_1K_2	131.1	18.9	29.2	0.67	214.0	−19.0	54.3	4.04
	N_1K_3	149.6	45.4	31.9	0.77	199.2	54.3	35.9	2.27
	N_2K_0	113.5	−113.5	—	—	113.6	−113.6	—	—
	N_2K_3	161.7	33.3	24.7	2.89	259.8	−6.3	57.7	1.78
黄泥田	N_1K_0	105.3	−105.3	—	—	175.8	−175.8	—	—
	N_1K_1	136.0	−31.0	29.2	5.53	190.6	−54.1	10.8	7.41
	N_1K_2	139.4	10.6	22.7	4.67	201.7	−6.72	13.3	5.64
	N_1K_3	154.3	40.7	25.1	3.75	228.0	25.5	20.6	3.16
	N_2K_0	128.4	−128.4	—	—	181.5	−181.5	—	—
	N_2K_3	171.6	23.4	22.2	4.65	246.1	7.4	25.5	5.18

在中量氮肥(N_1)水平下,早稻季钾肥的利用率:红黄泥田为 29.2%～31.9%,平均为 30.9%;黄泥田为 22.7%～29.2%,平均为 25.7%,红黄泥田比黄泥田平均高 5.2%;并均显示出施低量钾的利用率较高。晚稻红黄泥田钾肥利用率随钾肥用量增加而降低,黄泥田则相反,钾肥利用率随钾肥用量增加而增加。比较高量氮肥(N_2)与中量氮肥(N_1)水平下的钾肥利用率发现,早稻 2 种土壤高量氮配施高量钾(N_2K_3)的钾肥利用率均低于中量氮配施高量钾(N_1K_3),晚稻则相反,高量氮配施高量钾(N_2K_3)的钾肥利用率高于中量氮配施高量钾(N_1K_3)。

从钾素的农学效率分析,在中量氮肥(N_1)水平下,黄泥田的钾素农学效率高于红黄泥田,黄泥田的钾素农学效率为 3.75～5.53 kg,平均为 4.65 kg;红黄泥田的钾素农学效率为 0.67～2.00 kg,平均为 1.15 kg,且钾素农学效率随施钾量增加而降低。晚稻钾素的农学效率表现出与早稻相同的趋势,红黄泥田在 K_2 水平下最高,黄泥田随施钾量增加而降低。2 种土壤钾素农学效率均表现出晚稻高于早稻,说明在土壤有效钾含量均不高的 2 种土壤中,晚稻需连续施用较高量的钾肥,以更好地发挥其农学效率。

由肥料投入钾量和植株吸收钾量的差值计算钾素表观平衡(见表 3),在施中量氮(N_1)条件下,早稻不施钾和低施钾(K_2O)量(105 kg/hm^2)(K_1)时 2 种土壤钾素均为亏缺,施钾处理的钾亏缺量低于不施钾处理,K_2 和 K_3 处理均为钾素盈余,盈余量随施钾量的增加而增加。晚稻钾素表观平衡表现出类似的规律,但是施钾量达到 K_3 水平时才表现为钾素盈余。说明在该试验条件下,早稻施 N 150 kg、晚稻施 N 195 kg 要维持土壤钾素表观平衡,早、晚稻需分别施用 150 kg/hm^2 和 253.5 kg/hm^2 以上的 K_2O。比较不同氮水平配施钾肥的钾素表观平衡发现,红黄泥田和黄泥田上早稻均表现为钾素盈余量随氮肥施用量增加而降低($N_1K_3>N_2K_3$);晚稻中量氮肥(N_1)配施高量钾肥(K_3)的红黄泥田上钾素表现为盈余(K_2O 盈余量

54.3 kg /hm²)，高量氮肥(N_2)配施高量钾肥(K_3)的钾素为亏缺(K_2O 的亏缺量 6.3 kg/hm²)；黄泥田上 N_1K_3 和 N_2K_3 处理的钾素均为盈余，钾素盈余量随氮肥施用量增加而降低。

2.3 氮钾配施对土壤中速效钾和缓效钾含量的影响

2.3.1 施钾对丘陵区 2 种土壤上速效钾含量的影响

早、晚稻收获后取耕层土样测定速效钾含量，结果表明(见图 1)，与试验前比较，红黄泥田早稻 N_1K_2、N_1K_3 和 N_2K_3，晚稻 N_1K_3 和 N_2K_3 处理的土壤速效钾含量分别提高 16、41、55、11、38 mg/kg，其他处理的土壤速效钾含量低于试验前。黄泥田 N_1K_2、N_1K_3、N_2K_3 处理的早、晚稻收获后，土壤速效钾含量分别比试验前提高 14、41、56 mg/kg 和 1、17、5 mg/kg，其他处理土壤速效钾含量均低于试验前(见图 1)。且 2 种土壤在同一氮肥水平下，早稻收获后土壤速效钾含量随钾肥施用量增加而提高，晚稻除 K_0 与 K_1 水平下土壤速效钾含量基本相同，也为随施钾量增加土壤速效钾含量提高。

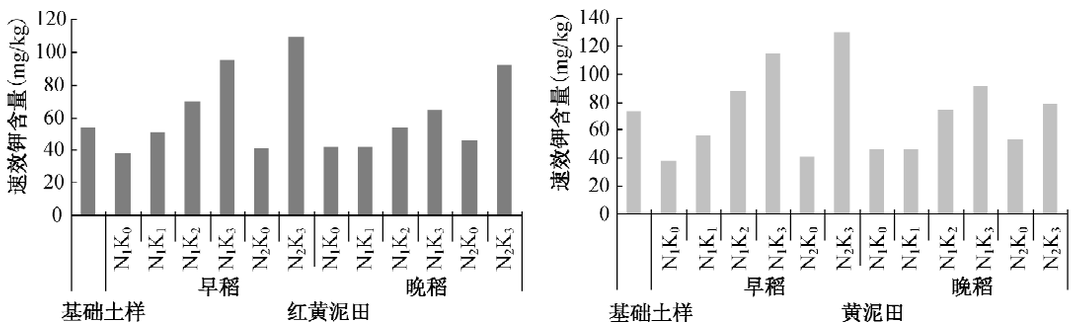

图 1 施钾对丘陵区 2 种土壤速效钾含量的影响

Fig. 1 Effects of potassium application combined with nitrogen on avalable K contents in two paddy soils in hilly regions

分析不同用量氮肥配施相同用量钾肥对土壤速效钾含量的影响发现，除黄泥田晚稻高量氮配施高量钾(N_2K_3)的土壤速效钾含量低于中量氮配施高量钾(N_1K_3)，红黄泥田早、晚稻收获后及黄泥田早稻收获后土壤速效钾含量均表现为随氮肥施用量提高而增加。

2.3.2 施钾对丘陵区 2 种土壤上缓效钾含量的影响

土壤缓效钾是速效钾的贮备，其含量是评价土壤钾素供应能力的重要指标[9]。与试验前比较，每季试验结束后，红黄泥田施钾与否对土壤缓效钾含量无明显影响，仅早稻 N_1K_3、N_2K_3，晚稻 N_2K_3 处理的有所增加(4、6、8 mg/kg)。缓效钾含量较低的黄泥田，施钾后缓效钾含量得到不同程度提高，早稻提高 16～36 mg/kg，晚稻提高 0～31 mg/kg，其中分别以 N_2K_3 和 N_1K_3 处理提高最明显(见图 2)。

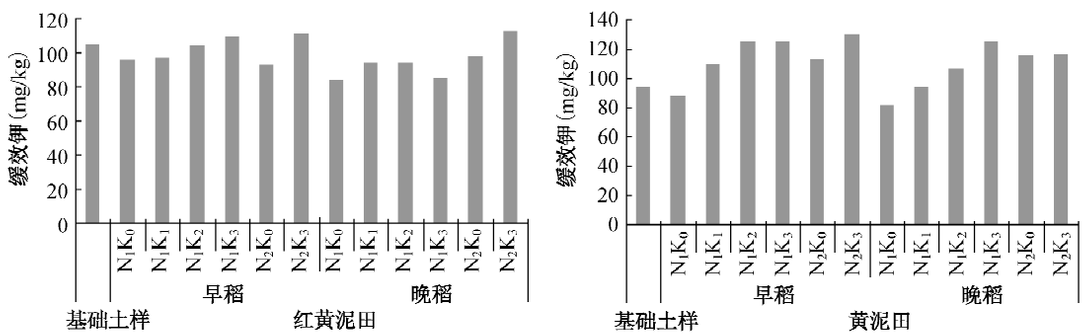

图 2 施钾对丘陵区 2 种土壤缓效钾含量的影响

Fig. 2 Effects of potassium application combined with nitrogen on slowly K contents in two paddy soils in hilly regions

2.4 氮钾配施对钾肥效益的影响

从经济效益来看(见表 4)，在 N_1 水平下，黄泥田早稻产量和产值随施钾量增加而提高，晚稻红黄泥田和黄泥田施钾(K_2O)量在 0～195 kg/hm² 范围内时产量和产值均随施钾量增加而提高，超过该范围产量和产值降低。比较相同施钾水平的不同施氮处理的产值发现不施钾时产量和产值随施氮量增加而提高，相同施钾水平(K_3)下产量和产值也随施氮量增加而提高。

表 4　丘陵区 2 种土壤各施钾处理的钾肥效益(元/hm²)

Table 4　Economic benefits of potassium application combined with nitrogen on in two paddy soils in hilly regions

土壤名称	处理	早稻季					晚稻季				
		产值	增产值	投肥成本	增加利润	产/投比	产值	增产值	投肥成本	增加利润	产/投比
红黄泥田	N_1K_0	14 893	—	1 308	—	—	16 196	—	1 255	—	—
	N_1K_1	15 666	773	2 115	−34	0.96	17 661	1 464	2 210	509	1.53
	N_1K_2	15 257	364	2 358	−686	0.35	18 447	2 251	2 620	886	1.65
	N_1K_3	15 439	546	2 673	−819	0.40	17 841	1 645	3 029	−130	0.93
	N_2K_0	14 937	—	1 543	—	—	17 732	—	1 536	—	—
	N_2K_3	16 988	2 051	2 908	686	1.50	19 019	1 287	3 311	−488	0.73
黄泥田	N_1K_0	15 630	—	1 308	—	—	17 783	—	1 255	—	—
	N_1K_1	17 233	1 604	2 115	797	1.99	20 675	2 891	2 210	1 936	3.03
	N_1K_2	17 562	1 932	2 358	882	1.84	20 929	3 146	2 620	1 781	2.30
	N_1K_3	17 647	2 018	2 673	653	1.48	20 077	2 294	3 029	519	1.29
	N_2K_0	16 803	—	1 543	—	—	18 275	—	1 536	—	—
	N_2K_3	19 303	2 501	2 908	1 136	1.83	20 315	2 039	3 311	265	1.15

注:稻谷价格按早稻 2.76 元/kg,晚稻 2.86 元/kg 计算;肥料价格按 N 5.22 元/kg, P_2O_5 7.00 元/kg, K_2O 7.00 元/kg 计算。

一般认为施肥产投比达到 2.0 时经济效益显著,产投比 1.0～2.0 时尽管经济效益不显著,但基本为农民所接受,产投比低于 1.0 时则会亏本。分析施钾产投比并同时分析施钾处理相比不施钾处理增加纯利润的结果(见表 4)可知,红黄泥田早稻除在 N_2 基础上配施高量钾处理、晚稻在 N_1 水平配施低量钾(K_1)和中量钾(K_2)处理的产投比大于 1.50,并且相比不施钾利润也是增加的外,其他处理产投比小于 1.0,且利润为负。黄泥田上早晚稻施钾产投比均大于 1.0,且能增加较高利润。说明黄泥田施用钾肥能较红黄泥田获得更高的经济效益。

3　结论与讨论

钾是实现水稻高产稳产的重要营养元素[9],大量研究表明稻田土壤施钾能显著提高水稻产量[10-11]。本研究结果进一步证明在 2 种稻田土壤上施用中量氮肥条件下,施钾能显著提高早晚稻产量,且晚稻施钾的增产效应好于早稻。因此,为发挥钾肥的最大增产效应,应重视轮作周期中前后茬作物钾肥的合理分配,因此,在稻-稻复种制中根据早晚稻钾肥产量效应的差异,应采取“早稻轻,晚稻重”的分配原则。

氮磷钾合理配施是保证作物高产稳产的重要农艺措施。影响钾肥肥效的因素很多,钾与其他养分合理配施是提高钾肥肥效的重要条件之一,氮钾合理配施不仅可充分发挥钾肥的作用,还可充分发挥氮肥的作用。已有研究表明,氮钾互作为正效应[12]。本研究结果显示,在施钾或不施钾条件下,早晚稻产量均随施氮量的增加而提高,尤其是早稻增产效果尤为显著。2 种土壤上高量氮配施高量钾(N_2K_3 处理)的增产效果尤为显著。说明在缺钾土壤双季稻种植制度中,氮肥或钾肥的增产效果随配施的另一肥料施用量增加而提高。因此,为实现水稻高产稳产,需提高氮肥用量并相应增加钾肥用量,“高氮配高钾”的增产效果在早稻上更为显著。

通常认为土壤供钾能力越低,钾肥施用效果越明显,钾肥利用率越高[13]。本试验中,不同土壤类型的钾肥利用率差异显著,红黄泥田早稻平均钾肥利用率为 30.9%,黄泥田平均为 25.7%;晚稻红黄泥田平均钾肥利用率为 51.9%,黄泥田平均为 14.9%。红黄泥田的早晚稻钾肥利用率显著高于黄泥田,这可能与红黄泥田缺钾程度较黄泥田高有关。本试验中,红黄泥田的早晚稻钾肥农学效率均低于黄泥田,这可能与 2 种土壤有效钾含量及产量水平不同有关。

南方水稻土因长期不施钾肥导致的土壤钾素严重亏缺已成为水稻高产和农民增收的主要限制因素之一[14-15],特别是长江中游双季稻集约化种植区。为了维持土壤钾素肥力,土壤钾素平衡是土壤肥料界关注的一个焦点问题。本试验结果表明,在施中量氮肥条件下,早稻施用 K_2O 0～105 kg/hm² 时土壤钾素呈现亏缺,且亏缺量随施钾量增加而降低;施用 K_2O 150～195 kg/hm² 时钾素呈现出盈余,且盈余量随施钾量增加而增加。晚稻施用 K_2O 0～195 kg/hm² 时钾素呈现出亏缺,亏缺量随施钾量增加而降低;施用 K_2O 253.5 kg/hm² 时钾素盈余。因此,对于供钾潜力较低的土壤,若不补充钾肥,将会严重影响氮、磷肥料效应和作物的产量和品质。对于目前钾素较为丰富的土壤,如果仅靠农田生态系统自身循环,即使暂时

不缺钾，以后也会缺钾。

速效钾和缓效钾含量是衡量土壤供钾能力的指标。近年来稻田土壤肥力监测结果表明，南方稻田土壤速效钾含量普遍呈下降趋势，年下降量(K)为 0.58～3.32 mg/kg[14]。在目前施肥水平下，农业生产“三要素”中，钾素一般处于亏缺状态，部分区域出现严重亏缺[16-18]，缺钾矛盾日益严重。本试验结果表明，同一施氮水平下土壤速效钾和缓效钾含量均随施钾量增加而增加，施高量钾肥土壤速效钾和缓效钾含量随氮肥用量增加而提高，而早晚稻不施钾处理的土壤速效钾和缓效钾含量均较试验前降低。这一结果表明施钾是增加水稻产量和保持或提高土壤供钾能力的重要措施。

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Effect of potassium application combined with nitrogen on potassium efficiency and potassium balance of double rice in hilly regions of Hunan Province

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Abstract: A field experiment under a double-rice cropping system was carried out to study the effects of potassium

application rate and 2 nitrogen rates combined with potassium on rice yield, K uptake, K-fertilizer use efficiency, potassium balance, status of soil K-fertility and economic benefit of 2 types of paddy soil in hilly regions of Hunan Province. Results showed that K fertilizer application could obviously increase grain yields of early rice and late rice. Under a certain K fertilizer application range (0～195 kg K_2O/hm^2), late rice yield was increased with potassium application rate increasing at the middle rate of nitrogen application. Early rice and late rice yields is increased with nitrogen application increase under high rate of potassium application or no potassium application. Potassium application and nitrogen application increased the amount of K uptake in rice plant which is increased with the increase of application of potassium or nitrogen. At the middle rate of nitrogen application, the apparent K balance in the soil-crop system were deficient under 0～105 kg K_2O/hm^2 application in early rice and 0～195 kg/hm^2 in late rice, and the potassium deficiency was decreased with K fertilizer application rate increase in early rice. While the apparent K balance is surplus under 150～195 kg K_2O/hm^2 application in early rice and 253.5 kg K_2O/hm^2 in late rice, and the potassium surplus were increased with K fertilizer application increase. Potassium surplus amount was decreased with nitrogen application combined with high rate of potassium. Soil K contents were affected by K fertilizer application rate obviously. Available K and slowly K contents were increased with potassium application rates increase. The results also showed that both soil available K and slowly K contents increased with nitrogen application increase in high rate potassium applied. The ratios of output to input of K fertilizer in yellow paddy soil were higher than in red-yellow paddy soil both in early rice and in late rice which indicated that higher economic benefit could be gained in red-yellow paddy soil by potassium application.

Key words: Hilly double rice regions in Hunan province, potassium fertilizer, potassium efficiency, potassium balance

长期不同施肥对高原小麦产量和土壤钾素的影响[①②]

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摘　要：通过连续17年对长期定位施肥试验进行研究，探讨增施钾肥和秸秆还田对青藏高原东部农业区春小麦产量及农田土壤钾素的影响。结果表明，长期增施钾肥和秸秆还田对春小麦产量无显著影响；长期单施氮磷化肥，土壤速效钾含量有下降趋势，化肥钾与秸秆配合，能够提高土壤速效钾含量；增施钾肥和或秸秆还田能够维持和增加土壤钾素，提高土壤钾库贮量。

关键词：长期定位试验；土壤钾素；秸秆还田

随着农作物产量和氮、磷肥用量的不断提高，作物从土壤中移走的钾量逐渐增加，而目前作为土壤钾有效补充方式之一的有机肥施用量逐年下降，土壤缺钾面积逐渐扩大，土壤钾素研究仍然是土壤科学尤其是土壤肥力研究的重要内容之一[1]。因此，对于目前逐渐发展的缺钾问题，IPNI北京办事处自1992年起在青海设立田间定位试验探讨土壤—作物体系钾循环及秸秆还田对保持土壤钾素平衡的作用，为该地区合理施用钾肥提供依据。

1　材料与方法

1.1　试验区概况

1992年开始种植春小麦，开展肥料长期定位试验。定位试验设在青海省农林科学院土壤肥料研究所试验地，位于E 101°49′17″，N 36°34′03″，海拔2 360 m。气候类型属半干旱大陆性气候，年降雨量368.2 mm，蒸发量1 150 mm，年均气温5.7℃，日照时数为2 762 h，大于10℃积温为2 037.3℃，大于0℃积温为2 749.5℃，无霜期130 d。土壤类型为栗钙土，质地为中壤。耕作制度为一年一熟制，小麦收获后人工翻耕冬灌休闲，至翌年春季播种。试验初始养分状况为：pH 7.6，阳离子交换量13.8 cmol/kg，有机质18.3 g/kg，全氮1.27 g/kg，铵态氮33.8 mg/kg，硝态氮42.6 mg/kg，速效磷90.4 mg/kg，速效钾177.3 mg/kg。

1.2　试验设计及方法

试验设6个处理：NP，NPK，NP＋50％秸秆还田（ST），NP＋100％ST，NPK＋50％ST，NPK＋100％ST（见表1）。每个处理4次重复，完全随机区组排列，小区面积5 m×5 m＝25 m^2，磷肥、钾肥和70％氮肥在播前作为基肥施入，30％氮肥于拔节期追施，秸秆还田处理分半还（50％ST）和全还（100％ST）。半还指小麦按小区脱粒后，一半秸秆经粉碎成约10 cm长度均匀撒施该小区，全还指将该小区全部秸秆粉碎后返回该小区，半还和全还均为人工翻入小区。供试春小麦品种2006年以前为“青春323”，由于同一品种长期种植产生退化现象，2007年更换为新品种“青春40”。土壤速效钾含量测定方法为醋酸铵-火焰光度计法。

表1　春小麦定位试验处理及肥料用量

Table 1　Treatment design and fertilization of the experiment

处理 Treatment	N（kg/hm^2）	P_2O_5（kg/hm^2）	K_2O（kg/hm^2）
NP	110	55.2	0
NPK	110	55.2	150
NP＋50％ST	110	55.2	0
NP＋100％ST	110	55.2	0
NPK＋50％ST	110	55.2	150
NPK＋100％ST	110	55.2	150

注：N、P肥料用量为2002年至今的施肥量，1993—2001年施肥量N 147 kg/hm^2，P_2O_5 73.5 kg/hm^2，K_2O用量一直未变化。

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2 结果与分析

2.1 长期施肥和秸秆还田对春小麦产量的影响

对该长期定位试验连续 15 个年份春小麦产量结果进行统计(表 2、图 1)可知,春小麦产量年季间变化很大,处理间差异不显著,但 NPK 处理春小麦产量在 15 年中有 9 个年份高于 NP 处理,平均增产 7.6%,NPK+100%ST 处理春小麦产量有 8 个年份高于 NPK 处理,平均增产 5.9%。各处理的小麦 15 年累计产量 NPK+50%ST>NPK+100%ST>NPK>NP+100%ST>NP+50%ST>NP,说明增施钾肥和秸秆还田均有利于维持或增加春小麦产量。

表 2 长期定位试验历年春小麦产量(单位:kg/hm²)

Table 2 Grain yield of the experiment from 1994 to 2008

处理 Treatment / 年份 Year	NP	NPK	NP +50%ST	NP +100%ST	NPK +50%ST	NPK +100%ST
1994	6 600	6 160	6 560	6 160	6 760	7 000
1995	6 100	5 200	5 500	5 640	5 500	5 460
1996	5 720	5 380	5 660	5 160	5 400	5 100
1997	5 400	5 238	5 670	5 562	5 778	5 832
1998	4 760	5 140	4 903	5 046	5 236	5 474
1999	4 170	4 355	4 329	3 710	3 950	3 745
2000	3 030	3 290	2 720	2 910	2 830	2 940
2001	5 075	5 015	5 030	4 935	5 735	5 020
2002	5 400	5 415	5 305	5 585	6 055	5 520
2003	4 021	4 776	4 029	4 780	4 159	4 120
2004	4 212a	4 082a	4 476a	4 582a	4 434a	4 188a
2005	5 054a	5 325a	5 066a	5 007a	5 055a	5 650a
2006	2 878a	3 003a	3 084a	2 853a	3 169a	2 890a
2007	2 795a	2 985a	2 845a	2 935a	2 765a	2 480a
2008	4 304a	4 810a	4 445a	4 983a	4 667a	4 789a

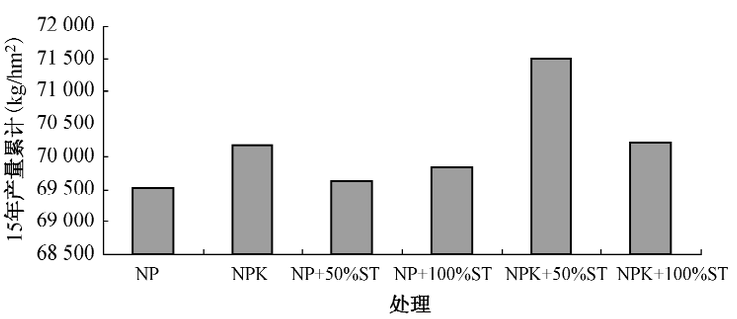

图 1 各处理的 15 年小麦累积产量比较柱状图

Figure 1 Accumulated yield of the experiment over 15 yaers

2.2 长期施肥和秸秆还田对土壤速效钾含量的影响

表 3 长期定位试验土壤速效钾含量(单位:mg/kg)

Table 3 Soil available K contents of the experiment from 1994 to 2005

处理 Treatment / 年份 Year	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
NP	127	112	146	142	181	106	122	117	116	94	117	121
NPK	177	166	176	209	218	146	180	144	144	121	141	174
NP+50%ST	115	135	151	178	191	141	145	130	105	116	130	140
NPK+50%ST	152	141	181	218	229	156	250	180	150	149	130	198
NP+100%ST	115	118	151	184	214	136	191	130	128	132	180	170
NPK+100%ST	152	153	161	202	255	196	264	208	144	181	208	245

从该长期定位试验连续 15 个年份土壤速效钾含量变化(见表 3)可以看出,历年土壤速效钾含量 NP 处理在 94～181 mg/kg 之间,NP＋50％ST 处理在 105～191 mg/kg 之间,NP＋100ST 处理在 115～214 mg/kg 之间,NPK 处理在 121～217.8 mg/kg 之间,NPK＋50％ST 处理在 130～250 mg/kg 之间,NPK＋100％ST 处理在 144～264 mg/kg 之间,有一定的梯度差异。土壤速效钾含量施钾处理高于未施钾肥处理,秸秆还田程度越高,土壤速效钾含量增加越明显。从 15 年土壤速效钾含量长期变化来看,NP、NPK 处理的土壤速效钾含量变化均呈下降态势,NP＋50％ST 处理的下降趋势较前两处理减弱,NPK＋50％ST 处理的变化基本稳定,而 NP＋100％ST、NPK＋100ST 处理的趋势线均呈上升态势,其中 NPK＋100％ST 处理的上升趋势更明显。可见 N、P、K 同时施用比只施 N、P 肥有助于提高土壤速效钾含量,单施化肥土壤速效钾含量有随着时间的延长而下降的趋势,而增施钾肥与秸秆还田措施同时采用能扭转这种下降趋势,并使土壤速效钾含量呈逐渐上升趋势。

2.3 长期施肥和秸秆还田对钾肥利用率和土壤钾素表观平衡的影响

钾肥累积利用率指在连续施肥时间内,作物从所施钾肥中吸收的钾素总量占钾肥施入总量的的百分数,计算公式为:

$$\text{钾肥利用率}(\%)=\frac{\text{施钾处理作物吸钾量}-\text{未施钾处理作物吸钾量}}{\text{施钾处理钾肥施用量}}\times 100$$

土壤钾素表观平衡指在试验时间内,通过施肥加入土壤中的钾素总量和作物从土壤中移走的钾素总量的差值,即:

钾素表观平衡＝施入土壤钾素总量－作物移走钾素总量

秸秆还田将秸秆中的钾归还到土壤中,因此本文将秸秆还田处理视为施钾处理。按照上述公式,根据 1996、1998、1999、2000、2002、2004 年的小麦产量、秸秆产量,以及籽粒、秸秆 K_2O 含量估算 15 年来钾肥利用率和土壤钾素表观平衡估算,结果见表 4。钾肥利用率各处理 NPK＋50％ST＞NP＋50％ST＞NP＋100％ST＞NPK＞NPK＋100％ST＞NP,分别为 14.6％、11.8％、10.8％、8.7％、7.6％、0。说明适度秸秆还田能够提高钾肥利用率,增施钾肥与秸秆还田配合,能够明显提高钾肥利用率;土壤钾素表观平衡 NP 处理亏缺最大,亏缺量为 2 256 kg/hm^2, NP＋50％ST、NP＋100％ST、NPK 处理依次次之。NPK＋50％ST、NPK＋100％ST 处理的土壤钾素表观平衡值均为正值,分别为 640 kg/hm^2、1 840 kg/hm^2。说明连续种植下,钾肥投入较少或不增施钾肥会打破土壤钾素收支平衡,造成土壤钾素亏缺,而增施钾肥和秸秆还田能够维持和增加土壤钾素含量,增加土壤钾库贮量。

表 4 15 年钾肥利用率和土壤钾素表观平衡

Table 4 Potassium use efficiency and soil superficial K balance

处理 Treatment	钾肥利用率 K use efficiency(％)	K_2O 投入量 K_2O input (kg/hm^2)		K_2O 移走量 K_2O loss (kg/hm^2)	钾素表观平衡 Superficial K balance (kg/hm^2)
		秸秆 From straw	肥料 From fertilizer		
NP	0	0	0	2 256	－2 256
NPK	8.7	0	2 250	2 451	－201
NP＋50％ST	11.8	968	0	2 370	－1 402
NP＋100％ST	10.8	2 043	0	2 476	－433
NPK＋50％ST	14.6	1 143	2 250	2 753	640
NPK＋100％ST	7.6	2 185	2 250	2 595	1 840

3 结果与讨论

张会明、徐明岗等人在甘肃灌漠土上的长期施肥定位试验表明,不施肥或单施化肥时土壤速效钾含量均有所降低,施 NP 肥时土壤速效钾含量降低速率达显著水平,施 NPK 肥时土壤速效钾含量略有增加。他们提出不施肥或不平衡施肥尤其是只施 NP 肥时土壤速效钾会日益亏缺,目前的钾肥施用量仅能维持土壤速效钾含量不降低,要提高灌漠土速效钾库贮量需要增加钾肥或有机肥施用量[1、4]。本文试验相关

结果和结论与以上观点相符，增施钾肥能够缓解土壤钾素亏缺状况，秸秆还田作为一种有机肥投入，能够有效地提升土壤速效钾贮量。洪春来等在秸秆全量直接还田对土壤肥力及农田生态环境的影响研究中得出全量还田土壤速效磷、速效钾含量多数在对照之上[5]，吴婕等指出秸秆覆盖处理的土壤速效钾含量较对照提高了1.06%～9.62%[6]，这些试验结果都很好地印证了上述观点。

氮磷钾平衡施肥和化肥与秸秆还田并重能够提高作物产量，很多相关研究也证实了这一结论[2、3、5、6]。在青海当地条件下，长期定量施肥，作物产量有随着年份的延长而逐渐下降的趋势，但本文作者尚未找到明确与该结论一致的相关文献报道；施钾或不施钾条件下，秸秆半量还田15年累计产量和钾素利用率均优于秸秆全量还田，但土壤钾素表观平衡与土壤速效钾含量均为秸秆全量还田优于半量还田；徐明岗等人提出土壤全钾含量的变化与土壤钾素表观平衡值有相关关系，钾肥利用率的变化及其趋势与土壤速效钾的演变特征有关[1]，因此本文还需进一步深入探讨此类相关问题。

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Effects of long-term different fertilization on grain yield and soil K in Qinghai-Tibetan Plateau

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Abstract: A 17 year sited field experiment was investigated to study effects of chemical K fertilizer and straw return based on N and P chemical fertilization on grain yield and soil K at eastern agricultural area, Qinghai-Tibetan Plateau. The results showed that based on N, P fertilization potassium fertilizer and straw return had no negative effect on grain yield of spring wheat; long-term application of N, P chemical fertilizer decreased soil available K content but addition of potash and or straw return increased soil available K; Conclusions: addition of potassium fertilizer or straw return based on N, P fertilizer can increase soil K content and make soil K pool abundant.

Key words: Long-term experiment, soil K; straw return

Current potassium management status and grain yield response of Chinese maize to potassium application §

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Abstract: The great achievement of intensive agriculture in China can be partly attributed to substantial increases in nutrient application. However, farmers tend to apply more nitrogen (N) and phosphorus (P) and neglect potassium (K). An improved understanding of the relationship between maize (*Zea mays* L.) grain yield and K application rate will result in a better rational K fertilization by farmers in the various agro-ecological regions of China. In this study, a total of 2 765 farmers' survey data and 3 124 on-farm experiments across major maize agro-ecological regions in China were collected and evaluated for farmers' K management status and to determine grain yield response to K application. Nationally, the average K application rate on farms is 26 kg K ha^{-1} and varies from 0 to 158 kg K ha^{-1}, with a coefficient of variation of 107%, but the applied K fertilizer rates were not related to grain yield. The maize grain yields at recommended K rates increased 14.0%, 14.7%, 19.4%, and 4.3% in Northeast China, North China Plain, Southwest China, and Northwest China, respectively, compared to zero K fertilization (K_0). Increased yield due to K fertilization (IY_{max}, difference between maximum yield across all treatments and K_0 treatment yield for each experiment) averaged 1.4 t ha^{-1} but varied widely in different agro-ecological regions. Soil extractable K (NH_4OAc-K) and inter-county variation resulted in large variation in IY_{max} in agro-ecological regions, as did other factors, such as use of maize hybrids, soil types, or years in different regions.

Key words: Maize yield, potassium fertilization, variation, region

1 Introduction

The development of sustainable agriculture faces dual challenges: ensuring current and future food security (*Tilman* et al., 2001; *FAO*, 2009; *Godfray* et al., 2010) while also reducing the substantial environmental impact of intensive agriculture (*Tilman* et al., 2004; *Foley* et al., 2005). A balanced application of fertilizer is a key in developing and sustaining modern agricultural systems (*Dobermann* et al., 1998; *Aulakh*, 2006). Long-term experiments have suggested that the combined use of nitrogen (N), phosphorus (P), potassium (K) fertilizers can sustain yields and soil productivity, whereas inadequate mineral nutrients and imbalanced mineral nutrient application results in yield stagnation and soil degradation over time in agricultural ecosystems (*Rupa* et al., 2001; *Belay* et al., 2002; *Tan* et al., 2007; *Yu* et al., 2009; *Niu* et al., 2011; *Zhang* et al., 2011b). In practice, over-fertilization with N and P in China is prevalent in intensive agricultural production areas, resulting in low nutrient use efficiency, eutrophication, groundwater pollution, greenhouse gas emissions, and soil acidification (*Guo* et al., 2010; *Chen* et al., 2011). However, application of K (either as organic matter or mineral K) has often been neglected, which has resulted in the continuous depletion of soil K and has prevented farmers from obtaining attainable yields (*Dobermann* et al., 1998; *Römheld* and *Kirkby*, 2010; *Zhang* et al.,

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2010). Achieving and sustaining the food production system requires a rational K management strategy based on a better understanding of the relationship between crop yield and K application rate.

Decisions on K fertilizer application require knowledge of the expected crop yield response to K application, which is usually a function of exchangeable K obtained by chemical extraction of dried soil (*Römheld* and *Kirkby*, 2010; *Kuchenbuch* and *Buczko*, 2011). However, the relationship between soil K content and the effect of K fertilizer application on crop yield may have a high degree of spatial variability (*Römheld* and *Kirkby*, 2010; *Kuchenbuch* and *Buczko*, 2011). For example, *Dobermann* et al. (1998) reported that yield response to applied K was influenced by a series of factors, including duration of intensive cropping, yield level, amount of NPK fertilizer applied, clay mineralogy, soil texture, straw management, and net K inputs from irrigation.

In China, use of K fertilizer is much lower than that of N fertilizer (*Zhang* et al., 2010), and even lower than that of P fertilizer. In part, this is because of limited native potassium supplies, and most potassium fertilizers are imported and therefore cost-prohibitive. The other primary reason for low K application is the relatively high soil K surveyed in the 1980s, especially in Northern China (*Xie* et al., 2000). Thus, most farmers and even some agronomists believe that no yield improvement could be attained with increased K fertilizer application. However, soil conditions and crop management practices have changed significantly, requiring new knowledge of expected crop yield responses to K applications.

Many reports have shown that negative K budgets are common across different agricultural cropping systems and agro-ecological regions in China due to a lack of adequate nutrient recycling (*Chen* et al., 1997; *Xie* and *Zhou*, 1999; *Gao* et al., 2000; *Liu*, et al., 2000; *Niu* et al., 2011; *Zhang* et al., 2011b; *Tan* et al., 2012). The decline of soil K is widespread throughout the agricultural regions (*Chen* et al., 1997; *Xie* and *Zhou*, 1999; *Liu*, et al., 2000). *Wang* et al. (2012) found that in Hubei Province (South China), soil extractable K (NH_4OAc-K) had decreased by 10% on the paddy soils from 1980s to 2008. *Chen* (2001) reported that in Guizhou Province (Southwest China) soil extractable K in upland fields had decreased from 122 mg kg^{-1} to 89 mg kg^{-1} during from 1985 to 1998. Current soil extractable K in Xinjiang Province (Northwest China) had declined by 32% compared with 1980s (*Wu*, 2012). In addition, the evolution of varieties and production techniques (*Li* and *Wang*, 2009) also had an immense effect on crop responses to K. For example, previous research reported that genotypes differed in their K uptake and utilization efficiency (*Rengel* and *Damon*, 2008) and K use efficiency had a distinct influence on yield response to K (*Fageria* et al., 2003; *Kuchenbuch* and *Buczko*, 2011).

A re-evaluation of crop yield response to K application rate is needed to guide farmers in adjusting K fertilization practices in China. From 2005 to 2009, a total of 3 124 on-farm experiments in major Chinese maize production regions were conducted, which represent a wide range of cropping systems in different climatic conditions and geographical environments. For comparison, we also collected and summarized the K fertilizer management status of 2 765 farmers' fields from 106 counties in 13 provinces to ensure a wide range of different K management practices in different regions. The goals of this study were to determine the status of K fertilizer use across major maize agro-ecological regions in China; quantify the impact of K application on maize yield in these regions; and understand the factors affecting the yield response to increase the sustainability of maize-based crop production systems in China.

2 Materials and methods

In China, maize is grown primarily in four agro-ecological regions, including Northeast China (NE), Northwest China (NW), North China Plain (NCP), and Southwest China (SW) (Fig. 1). The total maize sowing area in the four major maize-producing regions was about 24 million ha (the maize sowing area of NE, NW, NCP, and SW was 7.8, 3.8, 8.1, and 4.0 million ha, respectively), which represented 97% of total maize production in China (*National Bureau of Statistics of China*, 2004).

NE (40 – 55°N, 110 – 135°E) has a warm-temperate, sub-humid, continental monsoon climate, with cold winters and hot summers. NW (34 – 40°N, 95 – 115°E) is typified by cold winters and dry, hot summers. NCP (32 – 41°N, 113 – 120°E) has a warm-temperate, sub-humid, continental monsoon climate, with cold winters and hot summers. SW (21 – 34°N, 97 – 112°E) has a humid/sub-humid, subtropical climate, with cold winters and moist, hot summers.

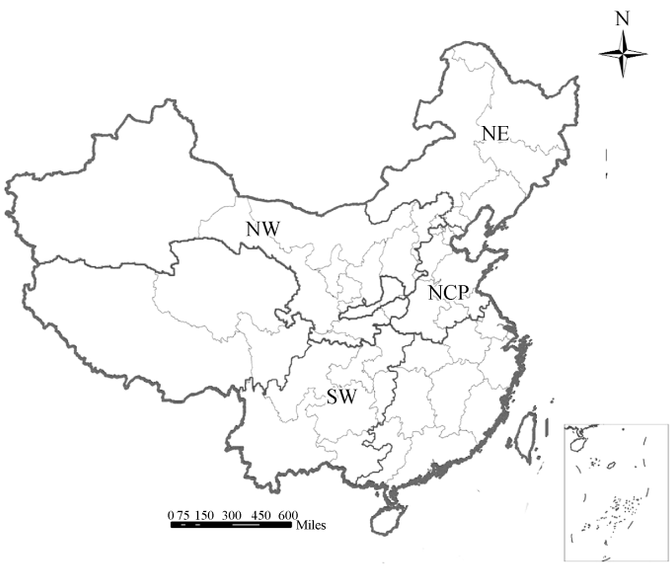

Figure 1 Major agro-ecological regions (NE: Northeast China, NW: Northwest China, NCP: North China Plain, SW: Southwest China) for maize production in China.

In NE and NW, maize grows in rain-fed conditions. Annual precipitation is 400 – 800 mm, with about 60%– 70% occurring during the summer. In NCP, maize grows with little irrigation. Annual precipitation is 500 – 700 mm, with about 70%– 80% occurring during the summer maize growing season. In SW, maize also grows without irrigation, and annual precipitation is 800 – 1 200 mm, with about 70%– 80% occurring between April and October.

2.1 K management survey of farm fields

In 2009, we collected and summarized data on the status of K fertilizer use of 2 765 farm fields from 106 counties in 13 provinces. A multistage sampling method was used to select representative farmers for the survey. In each county, 2 – 5 townships were randomly selected, and then 5 – 10 farmers from the townships were randomly surveyed to determine the form of fertilizer they used, application rate, timing, used techniques, and grain yield in the past year.

2.2 On-farm experiments

A total of 3 124 on-farm maize production experiments were conducted from 2005 to 2009 in the NE (n=2 188) and NW (n=101) spring maize areas and the NCP (n=410) and SW (n=425) summer maize areas. At all sites, 27 typical soil types were involved and included Chernozems (Haplic Chemozems) and Black soils (Phaeozems) in NE; Castanozems (Kastanozems) in NW; Fluvo-aquic soils (Calcic Cambisols) and Cinnamon soils (Chromic Cambisols) in NCP; Yellow soils (Orthic Acrisols) and Purple soils (Chromic Cambisols) in SW. Soils classified according to Genetic Soil Classification of China (*The Office for the Second National Soil Survey of China*, 1998) and the matching soils name based on the FAO / Unesco Soil Map of the World (*Zhang*, 1990) were provided in brackets. All experimental fields received the following treatments without replication: 0 K control (K_0), recommended K rate (RKR), 50% RKR, and 150% RKR. The RKR was determined by agronomist recommendations based on experience and target yield (1.1 times the average yield of the past 5 yr), which varied by field. Across all sites, RKR averaged 75 kg K ha^{-1}(25 – 188 kg K ha^{-1}) (Table 1).

Table 1 Basic soil properties and recommended fertilizer rates of the four agro-ecological regions (NE, Northeast China; NW, Northwest China; NCP, North China Plain; SW, Southwest China) among 3 124 experimental fields in China.

Region	n	Organic matter g kg^{-1}		Olsen-P mg kg^{-1}		NH_4OAc-K mg kg^{-1}		Recommended fertilization rate (kg ha^{-1})					
								N		P		K	
		Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
NE	2 188	18.5	1.0 – 99.6	18.5	0.3 – 113	133	20 – 365	172	120 – 225	44	26 – 66	61	38 – 63
NW	101	16.1	1.3 – 52.0	18.1	1.1 – 86	176	23 – 376	217	120 – 270	55	39 – 66	78	25 – 100
NCP	410	14.2	1.0 – 28.1	26.0	5.0 – 113	122	22 – 311	197	150 – 240	30	20 – 52	78	50 – 100
SW	425	27.4	0.7 – 80.1	18.5	0.5 – 148	126	19 – 330	212	150 – 270	52	20 – 59	142	50 – 188
China	3 124	19.2	0.7 – 99.6	19.5	0.3 – 148	132	19 – 376	183	120 – 270	44	20 – 66	75	25 – 188

n, number of observation.

The experiments were conducted in a continuous spring maize system in NE/NW China, a typical winter wheat-summer maize rotation system in NCP, and a continuous maize or intercropping system in SW. Plot size was about 40 m^2. Potassium was broadcast and incorporated with plowing before sowing. Based on the estimated soil fertility, all plots received appropriate amounts of urea (120 – 270 kg N ha^{-1}, average of 183 kg N ha^{-1}) (Table 1). Approximately one-third of the N fertilizer was applied at pre-sowing, with the remaining N applied as sidedressing at around the 6-leaf stage of growth. Nitrogen was broadcast as urea by hand with plowing before sowing and deep placement at the 6-leaf stage. All plots received 20 – 66 kg P ha^{-1} (average of 44 kg P ha^{-1}, Table 1) as triple superphosphate at pre-sowing, based on soil testing. No manure was applied.

All experiments were managed according to the practices of each individual producer, whereas the treatments and crop and soil sampling were implemented by the researchers. 44 maize hybrids with high yield potential were used among the experimental sites and selected by the respective farmers. We presented several common varieties, such as Zhengdan 958 (released in 2001, used in 508 sites), Jidan 198 (released in 2003, used in 125 sites), Xianyu 335 (released in 2005, used in 118 sites), Jundan 20 (released in 2003, used in 91 sites), Kehe 8 hao (released in 2005, used in 90 sites), Shendan 16 hao (released in 2001, used in 71 sites), Neizao 9 (released in 2004, used in 70 sites). In NE and NW, spring maize was planted at the beginning of May and harvested at the end of September, whereas maize in NCP grew from June to October and in the SW from April to August. Plant densities varied from 50 000 to 65 000 plants ha^{-1} in NE, 65 000 to 75 000 in NW, 70 000 to 75 000 in NCP, and 45 000 to 50 000 in SW. Weeds and pests were well hand controlled, and no obvious water deficiency stress was observed during maize growing seasons.

2.3 Sampling and laboratory procedures

At the beginning of the experiment, composite samples (0 – 20 cm soil layer) from at least five cores per field were air-dried, sieved, and used to measure the Olsen-P (*Olsen* et al., 1954) and NH_4OAc-K (*van Reeuwijk*, 1992) of all plots as well as organic matter (*Walkley*, 1947). For each experiment, the grain yield at maturity of a 2.5 × 8 m^2 area of each plot was assessed by hand, and the value was adjusted to 15% moisture.

Considering 3 124 experimental sites, mean organic matter was 19.2 g kg^{-1} with a range from 0.7 to 99.6 g kg^{-1}, mean Olsen-P was 19.5 mg kg^{-1} with a range from 0.3 to 148 mg kg^{-1}, and NH_4OAc-K varied from 19 – 376 mg kg^{-1} with a mean of 132 mg kg^{-1}. The soil nutrient contents are shown in Table 1.

2.4 Data analysis

For all of the experimental sites, we used the experimental fields as blocks, and data were analyzed using analysis of variance (ANOVA) (*Guarda* et al., 2003). A one-way ANOVA was used to compare the mean yields of K treatments in the different maize agro-ecological regions based on the least

significant difference (LSD) at a 0.05 level of probability. A mixed ANOVA model with soil extractable K (as a covariate), counties, hybrids, years, and soil types was used to assess the overall variability of maximum yield (Max. yield, the highest yield of all K treatments of each experiment), and increased yield due to K fertilization (IY_{max}, the difference between maximum grain yield and yield of the K_0 treatment for each experiment) across all treatments in the respective agro-ecological regions.

3 Results

3.1 Current K fertilizer management by farmers

Across all 2 765 farm fields, the mean K application rate of the main maize production areas was 26 kg K ha^{-1}, ranging from 0 to 158 kg K ha^{-1}, with a coefficient of variation (CV) of 107% (Table 2). Grain yield varied from 1.9 to 13.9 t ha^{-1}, with a mean of 7.1 t ha^{-1} (CV=31%, Table 2). K fertilizer application rates on farms varied widely across the four agro-ecological regions (Table 2). NE ranked highest, with a mean of 37 kg K ha^{-1}, followed by NCP (28 kg K ha^{-1}), SW (22 kg K ha^{-1}), and NW region with just 13 kg K ha^{-1}. Across the four agro-ecological regions, however, the K rate and maize yield were not significantly correlated (Fig. 2). This indicates that other factors (e.g., crop management, soil and weather conditions) may contribute to the missing correlation between maize grain yield and K rate.

Table 2 Comparison of potassium (K) fertilizer application rate and farm yields of maize in the four agro-ecological regions (NE, Northeast China; NW, Northwest China; NCP, North China Plain; SW, Southwest China) among 2 765 farmers' fields in China.

Region	*n*	K application rate (kg K ha^{-1})			Grain yield (t ha^{-1})		
		Mean	Range	CV (%)	Mean	Range	CV (%)
NE	555	37	0-158	76	8.8	3.5-13.9	22
NW	446	13	0-107	172	6.7	1.9-11.8	34
NCP	1 062	28	0-125	91	7.7	2.7-11.3	20
SW	702	22	0-127	135	5.2	2.1-10.9	32
China	2 765	26	0-158	107	7.1	1.9-13.9	31

n, number of observation; CV, coefficient of variation.

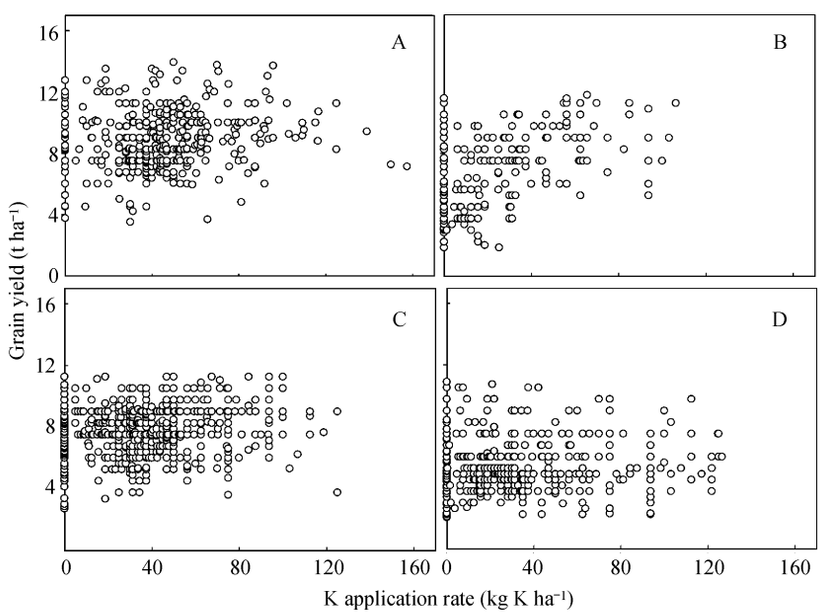

Figure 2 Relationship between potassium (K) rate and maize yield of farms in the agro-ecological regions of (A) Northeast China (n=555), (B) Northwest China (n=446), (C) North China Plain (n =1 062), (D) Southwest China (n=702).

About 22%, 30%, 45%, and 63%farmers for NE, NCP, SW, and NW don't use any chemical K fertilizer in maize production, respectively (data not shown). Farmers' decisions about K fertilizer application mostly depended on their household income (*Gao* et al., 2006). In the economically less developed western regions (NW and SW), the averaged K fertilizer application rates was much lower than that of eastern regions (NE and NCP) (Table 2). The highest ratio of no K application in NW also reflected the higher soil extractable K (NH_4OAc-K) nutrient supply capacity (176 mg kg^{-1}, Table 1) and no significant yield response to K (Table 3).

Table 3 Mean maize grain yield (t ha^{-1}) at different potassium (K) treatments, maximum yield (Max. yield, the highest yield of all K treatments of each experiment), and increased yield due to the application of K fertilizer ($IY_{50\%RKR}$, $IY_{100\%RKR}$ and $IY_{150\%RKR}$ represented the difference between yield of the 50% RKR, 100% RKR, 150% RKR treatment and yield of the K_0 treatment for each experiment, respectively; IY_{max}, the difference between Max. yield and K_0 treatment yield for each experiment) in the four agro-ecological regions (NE, Northeast China; NW, Northwest China; NCP, North China Plain; SW, Southwest China) among 3 124 experimental fields in China. Within each region, grain yield means followed by the same letter are not significantly different at $p < 0.05$.

K treatment	NE (n=2 188)		NW (n=101)		NCP (n=410)		SW (n=425)	
	Mean	Range	Mean	Range	Mean	Range	Mean	Range
Yield at K_0	8.6a	1.8-16.7	9.4a	3.2-14.6	6.8a	3.7-10.7	6.7a	3.0-10.7
Yield at 50%RKR	9.2b	1.6-19.4	9.7a	4.1-15.3	7.5b	4.4-11.4	7.4b	3.6-12.0
Yield at 100%RKR	9.8c	2.1-17.9	9.8a	3.6-15.3	7.8c	4.8-11.7	8.0c	4.1-12.0
Yield at 150%RKR	9.4d	1.5-19.0	9.6a	4.0-15.0	8.1d	4.9-11.9	7.5b	3.1-11.6
Max. yield	10.1	2.2-19.4	10.2	4.1-15.3	8.1	4.9-11.9	8.1	4.1-12.0
$IY_{50\%RKR}$	0.6	−5.3-7.1	0.3	−3.0-3.6	0.6	0.0-2.0	0.7	−2.4-5.2
$IY_{100\%RKR}$	1.2	−2.8-7.6	0.4	−3.0-2.8	1.0	0.2-2.1	1.3	−2.2-5.0
$IY_{150\%RKR}$	0.8	−4.8-7.2	0.2	−4.3-4.0	1.3	0.3-2.3	0.9	−2.0-4.9
IY_{max}	1.5	0.0-7.6	0.8	0.0-4.0	1.3	0.3-2.3	1.5	0.0-5.2

Source of variation for Max. yield and IY_K

Source	Max. yield	IY_K	Max. yield	IY_K	Max. yield	IY_K	Max. yield	IY_K
Available K	**	**	ns	**	ns	*	ns	**
Counties	**	**	**	**	**	**	**	**
Hybrids	**	**	*	ns	ns	ns	ns	ns
Years	**	*	ns	ns	**	**	**	ns
Soil types	**	ns	ns	*	ns	ns	ns	*

* significant ($p < 0.05$); ** significant ($p < 0.01$); ns, not significant at 0.05 probability level.
n, number of observation; RKR, recommended K rate.

3.2 Estimated maize yield response to K in the agro-ecological regions

Nationally, across all 3 124 fields, the grain yield of the K_0 treatment averaged 8.1 t ha^{-1}, varying from 1.8 to 16.7 t ha^{-1}, with a CV of 30% (data no shown). Adding K fertilizer significantly increased maize yields 8.6%, 14.8%, and 11.1% for 50% RKR, RKR, and 150% RKR, respectively (data no shown). RKR across all 3 124 fields averaged 75 kg K ha^{-1}, varying from 25 to 188 kg K ha^{-1}(Table 1). Grain yield after RKR fertilization averaged 9.3 t ha^{-1} and varied from 2.1 to 17.9 t ha^{-1}, with a CV of 26%. Compared to RKR, adding K beyond RKR (+50%) did not increase yields and resulted in profit loss; treatments below RKR (−50%) resulted in a 6.2% crop yield loss from 9.3 to 8.8 t ha^{-1} ($p < 0.05$; data no shown). Clearly, these results indicate that the RKR was within a range that attained maximum grain yield without a K deficit resulting in yield loss.

Maize yield response to RKR varied widely across the four agro-ecological regions (Table 3). Across regions, the mean yield at RKR in NE, NW, NCP, and SW was 9.8, 9.8, 7.8, and 8.0 t ha^{-1}, respectively, and the increased maize yield (compared to K_0) in NE, NW, NCP, and SW was 14.0%, 4.3%, 14.7%, and 19.4%, respectively. K application in SW had the highest potential to increase yield, followed by NCP and NE, but increased it only to a small degree in NW (Table 3).

The yield response to applied K varied widely in the respective agro-ecological regions (Table 3).

Nationally, IY_{max} (difference between maximum grain yield and K_0 treatment yield for each experiment) averaged 1.4 t ha^{-1} and varied from 0 to 7.6 t ha^{-1} (data no shown). The IY_{max} averages were as follows: NE, 1.5 t ha^{-1}, varying from 0 to 7.6 t ha^{-1}; NW, 0.8 t ha^{-1}, varying from 0 to 4.0 t ha^{-1}; NCP, 1.3 t ha^{-1}, varying from 0.3 to 2.3 t ha^{-1} and SW, 1.5 t ha^{-1}, varying from 0 to 5.2 t ha^{-1} (Table 3).

3.3 Variation in maize yield response to applied K fertilizer with soil K supplies, counties, hybrids, years, and soil types

Across the different agro-ecological regions, the maize yield response to K fertilizer applications varied widely by counties and soil K. Hybrids, years, and soil types contributed to the difference in IY_{max} in some maize agro-ecological regions (Table 3). In NE, soil K (as a covariate), counties (df=88), and maize hybrids (df=29) all significantly affected variation in IY_{max} (Table 3, $p < 0.01$). As soil K supplies decreased, the effect of K fertilizer application on yield increased (Fig. 3), which accords with current K fertilizer recommendations based on soil exchangeable K testing (*Zhang*, 2011a). The great difference in IY_{max} among counties (Table 3) indicated that regional-specific conditions (e.g., crop management practices, weather conditions, soil properties) lead to a high degree of inter-county variability in the yield response to applied K fertilizer. Mean IY_{max} among different maize hybrids varied from 0.5 to 2.9 t ha^{-1} (data not shown), which might contribute to differential uptake and use efficiency of K.

In NE, IY_{max} significantly differed among years (df=5), varying from 1.3 t ha^{-1} (2005) to 1.6 t ha^{-1} (2008; Table 3, $p < 0.05$). Thus, year-to-year environmental variation (e.g., weather changes) might have impacted the yield response to K application. The IY_{max} did not vary significantly among soil types (Table 3, $p < 0.05$), suggesting that soil-to-soil variation in individual fields was too small to be significantly affected by the across-field comparison. Similar to NE, counties and soil K in the other three agro-ecological regions (NW, NCP, and SW) contributed to a significant difference in IY_{max} (Table 3, Fig. 3), but IY_{max} did not vary significantly among maize hybrids. Years (df=4) significantly affected the variation in IY_{max} in NCP, but not in NW and SW (Table 3, $p < 0.01$). In contrast, soil types significantly affected the variation in IY_{max} in NW and SW, but not in NCP (Table 3, $p < 0.05$).

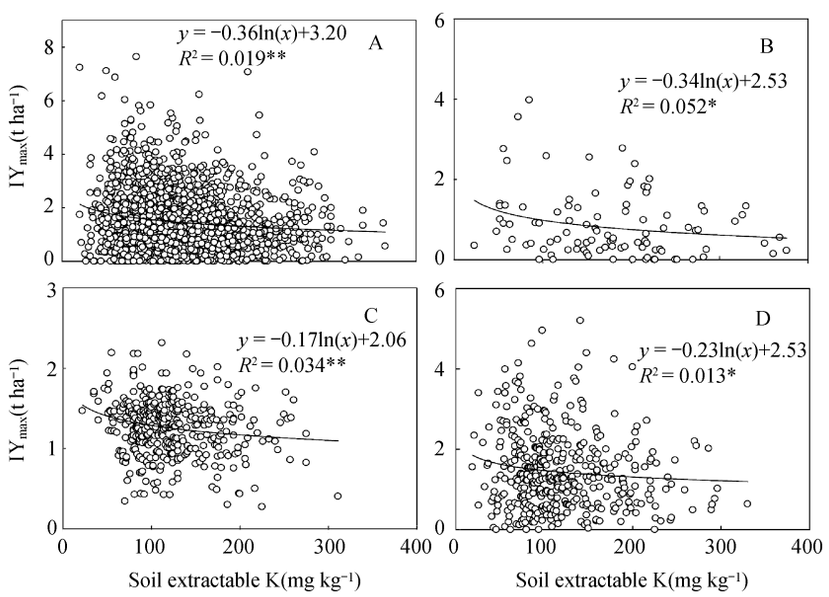

Figure 3 Relationship between soil extractable K (NH_4OAc-K) and increased yield due to the application of K fertilizer (IY_{max}, the difference between maximum yield across all treatments and K_0 treatment yield for each experiment) in the agro-ecological regions of (A) Northeast China (n=2 188), (B) Northwest China (n=101), (C) North China Plain (n=410), (D) Southwest China (n=425). * significant ($p < 0.05$); ** significant ($p < 0.01$).

4 Discussion

In the 1980s, K fertilizer improved crop yields in Southern China, where soil K was low, but not in Northern China (*Lin* and *Li*, 1989). Compared to the situation in the 1980s, nowadays maize is increasingly responding to K fertilizer applications in Northern China (except for NW). The first of two major reasons for this is that the soil K status is progressively declining because of the high removal of nutrients from soils, which have not been replenished through applications of organic or inorganic fertilizers or both. Many studies have found a negative K balance in maize-based systems, regardless of K fertilizer application (*Niu* et al., 2011; *Zhang* et al., 2011b; *Tan* et al., 2012). The input of chemical K fertilizer has been inadequate to replenish K removal by aboveground parts of crops. For example, *Tan* et al. (2012) found that negative K balances persist in wheat-maize rotation systems, even when chemical K application rates are as high as 250 kg K ha^{-1} yr^{-1} for double crops. In a previous study in China, total organic manure contained more than five-fold greater K nutrients than current chemical K fertilizer, but only a third of that level could be returned to the agro-ecosystem (*Xi*, 2004).

Second, higher maize yields due to the development of better production techniques have resulted in a significant K response, markedly increasing K requirements. In China, during the last 50 years, the development of breeding techniques and planting techniques has increased maize yields 437% (*Li* and *Wang*, 2009). Supplemental K was required to meet crop yield enhancements, which influence osmoregulation, turgor generation, enzyme activation, photosynthesis, protein synthesis, and stomatal movement (*Marschner*, 2012; *Mengel* and *Kirkby*, 2001; *Pettigrew*, 2008). In addition, the K also plays an important role in alleviating the adverse effects of abiotic stresses and reducing stalk lodging, particularly at higher maize yields (*Cakmak*, 2005; *Pettigrew*, 2008).

Fertilizer recommendations based on using available K obtained by chemical extraction of dried soil are universal (*Römheld* and *Kirkby*, 2010). We found that soil extractable K (NH_4OAc-K) had significant relationship with IY_{max} in all four regions. Howerver, the broad scatter displayed in Fig. 3 for the relation soil extractable K versus IY_{max} suggested the yield response was only partly related to soil values, and variation was influenced largely by other factors. Similar results also were reported by previous research (*Kuchenbuch* and *Buczko*, 2011), reevaluations of K responses in about 9 000 experimental field harvests conducted in Germany and Austria suggested that in addition to soil K, nutrient use efficiency and site properties had a significant influence on yield increase to K. *Tan* et al. (2012) also found that the effect of K fertilizer application on maize yield varied widely. *Niu* et al. (2011) found that production practices directly affected the maize yield response to K fertilizer. In this study, variability due to site-specific conditions (e.g., counties, hybrids, soil types, and years) had a considerable impact on the yield response to applied K fertilizer (Table 3). Great difference in max. yield and IY_{max} among and within counties (Table 3) suggested that regional-specific conditions (e.g., crop management practices, weather conditions, soil properties) lead to a high degree of inter-county variability in the yield response to applied K fertilizer.

5 Conclusions

In China, due to the relatively low grain yield response to K in the 1980s, most farmers still believe that increased K fertilizer applications would not be profitable and thus neglect them. We found significant maize responses to K in all of the agro-ecological regions expect NW. Across the four agro-ecological regions, the mean maize yield at recommended K rate (RKR, compared to K_0) increased 14.0% in NE, 4.3% in NW, 14.7% in NCP, and 19.4% in SW. Clearly, optimized K management has a great potential to improve the overall productivity of intensive maize-based crop production systems in China. Variation in yield response to K application was mainly caused by the mixed impacts of soil K,

counties, hybrids, soil types, and years. The large variation in yield response to K among counties indicated that region-specific simplified and optimized K management based on yield response to K might be crucial for reducing region-to-region variation and increasing crop production.

Acknowledgments

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中国玉米钾肥管理现状和产量随钾肥供应水平的反应

摘　要：中国农业的巨大成就离不开养分投入的增加。然而，农民往往习惯应用较多的氮肥和磷肥，而忽略钾肥的应用。因此，更好地掌握作物施钾增产效应将有助于制定科学钾肥管理策略。本文收集与分析了在中国玉米主产区开展的对2 765个农户调查的结果和3 124组田间肥效试验来评估钾肥管理现状和定量化不同区域的钾肥效应。我国的平均钾肥用量为26 kg/hm^2（变幅为0～158 kg/hm^2），变异系数为107%。然而，不同区域间，钾肥用量和玉米产量间并没有显著的相关关系。与空白对照相比，优化施钾下东北区、西北区、华北区和西南区的增产率分别为14.0%，4.3%，14.7%，19.4%。施钾的最大增产量（IYmax）平均为1.4 t/hm^2，不同区域间的变异极大。不同区域的施钾增产效应均随着县域和土壤速效钾含量的变化而产生较大的差异，而品种、年份、土壤类型因素等仅在一些区域有影响。

关键词：玉米产量；钾肥；变异；区域

Potassium management in rice-maize systems in South Asia §

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Abstract: Potassium (K) availability in soils is largely governed by their mineralogical composition. The extent of weathering of primary K-bearing minerals, the chemical pathways through which weathering takes place, as well as the dynamic equilibrium between various K fractions in soils are factors which determine different soil types of varying K-supplying capacity. The marked variability of K availability in soils in South Asia needs to be taken into account when formulating K-management strategies in intensive cereal-based systems in response to K application. Evidence from long-term fertilizer experiments in rice-rice (R-R) or rice-wheat (R-W) systems strongly indicates significant yield responses to K application and negative K balances where K application is either omitted or applied sub-optimally. However, K fertilizer recommendations in South Asia, are generalized over large areas while farmers neglect K application to crops and remove crop residues from fields. These practices may strongly affect yield and soil K-fertility status in the emerging rice-maize (R-M) systems in different locations of South Asia. The dry matter yield of the R-M system is usually much higher than that of the R-R or R-W system causing high withdrawal of nutrients from the soil. The current review assesses various K forms and K availability in diverse soil types of South Asia supporting rice-based systems. Aspects considered include: long-term crop yield and its response to added nutrients, K balance for intensive rice-based systems, and the role of crop residues in supplying K to crops. Emerging data from either completed or on-going experiments on the R-M systems in India and Bangladesh have revealed very high system productivity and variable responses and agronomic K-use efficiency of maize and rice. Potassium responses of maize are extremely high and variable for soils in Bangladesh. Finally, a plant-based strategy for field-specific nutrient management is presented and the need for models and decision support systems for developing efficient K management of the R-M system is also discussed.

Key words: DSS/*Oryza sativa*/potassium-use efficiency/soil fertility/South Asia/*Zea mays*

1 Introduction

Potassium (K) is one of the 17 essential elements for plant growth and development. Plants need large quantities of K, as much as, or even more than nitrogen (N). Potassium plays a key role in many metabolic processes in the plant. Plants deficient in K become susceptible to drought, excess water, high and low temperature, and to pests, diseases and nematodes. It has been widely reported that most soils of South Asia have high K status due to continuing K additions from rainfall, irrigation water, and release from K-rich clay minerals (*Dobermann* et al., 1996a, b; 1998). Rice-rice (R-R), rice-wheat (R-W), and rice-maize (R-M) are the main rice-based cropping systems practiced on a range of soil types in South Asia. Rice-wheat systems are extensive in the sub-tropical areas of the Indo-Gangetic Plain (IGP) of South Asia and in China (*Timsina* and *Connor*, 2001) while R-M systems have potential in all climates ranging from tropical to subtropical to warm temperate regions of Asia (*Timsina* et al., 2010, 2011). Rice-rice systems prevail in the irrigated areas of eastern and southern India and in Bangladesh. Several studies have shown that intensive rice-based systems can cause heavy depletion of soil K (*Dobermann* et al., 1996a, b; 1998; *Bijay-Singh* et al., 2004; *Yadvinder-Singh* et al., 2005a). Withdrawal is especially large in these systems because straw is often harvested along with grain

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(*Timsina* and *Connor*, 2001). Recent soil tests now show that many soils of the IGP of South Asia are becoming K-deficient despite originally high K contents (*Dobermann* et al., 1998; *Bijay-Singh* et al., 2004; *Singh et* al., 2012). Depletion of soil nutrients, particularly K, has been considered as a possible cause of yield decline of rice and wheat in long-term R-W experiments (LTEs) in the IGP of South Asia (*Ladha et al.*, 2003; *Bhandari* et al., 2002; *Regmi* et al., 2002).

Rice-maize systems are vital for meeting food requirements and improving food security for a large number of urban and rural poor of South Asia. While there is a large body of literature on nutrient dynamics, including K dynamics, of the R-R and R-W systems, such literature for the R-M systems is scarce. *Timsina et al.* (2010) recently reported the current status, future prospects, and research priorities for nutrient management in R-M systems in South Asia. They concluded that the nutrient demand of the R-M system is very high because high-yielding rice varieties and maize hybrids are cultivated that have high nutrient demand. *Buresh* et al. (2010) also reported that K demand of the R-M system is high due to use of high-yielding maize hybrids in the system. High nutrient demand is associated with high extraction of nutrients from soils, which leads to declining fertility unless the extracted nutrients are replenished from external sources. This scenario is particularly true for the R-M systems where residues of both crops are generally removed from fields aggravating soil fertility depletion, especially that of K.

The principles of K requirement, and hence K fertilizer recommendations are fairly similar for rice, wheat and maize. Hence, the current review includes some findings for the R-R and R-W systems, and then presents results from some experiments on the R-M systems in India and Bangladesh. The presentation of findings for the R-R and R-W systems is necessary to develop K management principles for the emerging R-M systems in South Asia.

2 Forms and availability of potassium in soils

Potassium in soil exists in four pools: (i) the soil solution K (K_{sl}); (ii) the exchangeable K (K_{ex}); (iii) the fixed or non-exchangeable K (K_{nex}); and (iv) the K in the lattice of certain primary minerals (K_l), all of which are in dynamic equilibrium. The amount of K_{sl} and K_{ex} is usually a small fraction of total K (1%-2% and 1%-10%, respectively) but is most readily available to plants; the bulk of soil K exists in K-bearing K_{nex} and K_l pools that are less readily available to plants (*Bijay-Singh* et al., 2004). The amount of K present in the soil solution is often smaller than the crop requirement for K and may need continuous renewal for adequate nutrition of high-yielding varieties of cereals. Hence, K nutrition of crops is a function of the amounts of different forms of K in soil, their rates of replenishment, and the degree of leaching (*Bijay-Singh* et al., 2004). The amount of K in each pool varies and depends on the past cropping history, past fertilizer and manure use, and soil water content. Potassium present in micas and feldspars (mineral matrix K) is very slowly released by weathering and is not adequate to supply the needs of modern crop cultivars with a large yield potential. Nevertheless, it may be important for long-term K balance of cropping systems.

Johnston and *Mitchell* (1974) and *Syers* (1998) showed that the release of K from the non-exchangeable pool is linearly related to the content of initial K_{ex} and there is a close inverse relationship between the decrease in K_{ex} and the release from the K_{nex} pool. Much current evidence suggests that K_{ex} is a good indicator of the likely response of crops to application of K. However, crops with a poor root system that does little to explore the soil for nutrients will have a lower critical K_{ex} value and respond more to K fertilization than crops with a dense root system. *Johnston* and *Krauss* (1998) showed that the K_{nex} as well as residual K from past applications act as a reserve for K released from weathering of soil minerals.

Potassium availability in soils is largely governed by their mineralogical composition. Thus, K

fertility of soils can be defined with greater precision by a more detailed understanding of the mineralogy of soil K, forms of K, and different kinds of K transformations occurring in the soil (*Bijay-Singh* et al., 2004). *Sekhon* et al. (1992) reported that illite was the dominant clay mineral in a soil series of the NW IGP spread over Punjab, Uttar Pradesh (UP) and Bihar, containing 39－70 mg kg^{-1} K_{ex} whereas in two soils from the lower Gangetic Plain in West Bengal (WB) smectite and kaolinite were the dominant clay minerals, with K_{ex} values of 87 and 27 mg kg^{-1} soil, respectively. The effect of clay mineralogy was also very striking in influencing the K_{nex} content of the soils. The two soils from WB contained only 601 and 98 mg kg^{-1} K_{nex}, whereas all the remaining six soil series showed K_{nex} varying from 1 330 to 2 200 mg kg^{-1} soil. Trends in total K content were also similar to those for K_{nex}, with minimum total K content in soils from WB. These workers also reported that total K in alluvial soils of the IGP in India ranges from 1.23 to 2.75% while the K_{ex} content ranges from 78 to 273 mg kg^{-1} soil.

The extent of weathering of primary K-bearing minerals and the chemical pathways through which weathering takes place as well as the dynamic equilibrium between different K fractions in soils are together responsible for the development of different soil types of varying K-supplying capacity in South Asia. Currently, the major unknown factor is what proportion of the total K requirement of a growing crop is supplied from the K_{nex} pool. *Mukopadhyay* and *Datta* (2001) observed that although continuous cropping without K applications decreased the available K from 166 to 85 kg ha^{-1} in the Punjab soils there was still no response to applied K because 90% of the crop K demand was met by K released from the K_{nex} pool. Similarly *Naidu et al.* (2011) also showed that the K_{nex} can contribute significantly to total crop K-uptake and there may be no response to added fertilizer K when soils rapidly release K from non-exchangeable sources. *Kinekar* (2011) reported that, for 371 districts of India analyzed for K, 76 districts (21%) were low (<130 mg kg^{-1}), 190 (51%) medium (130－335 mg kg^{-1}) and 105 (28%) were high (>335 mg kg^{-1}) in available K. *SrinivasRao* et al. (2010, 2011) grouped the various districts of India into nine categories, considering different combinations of K_{ex} and K_{nex} pools, and suggested different K management strategies for each of these categories. *SubbaRao* et al. (2001) reported findings from 29 soil series, all red and lateritic soils low in available and reserve K. Illite-dominated alluvial soils were medium in available but high in reserve K, whereas vertisols containing smectite clay were high in available but relatively low in reserve K. *Naidu et al.* (2011) reported that in most soils of India, there is negative K balance and these soils are now undergoing K depletion varying in magnitude. *Samra* and *Swarup* (2001) observed that intensive cropping over a long period reduced the K_{ex} to a minimum level at which stage release of K_{nex} began. They further concluded that contribution of the K_{nex} towards total K removal was above 90% in the absence of applied K while it was less than 80% with K fertilization. Under intensive cropping, a concentration gradient is set up between the high concentration of K in the unexpanded region of the clay lattice and the K-depleted and expanded part of the clay.

Soils of Bangladesh contain K_{ex} as low as 0.1 to 0.9 meq kg^{-1} soil in the Barind tract (*Saleque* et al., 1998) to as high as1.7 to 4.3 meq kg^{-1} soil in the Ganges floodplain (*Saleque* et al., 1990; 2009). In the R-M systems practising areas in NW and Central Bangladesh, the K_{ex} content ranges from 1.5 meq kg^{-1} soil in Comilla to 3.2 meq kg^{-1} soil in Rangpur (Timsina, unpublished data). Exchangeable K content is generally higher in the R-W and R-M practising areas in central western districts of Jessore and Jhenaidah (0.7－3.9 meq kg^{-1} soil). The K_{ex} ranges from 0.3 to 1.4 and from 0.9 to 6.9 meq kg^{-1} soil in saline areas of Barisal and Khulna respectively where farmers have started to grow winter maize (Timsina, unpublished data).

The growth environment of crops has a profound effect on K nutrition of R－M systems. Soil solution K is kept at relatively high levels in flooded rice soils because large amounts of soluble Fe^{2+}, Mn^{2+} and NH_4^+ ions brought into solution displace cations from the clay complex, and K_{ex} is then released into the soil solution. The displacement of K from the exchange complex, however, ceases on

return to aerobic conditions prevalent during maize planting. In fields with adequate drainage, K and other basic cations are then lost via leaching. Leaching losses of K can be substantial in highly permeable soils with low cation exchange capacities. *Yadvinder-Singh* et al. (2005b) found that leaching losses of K were 22 and 16% of the applied K respectively in sandy loam and loamy soils maintained at submerged moisture regimes. For Bangladesh such losses can be as high as 0.1 - 0.2 kg K ha^{-1} d^{-1} (*Timsina* and *Connor* 2001). Despite often having a relatively large total K content, the K nutrition of R-M systems grown on the soils of South Asia is not assured, because many heavy textured alluvial floodplain Terai soils of Nepal and northern and eastern India, and soils of Bangladesh contain vermiculite, illite, or other K-fixing minerals (*Dobermann* et al., 1996b, 1998).

3 Potassium balance in long-term experiments on rice-based systems

Long-term experiments (LTEs) on major cropping systems practised in major agro-ecological zones (AEZs) or predominant soil types are useful for understanding yield trends, determining changes in soil physical and chemical properties, estimating nutrient balances and identifying the causes of increase or decline in yield over time. Several of such LTEs exist in India, Bangladesh and Nepal, some for more than 40 years. Results of LTEs currently being conducted in India under the All India Coordinated Research Project on Cropping Systems (AICRP-CS) show progressive increase in response to K fertilizer in both rice and wheat in R-W with greater response in rice (*SubbaRao et al.*, 2001). On most soils, including those with illites as dominant clay minerals, K uptake by crops even at recommended NPK doses is far in excess of fertilizer K applied, indicating inadequate K application and much greater exploitation and depletion of native soil K reserves (*SubbaRao et al.*, 2001; *Tiwari* et al., 1992; *Samra* and *Swarup*, 2001). By citing the work of Yadav et al. (1998), *SubbaRao* et al. (2001) reported that, for 11 cropping systems studied under AICRP-CS, K application ranged from 0 to 100 kg ha^{-1} while the removal ranged from 168 to 483 kg ha^{-1}. For an LTE on R-W in the Punjab, *Bhandari* et al. (2002) also concluded that N and K depletion collectively contributed to a decline in yields of both crops and that increased K input would be required to maintain soil K above sufficiency level and to maintain yields. Likewise, for the R-R system too, there has been a gradual increase in the magnitude of K response over years in locations where there was negative response in initial years. In another set of LTEs conducted over 30 years in different AEZs with diversified cropping systems and soil types, different crops showed significant responses to K application, the effects being more pronounced in Alfisols and acidic Inceptisols (*Samra* and *Swarup*, 2001). After several years of intensive cropping, response to K application occurred even in alluvial soils dominated by K-bearing illites. On some soils, crops responded to K only after a few years of cropping because of a wide spatial K distribution and its exploitation by roots whereas on other soils yield declined from the beginning.

In an LTE on a rice-rice-wheat system conducted over 30 years in Bhairahawa, Nepal, the yield of the first rice crop, fertilized with recommended NPK fertilizers or farmyard manure (FYM), declined by an average of 0.09 t ha^{-1} yr^{-1} and wheat yield declined by 0.05 t ha^{-1} yr^{-1}. This was because the available K content of soil declined and the apparent K balance showed net losses of 63.2 and 15.2 kg K ha^{-1} yr^{-1} with NPK and FYM treatments, respectively. The yield of the second rice crop, however, did not decline after 20 years due to increased P and K availability under continuous submergence during the monsoon season when the second rice was grown (*Regmiet al.*, 2002b). In another LTE on R-W also in the same location, yields of both crops declined with time and both crops responded to K application, but there was a substantially higher response of wheat (*Regmiet al.*, 2002a). These studies suggest that depletion of native soil K and inadequate K fertilization are the main reasons for declining yields of the first rice and wheat in the first LTE and that of wheat in the second LTE.

In an LTE on R-R at Gazipur in Central Bangladesh, *Miah* et al. (2008) reported that rice grain

yield decreased sharply in a clay loam soil from about 10 t ha^{-1} in 1985 to 6.2 t ha^{-1} in 2000 in the K omission plots while K application at 50 kg ha^{-1} resulted in positive K balance and maintained yield of both rice crops. In another LTE on R-W in sandy loam soil in NW Bangladesh, 54 kg K ha^{-1} were needed to maintain positive K balance and yield levels of both crops (*Miah* et al., 2008). In another study also on R-W in NW Bangladesh (*Miah* et al., 2008), application of 54 kg K ha^{-1} increased average grain yield of rice and wheat by 25%-30% and 53%-86%, respectively, across a range of demonstration plots in farmers' fields. Crop residue incorporation alone increased grain yield of both crops by 20%-21% in K omission plots.

Maize hybrids grown in the winter season in Bangladesh have an attainable grain yield of about 10-12 t ha^{-1}, with similar amount of non-grain biomass. To obtain such high yields, maize plants generally take up around 200 kg N, 30 kg P, 167 kg K and 42 kg S ha^{-1}. Farmers, on the other hand, apply imbalanced fertilizers, with a high amount of N and low amounts of P, K, S and micronutrients. In the R-M system in Bangladesh, the apparent nutrient balances have been highly negative for N and K (−120 to −134 and −80 to −109 kg ha^{-1}, respectively), while the P balance has been positive (15 to 33 kg ha^{-1}; *Ali* et al., 2009). Other nutrient depletion-replenishment studies in the R-W systems in Bangladesh have also shown negative balances for N (*Timsina* et al., 2006) and K (*Panaullah* et al., 2006) but positive balance for P (*Saleque* et al., 2006).

A 5 yr experiment on the rice-soybean-rice, soybean-rice-maize, and rice-rice-maize systems with seven combinations of N, P, K and FYM in the Red River Delta in northern Vietnam showedthat K was the most yield-limiting nutrient and that regular K applications were required to make investments in the application of other mineral nutrients profitable. In the absence of K application, the average yield gap for rice ranged from 1.2 to 2.2 t ha^{-1} depending on season. For soybean and maize, the yield gap resulting from K omission averaged 0.9 and 3.4 t ha^{-1}, respectively. The application of FYM increased grain yield and K balances more in upland crops than in rice (*Mussgnug*, 2006).

The results from various LTEs on intensive rice-based systems suggest that K in all the LTE sites is continuously being mined resulting in negative balance and that fertilizer K recommendations for crops should take into consideration the non-exchangeable fraction of soil K.

4 Role of crop residues in potassium supply to crops

Crop residues contain large quantities of K, and their recycling can markedly increase K availability in soils (*Chatterjee* and *Mondal*, 1996; *Sarkar* et al., 1997). Recycling of crop residues can improve crop yields at low rates of K application and can decrease crop response to applied K. *Yadvinder-Singh* et al. (2004) reported that release of K from rice straw occurred at a fast rate, and available soil K content increased from 50 mg kg^{-1} soil in the untreated control to 66 mg kg^{-1} soil in straw-amended treatments within 10 d after incorporation. *Tiwari* et al. (1992) also reported that most of K in the rice residue was released in less than 41 d while *Sarkar* et al. (1997) concluded that the amount of K released from organic materials in the first month was highly correlated with the water-soluble K. *Mishra* et al. (2001) reported that about 79% of total K in rice straw was mineralized within 5 weeks after incorporation and 95.3% by the end of 23 weeks. *Yadvinder-Singh* et al. (2010) reported that 85%-88% of K from buried rice residue had been released at maximum tillering while more than 97% at the end of the decomposition cycle during the wheat season. In contrast, release of K from surface-retained residue averaged about 76%. Thus rice residues can supply a substantial amount of K to the succeeding wheat or maize.

To understand better the K response under different tillage and residue management situations, we analyzed data from a field experiment conducted from 2007/08 to 2009/10 at Modipuram (29°4′N, 77°46′E) in NW India to investigate three methods of tillage and crop establishment. The tillage methods

were: transplanted puddled rice followed by conventionally tilled maize, (TPR-CTM); conventionally tilled direct-seeded rice followed by CTM, (CTDSR-CTM); and zero-tilled DSR followed by zero-tilled maize (ZTDSR-ZTM). There were two rates of K (0 or 62 kg K ha^{-1}) together with two residue levels, the residues of both crops being either fully removed or partially retained with 5 tresidue ha^{-1} of each crop on the surface. The soil of the experimental site was a TypicUstochrept sandy loam with a medium level of soil K_{ex} (113 mg kg^{-1} soil) content. Mean rice yield response to K of the residue management treatments was highest with TPR-CTM (610 kg ha^{-1}) compared with responses under CTDSR-CTM and ZTDSR-ZTDSM (Tab 1). Mean yield response to K of the residue management treatments of the succeeding maize was 735, 410 and 345 kg ha^{-1}, respectively, for the three tillage and crop establishment methods. Mean K response for rice and maize was comparatively higher for residue removal (623 to 637 kg ha^{-1}) than residue retention (287 to 370 kg ha^{-1}). Growing DSR also had a pronounced effect on K response of succeeding CTM. Compared with TPR-CTM, maize yield response to K after DSR declined by 43.6% and 44.6% in the residue removed and retained plots, respectively. Despite residue retention there was still reasonable K response under all tillage and crop establishment systems indicating that K released from soil and applied as K fertilizer was not enough to meet crop demand.

Table 1 Response of rice and maize (kg ha^{-1}) to K application with different crop establishment practices and residue management options under R-M system. PDFSR, Modipuram, India (2007/08-2009/10).

Crop establishment technique	Response to K		Mean response to K
	Residue removed (−R)	Residue retained* (+R)	
	Rice		
TPR-CTM§	830	390	610
CTDSR-CTM	630	260	445
ZTDSR-ZTM	450	210	330
Mean K response	637	287	462
	Maize		
TPR-CTM	920	550	735
CTDSR-CTM	510	310	410
ZTDSR-ZTM	430	250	340
Mean K response	620	370	495

* In TPR-CTM maize residue was incorporated before rice transplanting

§ TPR = Transplanted puddle rice, CTDSR = Conventional-till, direct seeded rice, ZTDSR = No-till, direct-seeded rice, CTM = Conventional till maize, ZTM = No-till maize

Buresh et al. (2010) reported that for R-M with 5 t ha^{-1} rice and 12 t ha^{-1} maize yield, the retention of maize residues can markedly reduce the net K export but does not eliminate the deficit in K balance when rice residues are not retained. Retention of all maize and rice residues is required to achieve near-neutral K balances. The R-M system of South Asia with much higher maize yield than wheat or rice yield in the winter season is more extractive of nutrients, particularly K, than R-R or R-W. Hence residue retention is necessary to sustain the soil fertility and productivity of the R-M systems. Nevertheless, since farmers in South Asia generally remove residues from their fields, modest rates of K fertilizer together with some crop residues need to be applied to optimize K nutrition and to prevent K mining from the soil.

Bijay-Singh et al. (2008) have proposed a simplified "decision tree" to illustrate guidelines for managing residues in rice-based cropping systems. They suggest that for the systems in which residues from rice or a non-flooded crop are retained or incorporated to ensuing rice, the management of the residues depends upon whether the soil was puddled during the recipient rice crop. For the non-puddled rice production, they recommend a no-till system in which the residues are left on the surface as mulch. For puddled rice production, where crop residues can not readily be used as mulch, however, the residue of the preceding maize crop can typically be safely removed from the field without any loss in

productivity or sustainability of the system. However, an appropriate increase in fertilizer addition, particularly K, is required to compensate for nutrient removal in the residues.

5 Rice-maize systems

This section presents grain-yield response and agronomic use efficiency of K of rice and maize in four experiments on R-M systems in India and Bangladesh. Two experiments in India were conducted in several farmers' fields in Sabour, Bhagalpur, Bihar and in Bangalore, Karnataka; a further experiment was carried out at the research station in Sabour, Bhagalpur. In Bangladesh, one experiment was carried out in several farmers' fields in three districts of the country.

5.1 On-farm trials in Bhagalpur, Bihar, India

Twelve on-farm trials were conducted during 2006-07 in Sabour, District Bhagalpur (25°15′N, 87°1′E) of Bihar state. Four treatments were compared: (i) farmers' fertilizer practice (FFP); (ii) FFP+62 kg K ha^{-1} (FFP+K_{62}); (iii) FFP+K_{62}+40 kg S ha^{-1}+5 kg Zn ha^{-1} (FFP+K_{62}+S_{40}+Zn_5); (iv) FFP+S_{40}+Zn_5. The same rate of K was applied to both crops while S and Zn were applied to rice only. The average use of fertilizer by farmers (FFP) of the locality was 80 kg ha^{-1} N and 23 kg ha^{-1} P in rice and 100 kg ha^{-1} N and 23 kg ha^{-1} P in maize while K application was negligible. Inclusion of K in the FFP significantly ($p \leqslant 5\%$) increased rice yield by 1.8 t ha^{-1} while such increase due to K application over FFP+S+Zn was 3.02 t ha^{-1} (Tab. 2). Although the information on conjoint use of K, S and Zn in rice in farmers' field is not available in the Indo-Gangetic Plain (IGP), several on-station studies have revealed the pronounced effect of deficient macro and micro-nutrients on rice productivity (*Singh* et al., 2008). The significant increase in rice yield due to K application observed in this experiment is in contrast to an earlier assumption that the release of native K from illitic clay minerals of the soils of the IGP is sufficient to meet the K needs of the crops (*Bijay-Singh* et al., 2004). These results, however, corroborate findings from recent on-station studies conducted under the aegis of the AICRP-CS at seven locations on the IGP, which showed that the high-yielding cultivars of rice required fertilizer K ranging from 75 to 101 kg ha^{-1} for attaining maximum economic yield (*Tiwari* et al., 2006). Application of 62 kg ha^{-1} K increased ($p \leqslant 5\%$) maize yield over FFP by 0.83 t ha^{-1} and over FFP+S+Zn by 1.31 t ha^{-1} (Tab. 2). The productivity of R-M, measured in terms of maize equivalent yield for the system (SMEY), increased significantly with K or conjoint use of K+S+Zn. Use of 62 kg K ha^{-1} over FFP produced additional SMEY by 2.82 t ha^{-1} ($p \leqslant 5\%$). The SMEY with K+S+Zn, on the other hand, was greater (4.64 t ha^{-1}) compared to their application individually. The FFP in R-M as recorded in this study, as well as in earlier surveys (*Dwivedi* et al., 2001), reveals that farmers applied greater than recommended rates of N along with optimum to sub-optimum rates of P, but largely ignored the application of other nutrients particularly K which resulted in K mining and increased crop response to K.

Table 2 On-farm productivity of rice, maize and R-M systemas influenced by SSNM under R-M system at Sabour, Bhagalpur, Bihar.

Treatment	Rice yield (t ha^{-1})	Increase over FFP (%)	Maize yield (t ha^{-1})	Increase over FFP (%)	System-level maize equivalent yield, SMEY (t ha^{-1})
FFP*	5.21	—	6.75	—	12.49
FFP+K_{62}	7.01	34.55	7.58	12.30	15.31
FFP+K_{62}+S_{40}+Zn_5	8.23	57.97	8.06	19.41	17.13
FFP+S_{40}+Zn_5	6.07	16.51	7.26	7.56	13.95
CD ($p \leqslant 5\%$)	0.83	—	0.54	—	1.23

* FFP=80 kg ha^{-1} N and 23 kg ha^{-1} P in rice and 100 kg ha^{-1} N and 23 kg ha^{-1} P in maize; data are means of 12 farmers fields (AICRP-CS Report, 2007-10).

Potassium application over FFP decreased initial KCl-extractable soil available N and Olsen P content by 14 mg kg^{-1} and 1.7 mg kg^{-1}, respectively, after one R-M cycle (Tab. 3). Available N and Olsen P content also declined as a result of Zn+S application, with higher decline when K+S+Zn were applied. Greater mining of soil N due to increased biomass production and consequently higher N uptake could be the reason for such a decline in available N content. Long-term experiments on R-W support these results as the available N content generally decreased with the inclusion of K along with NP (*Hedge* and *Dwivedi*, 1992).

Table 3 Changes in soil N, P, K, S and Zn content (mg kg^{-1}) due to K, S and Zn application after one R-M cycle at Sabour, Bhagalpur, Bihar.

Treatment	Available N		Available P		Exchangeable K		Extractable S		DTPA-Zn	
	After 1 RM cycle	Change over initial*	After 1 RM cycle	Change over initial*	After 1 RM cycle	Change over initial*	After 1 RM cycle	Change over initial*	After 1 RM cycle	Change over initial*
FFP	119.0	8.0	12.6	0.9	97.3	−5.0	16.3	−2.3	3.8	−0.4
FFP+K_{62}	105.0	−6.0	10.9	−0.8	111.2	8.9	15.8	−2.7	3.6	−0.6
FFP+K_{62}+S_{40}+Zn_5	101.0	−11.0	10.2	−1.5	107.3	5.0	21.5	3.0	4.5	0.3
FFP+S_{40}+Zn_5	108.0	−3.0	12.1	0.4	96.1	−6.2	23.2	4.7	4.5	0.3

* Initial soil content for KCl-extractable available N, Olsen-P, 1M NH_4OAc-extractable K, 0.15% $CaCl_2$-extractable S and DTPA-Zn was 111 mg kg^{-1}, 11.7 mg kg^{-1}, 102.3 mg kg^{-1}, 18.5 mg kg^{-1} and 4.2 mg kg^{-1}, respectively (AICRP-CS Report, 2007-10)

Soil K_{ex} content improved with K fertilization alone (13.9 mg kg^{-1}) or in combination with S and Zn (10 mg kg^{-1}), whereas a moderate decline in K_{ex} (1.2 mg kg^{-1}) was noticed with S+Zn application over FFP. Available S and Zn contents, averaged across K treatments, were greater for S+Zn and the magnitude of increase over FFP was 6.05 mg kg^{-1} and 0.7 mg kg^{-1}, respectively. Fertilizer K input on the other hand, resulted in significant decline in S and Zn contents after the completion of one R-M cycle (Tab. 3). Application of K or K+S+Zn in R-M enhanced K_{ex} as compared with the initial content, increasing it from 5.0 to 8.9 mg kg^{-1} (Tab. 3). On the other hand, omission of K from fertilizer schedule resulted in a decline of K_{ex} (−5.0 to −6.2 mg kg^{-1}). The apparent differences in K_{ex} content for no−K and+K was 10.0 to 15.1 mg kg^{-1}. The decline in K content under no−K revealed that higher rates of N (>180 kg ha^{-1}) and optimal to suboptimal rates of P (20 - 26 kg P) used by the farmers encouraged K mining from soil and adequate input was essential to prevent or at least mitigate this adverse effect of imbalanced fertilizer use. *Tandon* and *Sekhon* (1998) reported earlier that applications of N alone increased K uptake by 57% over control, and N and P applications together increased the K uptake by 145%. The K extraction is especially large in R-W and R-M because straw is often harvested along with grain, for its competitive use as thatching material, fuel, or animal feed, or burnt to facilitate tillage (*Timsina* and *Connor*, 2001). To overcome such K mining, adequate amounts of K fertilizer need to be used.

5.2 On-farm trials in Bangalore, Karnataka, India

On-farm trials (24 each in 2008-09 and 2009-10) were conducted in Bangalore (12°8′N, 77°37′E), Karnataka with four treatments (control; 100 kg N ha^{-1}; 100 kg N ha^{-1} and 10 kg P ha^{-1}; 100 kg N ha^{-1} and 35 kg K ha^{-1}; 100 kg N ha^{-1}, 10 kg P ha^{-1} and 35 kg K ha^{-1}). Results showed that application of recommended doses of NPK (100, 10, 35 kg N, P and K, respectively) to rice produced grain yield of 4.26 and 5.80 t ha^{-1} during 2008-09 and 2009-10, respectively (Tab. 4). Omission of P or K fertilizers caused a yield loss of 0.6 to 0.9 t ha^{-1} and 1.0 to 1.02 t ha^{-1}, respectively. Agronomic response to P and K application was between 45.5 to 46.4 and 13.8 to 21.4 kg grain kg^{-1} for P and K, respectively. Similar response to P and K over N alone was 19.1 to 69.5 kg kg^{-1} for P and 7.6 to 26 kg kg^{-1} for K.

Table 4 On-farm yield and agronomic efficiency of N, P and K in rice and maize under R-M system in Bangalore, Karnataka, India (AICRP-IFS report, 2009-11); data are means of 24 farmers' fields in each year.

Treatment	2008-09	2009-10	Treatment	2008-09	2009-10
	Rice yield (t ha^{-1})			Maize yield (t ha^{-1})	
Control	2.23	2.50	Control	1.98	2.45
N_{100}	2.94	3.69	N_{150}	2.87	3.49
N_{100} P_{10}	3.36	5.22	N_{150} P_{15}	4.29	5.27
N_{100} K_{34}	3.26	4.78	N_{150} K_{27}	3.87	4.67
N_{100} $P_{10}K_{34}$	4.26	5.80	N_{150} P_{15} K_{27}	6.22	7.09
CD ($p \leqslant 0.05$)	0.22	0.24	CD ($p \leqslant 5\%$)	0.28	0.2
	Agronomic efficiency (kg grain kg^{-1} nutrient)			Agronomic efficiency (kg grain kg^{-1} nutrient)	
N over control	7.1	11.9	N over control	7.9	6.9
P over N	19.1	69.5	P over N	43.0	53.9
K over N	7.6	26.0	K over N	30.3	35.8
P over NK	45.5	46.4	P over NK	71.2	73.3
K over NP	21.4	13.8	K over NP	58.5	55.2

Like rice, maize grain productivity was also at a maximum under the plots treated with recommended doses of NPK (6.22 to 7.09 t ha^{-1}). Omission of P or K resulted in significant ($p \leqslant 5\%$) yield loss of 2.35 to 2.42 t ha^{-1} and 1.82 to 1.93 t ha^{-1}, respectively over the 2 years (Tab. 4). At these response levels, agronomic efficiency of P and K was 71.2 to 73.3 kg kg^{-1} and 55.2 to 58.5 kg kg^{-1}, respectively. These results agree closely with the recent on-farm study by *Majumdar* et al. (2012) in which yield loss due to omission of K application to rice and maize was of 90 - 1 806 kg ha^{-1} (mean: 622 kg ha^{-1}) and 140 - 1 320 kg ha^{-1} (mean: 700 kg ha^{-1}), respectively. Further, considerable increase in agronomic efficiency of P and K may be visualized as P ×K interaction as reported by *Tiwari* (2002), which reveals that efficiency of applied P increased with increasing initial available K status of soils. Responses to P were generally higher in high-K soils followed by medium and low-K soils. Thus, to obtain full benefit from P fertilization and to maintain high soil K status, adequate K supply should be ensured.

5.3 On-station experiment at Bhagalpur, Bihar, India

Site-specific nutrient management (SSNM) options (see Section 5 for details) for rice and maize in the R-M systems were investigated under on-station experimentation from 2006-07 to 2008-09 at Sabour, Bhagalpur (25°15′N, 87°1′E), Bihar. Eight treatments were compared: three levels of P (0, 13 and 26 kg ha^{-1}) and three levels of K (0, 42, and 83 kg ha^{-1}) to both crops; four levels of S (0, 20, 40, 60 kg ha^{-1}) to rice only; and 150 kg N ha^{-1} to both crops. The recommended doses of fertilizer for Bihar state (state recommendation-SR) were 100 kg N, 18 kg Pand 17 kg K ha^{-1} in rice and 120 kg N, 33 kg ha^{-1} P and 42 kg K ha^{-1} in maize while the average fertilizer used by the farmers (FFP) in the area was 70 kg N, 15 kg P and 8 kg K ha^{-1} in rice and 100 kg N, 13 kg P and 17 kg K ha^{-1} in maize (see Tab. 5 for treatment combinations). Initial available N, Olsen-P, exchangeable K, and extractable S of the experimental site were 134 kg ha^{-1}, 31.1 kg ha^{-1}, 185 kg ha^{-1} and 22 kg ha^{-1}, respectively. The results revealed that application of 150 kg N, 13 or 26 kg P, and 83 kg K to each crop along with 40 kg ha^{-1} S to rice only (SSNM treatments 1 and 2) gave highest productivity of the individual crops and of the system. Comparing these treatments with SR and FFP, the productivity gain of rice, maize and R-M with SSNM was 1.09, 0.58 and 1.79 t ha^{-1}, respectively, over SR and 2.38, 1.43, and 4.06 t ha^{-1}, respectively, over FFP (Tab. 5). These results corroborate very well with earlier work on the rice-based systems by *Singh* et al., (2011) where the advantages of SSNM over SR and FFP were mainly attributed to a favorable balance and adequate application of limiting nutrients. In the experiments reported here, gradient doses of K application in SSNM brought significant yield gain over no-K application in both crops as well as for the total system of about 16.7 to 20.5%, 15.1 to 19.1% and

15.9 to 19.8%, respectively. Total N, P, and K uptake increased with increasing K application rate in rice, maize and R-M system (Tab. 6). Application of 42 kg K ha^{-1} caused significant ($p \leqslant 5\%$) increase in total uptake of N and K over no-K and magnitude of increase was 15.1, 21.6 and 18.6% for N and 31.2, 20.1, and 25.2% for K in rice, maize and R-M system, respectively. Although the highest N and K uptake were recorded at 83 kg K ha^{-1} K application, this was not significant ($p \leqslant 5\%$) beyond 42 kg ha^{-1}. On the other hand, increase in total P uptake was significant ($p \leqslant 5\%$) only at 83 kg ha^{-1} K application over no-K. These results are in agreement with those of *Kinekar* (2011) who reported that for rice, wheat and maize that N uptake is 20, 25 and 29.9 kg t^{-1} grain while K uptake was 30, 33 and 32.8 kg t^{-1} grain, respectively. Balanced fertilization with K thus not only increased rice and maize productivity but also helped to mitigate N and P stresses by increasing uptake of these nutrients.

Table 5 Productivity of rice, maize and R-M system as influenced by different SSNM options at Sabour, Bhagalpur, Bihar (Means over 3 years)

Nutrient rates(kg ha^{-1})	Rice ($t\ ha^{-1}$)	Maize ($t\ ha^{-1}$)	System-level maize equivalent yield (SMEY)
$N_{150}\ P_{13}\ K_{83}S_{40}$	7.42	7.99	16.16
$N_{150}\ P_{26}\ K_{83}\ S_{40}$	7.78	8.55	17.13
$N_{150}\ P_{0}\ K_{83}S_{40}$	6.38	6.91	13.94
$N_{150}\ P_{13}\ K_{42}\ S_{40}$	7.19	7.72	15.65
$N_{150}\ P_{13}\ K_{0}\ S_{40}$	6.16	6.71	13.49
$N_{150}\ P_{13}\ K_{83}\ S_{60}$	7.46	8.18	16.39
$N_{150}\ P_{13}\ K_{83}\ S_{20}$	6.96	7.65	15.33
$N_{150}\ P_{13}\ K_{83}\ S_{0}$	6.66	7.49	14.83
State recommendation (SR)*	6.32	7.40	14.37
Farmers fertilizer practices (FFP)	5.03	6.55	12.10
CD ($p \leqslant 5\%$)	0.61	0.67	1.54

* SR=100 kg N, 16 kg P and 17 kg K ha^{-1} in rice and 120 kg N, 33 kg ha Pand 42 kg K ha^{-1} in maize; FFP=70 kg N, 15 kg P and 8 kg K ha^{-1} in rice and 100 kg N, 13 kg P and 17 kg K ha^{-1} in maize (AICRP-CS Report, 2007-10)

Table 6 N, P, and K uptake in rice, maize and R-M system as influenced by K fertilization at Sabour, Bhagalpur, Bihar (mean over 3 years). All nutrients were applied both to rice and maize except S which was applied to rice only (AICRP-CS Report, 2007-10)

Nutrient rates ($kg\ ha^{-1}$)	Rice	Maize	R-M system
	N uptake ($kg\ ha^{-1}$)		
$N_{150}\ P_{13}\ K_{83}\ S_{40}$	136.8	192.6	329.5
$N_{150}\ P_{13}\ K_{42}\ S_{40}$	134.9	187.6	322.3
$N_{150}\ P_{13}\ K_{0}\ S_{40}$	118.9	158.2	277.0
CD ($p \leqslant 0.05$)	15.3	22.3	41.5
	P uptake ($kg\ ha^{-1}$)		
$N_{150}\ P_{13}\ K_{83}\ S_{40}$	50.5	63.8	114.3
$N_{150}\ P_{13}\ K_{42}\ S_{40}$	48.2	58.1	106.3
$N_{150}\ P_{13}\ K_{0}\ S_{40}$	43.7	55.3	99.0
CD ($p \leqslant 5\%$)	4.7	7.8	11.4
	K uptake ($kg\ ha^{-1}$)		
$N_{150}\ P_{13}\ K_{183}\ S_{40}$	178.1	231.1	409.2
$N_{150}\ P_{13}\ K_{42}\ S_{40}$	159.1	212.9	372.0
$N_{150}\ P_{13}K_{0}\ S_{40}$	135.7	191.2	326.9
CD ($p \leqslant 5\%$)	21.1	20.7	41.4

Agronomic efficiency (AE) for P increased in rice, maize and R-M system with increasing K rates. On the other hand, AE for K declined with increasing K rates (Tab. 7). Recovery efficiency (RE) measured to assess the proportion of total nutrient applied being utilized by the crops also indicated that

RE for P was highest at the highest K level while RE for K was highest at the lowest K level. These results are consistent with the results of other experiments, in which recommended NPK fertilization increased annual productivity and fertilizer use-efficiency over N or NP alone (*Swarup* and *Wanjari*, 2000; *Tiwari* et al., 2006).

Table 7 Agronomic efficiency and recovery efficiency of phosphorus and potassium as influenced by gradient rates of K application under R-M system at Sabour, Bhagalpur, Bihar (mean over 3 years). All nutrient doses were used to rice and maize both except S which was applied to rice only (AICRP-CS Report, 2007-10).

Nutrient rates (kg ha^{-1})	Agronomic efficiency (kg grain kg^{-1} nutrient)			Recovery efficiency (%)		
	Rice	Maize	System	Rice	Maize	System
			Phosphorus			
N_{150} P_{13} K_{83} S_{40}	65.9	82.8	85.5	35.6	72.6	54.1
N_{150} P_{13} K_{42} S_{40}	52.8	62.6	65.9	18.9	29.6	24.3
			Potassium			
N_{150} P_{13} K_{13} S_{40}	15.2	15.4	16.1	51.1	48.0	49.6
N_{150} P_{13} K_{42} S_{40}	25.0	24.5	26.0	56.3	52.3	54.3

Application of gradient rates of K exerted a significant influence on various soil-fertility parameters (Tab. 8). Irrespective of treatments, the KCl-extractable available N, Olsen-P and $CaCl_2$-extractable S contents in soil increased over their initial status after 3 R-M cycles, however, a declining trend was noticed with increasing K rates. Highest contents of available N, Olsen-P, and extractable S were recorded in the no-K treatment where the K_{ex} content was lowest. Greater mining of soil N, P and S due to increased biomass production and higher uptake of N, P and S content with +K compared with no-K may be the reason for the decline in soil N, P and K content. Further, the AE and RE of P were greater when 83 kg were applied along with N, P and S. Such results indicate that balancing K supply in the fertilization schedule triggers the efficiency of other nutrients (N, P and S in the present case) and that crops utilize the available nutrients more efficiently. These results are consistent with findings of other workers (*Dwivedi* et al. 2011; *Tiwari* et al., 2006).

Table 8 Changes in soil fertility parameters after 3 years of R-M cropping with variable K rates at Sabour, Bhagalpur, Bihar. All nutrients were used both to rice and maize except S which was applied to rice only. Initial available N, Olsen-P, 1M NH_4OAc extractable K and 0.15% $CaCl_2$ extractable S were 134 kg ha^{-1}, 14 kg ha^{-1}, 154 kg ha^{-1}, 22 kg ha^{-1} (AICRP-CS Report, 2007-10).

Nutrient rates (kg ha^{-1})	Available N		Available P		Exchangeable K		Extractable S	
	After 3 R-M cycle (kg ha^{-1})	Change over initial (%)	After 3 R-M cycle (kg ha^{-1})	Change over initial (%)	After 3 R-M cycle (kg ha^{-1})	Change over initial (%)	After 3 R-M cycle (kg ha^{-1})	Change over initial (%)
$N_{150}P_{13}K_{83}S_{40}$	188.3	40.5	34.7	11.6	207.8	12.3	25.7	16.8
$N_{150}P_{13}K_{42}$ S_{40}	191.2	42.7	36.4	17.0	198.9	7.5	26.8	21.8
$N_{150}P_{13}K_0$ S_{40}	202.5	51.1	38.5	23.8	188.5	1.9	28.2	28.2
CD ($p \leqslant 5\%$)	11.8	—	3.0	—	15.1	—	1.0	—

5.4 On-farm trials on SSNM in R-M systems in Bangladesh

SSNM studies on R-M systems have been conducted for the past 4 years in several farmers' fields at three districts in Bangladesh. The District Comilla (23°28′N; 91°10′E) lies in the central eastern part while the districts Rajshahi (24°22′N; 88°39′E) and Rangpur (25°42′N; 89°22′E) lie in NW part of the country. At all sites, winter maize was planted after monsoon rice. In Comilla and Rangpur, the soils were quite acidic (pH 5.6) but those in Rajshahi were slightly alkaline. Organic carbon was higher in

Rajshahi (0.88%) than in the other two districts (0.75%-0.78%). Total N in all districts was quite low, with 0.1% in Comilla and 0.06% in the other two districts. Available P in all districts showed relatively higher values (26.7 to 46.8 mg kg^{-1}) than the critical level of 14 mg kg^{-1} for aerobic crops. Exchangeable K in the soils of Comilla and Rajshahi were 0.15 and 0.19 cmol kg^{-1} (more than the critical level of 0.1 cmol kg^{-1} for lowland rice and less than 0.2 cmol kg^{-1} for upland crops) while the Rangpur soils contained a very high level of K (0.32 cmol kg^{-1}).

On-farm omission plot trials on winter maize after rice tested the effect of nutrient omission and reduced doses of P and K on maize yield in all the three districts (Tab. 9). N, P, and K were applied at 255, 74, and 200 kg ha^{-1}, respectively, in the full NPK treatment at all sites. Omission of K decreased maize yield significantly at all sites in both years, with highest reduction in Comilla. The yields were maintained or just slightly reduced by application of a low level of K (-70% of the full rate; Tab. 9). In both years, available K poorly explained the yield of maize in -K treatments (Timsina, unpublished data).

Table 9 Grain yield (t ha^{-1}) of winter maize grown after rice in omission plot trials, ACIAR R-M and IPNI project sites, Bangladesh*.

Treatment	2009-10			2010-11		
	Comilla (n=18)	Rajshahi (n=9)	Rangpur (n=5)	Comilla (n=17)	Rajshahi (n=17)	Rangpur (n=8)
-K	5.3	7.8	7.5	3.4	6.7	6.0
NPK	8.3	9.3	8.3	9.0	8.8	8.1
NK Low P	8.0	8.2	7.7	8.7	8.0	6.0
NP Low K	7.9	8.5	7.3	9.0	7.7	5.8
N Low PK	7.9	8.8	6.8	8.8	7.7	5.7
CD($p \leqslant 5\%$)	0.8	0.6	1.2	0.7	0.5	0.9

* N, P, and K rates for the full NPK treatment are 240, 75 and 199 kg ha^{-1}, respectively. Low P and low K rates are 44 and 141 kg ha^{-1} Pand K, respectively.

The response of maize to applied N, P, and K varied in both years and the response was variable among farmers' fields within a district in each year. In 2009-10, there was a more than 3 t ha^{-1} response to K in more than 60% fields in Comilla while such response was only in about 20% fields in the other two districts. In 2010-11, all fields in Comillaand 50%-60% fields in the other two districts showed > 3 t ha^{-1} response (data not shown). Comilla had the lowest level of soil K_{ex} and hence response was highest. In both years, the agronomic efficiency of K (AE_K, kg grain kg^{-1} K applied) varied widely across districts as well as across farmers' fields within a district. AE_K in the individual fields ranged from 0.2 to 29.4 kg grain kg^{-1} K applied in the first and from 0 to 38.3 in the second year. The mean AE_K in the three districts ranged from 4.1 (Rangpur) to 15.4 kg grain kg^{-1} K applied (Comilla) in the first and from 10.1 (Rangpur) to 28.2 kg grain kg^{-1} K applied (Comilla) in the second year (data not shown). These results demonstrate high variability in grain yield of winter maize grown after rice across farmers' fields in Bangladesh and also remarkably high yield response to K in all districts, especially in Comilla. Comilla is also the district with the lowest level of exchangeable K and highest agronomic efficiency of applied K. Under these conditions if K fertilizer is not applied to winter maize according to crop demand, a tremendous yield loss will result accompanied by a decline in soil K-supplying capacity, and ultimately unsustainability of R-M systems.

6 Field-specific potassium management

The SSNM approach provides an opportunity to manage nutrients in a spatially and temporally variable manner in a production system. In small-scale production systems in Asia, this translates into managing nutrients in a field-specific manner. SSNM could be implemented through a soil test-based

approach or by a plant-based approach where actual crop responses under nutrient limitations are used as indirect estimates of soil nutrient-supplying capacities. In the plant-based approach, *Witt* et al. (1999) used the QUEFTS (QUantitative Evaluation of the Fertility of Tropical Soils) model developed by *Janssen* et al. (1990) to develop the generic relation between grain yield and nutrient accumulation in above-ground biomass and to predict nutrient requirement to achieve pre-determined yield goals (*Witt et al.*, 1999). They reported that 14.7 kg N, 2.6 kg P and 14.5 kg K in rice plants would be needed to produce 1 t grain yield of rice (referred to as reciprocal internal efficiencies, RIE) based on 60%-70% of yield potential. These values were subsequently combined with estimation of attainable yield, nutrient balances, and probable yield gains from added nutrient to determine field-specific fertilizer requirements for rice (*Witt and Dobermann*, 2004). Subsequently, *Buresh et al.* (2010) used several data sets from South and Southeast Asia and reported that 14.6 kg N, 2.7 kg P and 15.9 kg K in rice plants would be needed to produce 1 t grain yield of rice, also based on 60%-70% of yield potential. *Witt et al.* (2009) also used the SSNM approach for maize in Indonesia, Philippines and Vietnam. For maize, based on data sets from Nebraska (USA), Indonesia and Vietnam (*Setiyono* et al., 2010), *Buresh* et al. (2010) reported that 2.56 kg P and 17.4 kg K would be needed to produce 1 t grain yield of maize based on 80% of climate-adjusted yield potential of 14 t ha^{-1}. The K requirements to produce 1 t yield of rice or maize grain as reported by *Witt* et al. (1999) and *Buresh* et al. (2010) are smaller than 19.5 to 38.0 kg K required for rice and 13.2 to 30 kg K required *for* maize(*SubbaRao* et al., 2001) and 30 kg K for rice and 32.9 kg K for maize (*Naidu* et al., 2011) for different soils and locations of India. Obviously, crop requirement of nutrients to produce one unit amount of grain varies depending on soil, climate, and variety.

Buresh et al. (2010) developed several equations to estimate K balances in agricultural fields and recommended site-specific K fertilizer rates for single crops as well as cropping systems involving cereals. The essential components of such K-balance calculations included contributions (inputs) from retained residues, irrigation water and added organic matter, and loss (output) of K from the system through leaching and export through straw and grain of the crops. Farmers in the NW IGP, often use excessive irrigation water, which contains high amounts of K. *Singh* et al. (2012) reported that under intensively cultivated R-W in the NW IGP, the K input through irrigation water was in the order of 85 kg ha^{-1} $cycle^{-1}$. At the same time, the soils in this area are light-textured and percolation losses are quite high. This means that the potential for loss of K, added through irrigation water and released from K_{nex} pools of minerals, through percolation can also be high. *Buresh* et al. (2010) reported that the K balance can be negative even at an estimated addition of 125 kg K ha^{-1} from irrigation water if only 15% of the residues of both rice and wheat are retained in the field and can be neutral only at 100% retention of rice residues with similar addition of K through irrigation water. This suggests that the K balance in R-W or R-M in South Asia, where the system grain yield can reach 15 - 20 t ha^{-1} with equivalent amount of non-grain biomass, could be highly negative even with high addition of K through irrigation water. Hence external addition of K is required to sustain productivity and the high variability in K content inirrigation water and in residue management across the IGP will require site-specific estimation of K balance for the R-W or R-M system.

Witt and *Dobermann* (2004) suggested that expected yield gain from the added nutrient or estimated nutrient balance can be used to determine fertilizer K requirements to achieve a targeted yield. In the yield gain approach, the fertilizer K required to achieve a targeted yield is a function of the expected yield gain from the added nutrient, the reciprocal internal efficiency (RIE) for the nutrient, and the use efficiency of the nutrient. Fertilizer K requirement to achieve a targeted yield can also be estimated through nutrient input-output balances. *Witt* and *Dobermann* (2004) developed equations based on nutrient balance to estimate fertilizer K requirement for a crop with full maintenance of soil K. A distinctly undesirable feature of fertilizer K rate determined by the yield gain approach is higher K

depletion at high than at low target yields. *Buresh* et al. (2010) found that fertilizer K requirement determined by the yield gain approach increased with increasing target yield but the K rate did not increase sufficiently to prevent increasing depletion of soil fertility with increasing yield. This could accelerate the onset of nutrient limitations and subsequent declines in productivity in existing high-yielding areas. At the same time, the full maintenance approach can result in relatively large application of K that may not be profitable at no or low yield gain. Thus they examined two options using nutrient balances to calculate fertilizer K rates based on partial maintenance with gradual drawdown or depletion, rather than full maintenance of soil K. In the first option, fertilizer K requirement was calculated as a fraction of full maintenance of the nutrient input-output balance, the fraction to be drawn from soil nutrient reserve. In the second option, depletion of K from soil reserves was allowed up to a threshold limit, which was treated as an input in the nutrient balance. The authors showed that the second option has the risk of higher nutrient depletion and declining productivity at higher yield target. They also combined the partial maintenance and yield gain approaches for determining fertilizer K rate when crop response to K is certain. They showed that when the yield gain due to applied K is relatively small, fertilizer K requirements can be determined with only a partial maintenance approach but when yield gain is more pronounced, a partial maintenance plus yield gain approach can be considered. *Majumdar* and *Satyanarayana* (2011) and *Sanyal* et al. (2009) reviewed the mineralogy associated with K forms and availability, K uptake and balance, and strategies for K fertilizer management for rice-based systems in India, including the R-M systems. Acknowledging the work of *Witt* and *Dobermann* (2004) and *Buresh et al*. (2010), they also advocated the use of site-specific K management for rice-based systems in South Asia and particularly for India.

The emerging R-M system offers a major challenge to maintain K balance in the soil. The two major reasons for this are firstly that the ecosystems in which the R-M systems thrive (eastern and southern India, Bangladesh, Nepal, and parts of Pakistan) do not have high K concentration in irrigation water and secondly retention of residues of rice and maize in the field is not a common practice. Additionally, the dry matter yield of the R-M system is usually much higher than that of R-R and R-W involving high extraction of nutrients from the soil. In the absence of residue retention practices, a large amount of K is exported from the field with harvested product and the residues. This strongly suggests that higher K deficits and higher fertilizer K requirement are to be anticipated in the R-M system.

Finally, improved K management may have great potential for improving the overall productivity of the R-M systems of South Asia, but will require special consideration on soils containing K-fixing minerals. It may be appropriate to make separate applications of K to crops in the R-M systems on non-K fixing soils, with a lower application of K to rice with the aim of preventing loss by leaching, especially on permeable soils. Finally, occurrence of K deficiency and response to applied K depend on yield level, K buffering capacity of the soil, straw management, and net K inputs from sources other than fertilizer. Clay mineralogy, texture, and K inputs from irrigation or rainwater need to be considered (*Dobermann* et al., 1998) along with K inputs from sediments deposited from flood plains and flood water when formulating a K management strategy. Application of full maintenance rate of K (input=output) may not be profitable for rice and maize under situations where crop response to K is poor. In such soils, some K mining may be allowed by applying K below the maintenance rate. However, as discussed above, the extent of mining that could be allowed in a particular soil will require a complete understanding of K dynamics in the soil as well as the K input-output balance associated with the cropping system practiced.

7 Need for models and decision-support systems

Integrated process-based crop, soil and weather models can dynamically predict crop growth,

development and yield. The decision support systems for agro-technology transfer-DSSAT (*Hoogenboom* et al., 2004) software, was developed jointly by researchers in several universities in the USA working together with scientists from the developing countries in Asia and Africa. Several crop models are in use including those for rice and maize, which can predict crop yield and can assist in fertilizer management from soil, and weather data collected on a daily basis. In the released version of DSSAT (v. 4. 5), there is capacity to predict N and P fertilizer recommendations for most crops. The N and P models within DSSAT have been tested and applied for N and P fertilizer recommendations in Asia and Africa. In the unreleased version (v4. 6), there is a K model which can predict K uptake from K forms in soil and plant and can provide K fertilizer recommendations currently for rice and maize (U. Singh, IFDC, Alabama, USA, personal communication). However, the K model has not been evaluated against data sets from field experiments. Once evaluated, it can then be used for K fertilizer recommendations for rice and maize when grown under single or multiple crop systems, such as R-M. In contrast to the complex process-based models, the simple decision support systems (DSSs) such as "Nutrient Manager" for Rice and Maize developed by R. J. Buresh (at IRRI) and his co-workers and "Nutrient Expert" for Maize and Wheat proposed by The International Plant Nutrition Institute (IPNI), have the potential to estimate K fertilizer recommendation for R-M systems. Such DSSs could help to reduce the cost of production and increase yield and profit by reducing the fertilizer rates applied to these crops and, because of their simplicity in use, they would also help to extend the fertilizer management technologies to a large number of farmers over a short period of time. However, to use such DSSs with confidence would require more rigorous work to include soil and plant processes affecting the K forms and releases from different soils, as well as K availability and uptake, and conversion efficiency to grain. Once robust relationships between the different processes are established then the DSSs would require quality data to enable their evaluation for the environments where R-M systems are practiced.

8 Conclusions and research needs

South Asian soils vary in their genesis and mineralogy that affecting the exchangeable and non-exchangeable K pools. Besides affecting soil K availability, the mineralogical mcomposition of soils often influences fixation of K applied as K fertilizer or received from other sources such as crop residues or irrigation water. Potassium recommendations for cereals are often far lower than that required by removal by crops, and farmers seldom apply K fertilizer based on crop requirement. Low external application of K and the common practice of removing cereal residues from fields have led to depletion of K largely from non-exchangeable fractions that are rarely assessed in routine soil tests. Long-term experiments on R-W and R-R in South Asia have highlighted the significant effect of K on crop yields, uptake and use efficiencies of other essential nutrients, as well as on system nutrient-balance and native soil K-reserves. Rice-maize systems are emerging rapidly in various locations of South Asia that may be affected by K availability constraints and result in negative K balance. High-yielding R-M systems have high nutrient demand and may deplete soil K quickly when external supply is limited. Crop-residue removal from fields for competitive uses is common in South Asia and field-specific application of K and retaining some amount of crop residues will be required to maintain and improve crop yield and soil K fertility. Emerging data from either completed or on-going experiments on the R-M systems in India and Bangladesh have revealed very high system productivity and variable responses and agronomic use efficiency of maize and rice to applied K. Potassium responses of maize are extremely high and variable for soils in Bangladesh. Finally, the review presents a plant-based strategy for field-specific nutrient management and fertilizer K recommendation. This has the potential to effectively balance crop K demand and maintain native K fertility of soils, including the possible use of crop models and DSS for the R-M systems of South Asia.

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南亚地区水稻—玉米轮作体系中的钾素管理

摘　要:土壤钾素有效性主要由土壤矿物组成决定。主要含钾矿物的风化程度、化学风化途径,以及土壤中不同钾素形态之间的动态平衡,是决定各种土壤不同供钾能力的主要因素。在南亚地区以谷类为主的集约化种植系统中,制定相关的钾素管理措施时应当考虑到土壤钾素供应能力的显著差异。稻—稻轮作和稻—麦轮作的长期定位试验结果表明,不施钾或非优化施钾处理中,钾素施用及钾素收支负平衡对作物产量的影响极其显著。南亚地区钾肥推荐施用面积通常较大,但农民常不施钾或者将作物秸秆移出田间。这些做法会明显影响南亚地区新兴的水稻—玉米轮作体系中作物的产量及土壤钾素肥力水平。水稻—玉米轮作体系中的干物质产量远远高于稻—稻或稻—麦轮作体系,因而从土壤中吸收的养分物质也非常多。本文评估了南亚稻作体系不同类型土壤中的钾素形态和有效性,主要包括以下方面:长期定位试验作物产量及肥效、集约化稻作体系中钾素平衡以及秸秆对后茬作物的供钾影响。在印度和孟加拉国水稻—玉米轮作试验中,不论是已经完成的还是尚在进行中的试验,其结果均表明该轮作体系具有高生产力,玉米和水稻的施钾效果和钾素利用效率变化较大。最后,文章提出了基于作物的田间养分精准管理措施,并讨论了水稻—玉米轮作体系钾素高效管理对模型和决策支持系统的需求。

关键词:DSS(决策支持系统);水稻(亚洲栽培稻);钾素利用率;土壤肥力;南亚;玉米

沿江平原稻麦轮作系统维持钾素平衡和作物高产的钾肥运筹研究①②

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摘　要：在安徽沿江江南平原区的稻麦轮作试验结果表明，施用钾肥可明显增加稻麦产量，且随着施钾量的增加，稻麦产量也相应提高，但过多施用钾肥，产量呈现下降。随着施钾量的增加，除最高施钾处理，水稻的钾肥效率也随之提高，小麦则呈现相反的趋势。稻麦施钾收益差异与钾肥效率变化趋势一致。随着施钾量的增加，水稻和小麦地上部分K吸收量也呈上升趋势。水稻和小麦各处理籽粒N、P吸收量均高于秸秆，而秸秆K吸收量明显高于籽粒；随着钾肥投入的增加，水稻和小麦吸收产出的钾量也明显呈上升趋势；水稻收获后的土壤钾素均出现亏缺，但随着施钾量的提高，土壤钾素亏缺程度减轻，小麦施钾(K_2O)117 kg/hm^{2}以上时，土壤钾素开始相应盈余。水稻或稻麦合计，钾肥利用率均随着施钾量增多呈明显下降趋势。从保证稻麦高产高效，维持土壤钾素肥力考虑，水稻施钾 156 kg/hm^2、小麦施钾 117 kg/hm^{2}可作为类似生产条件农区的钾肥推荐用量。

关键词：水稻；小麦；产量；钾肥效率；钾素平衡

中图分类号：S143.3

钾是农作物必需的三大营养元素之一。随着化肥施用量的增加和相关农业技术的进步，作物产量大幅度增加，从土壤中带走的钾素逐渐增多，农田钾素的回补严重不足；施肥结构不合理，氮磷化肥用量相对增加较快，也加剧了作物对土壤钾的消耗[1]。有研究表明，安徽省水田土壤速效钾含量大于100 mg/kg的仅占8.7%，而小于50 mg/kg的达42.6%[2]。我国钾肥资源匮乏，工业生产能力也有限，世界已探明的钾盐储量为2 000亿t(K_2O)，而我国可溶性钾资源严重短缺，已探明储量不足世界总量的0.2%。据李金生、王石军研究推测，我国每年进口钾肥超过国产量的10倍以上[3]。进入21世纪，我国钾肥消费几乎以指数形式增长，2005年达到797万t(K_2O)[4]，按国际肥料工业协会(IFA)资料数据显示[5]，已超过当年全球需求量的30%。近年来的一些研究表明，钾肥的增产效果正在逐渐提高，钾肥显效的耕地面积也在不断扩大[6-9]。

稻麦轮作是沿江平原主要的种植制度。我国86%的水稻种植在南方，水稻施钾也主要集中在南方，约占水稻总施钾量的99%；小麦主要种植于长江流域和华北地区，这两个区域的小麦钾肥需求量占95%以上，按2004年统计，约占各种作物需钾总量的24%[2]。相对于类似农区土壤培肥和耕作管理方面的研究，目前关注更多的仍是如何长期维持较高和稳定的水稻和小麦产量，粮食安全问题已逐步成为影响人类生产发展的基本问题。人口增加、气候环境变化以及土地耕作施肥影响下的粮食生产力问题已逐渐成为国内外关注的焦点，探讨如何维持粮食作物高产和稳产的途径具有重要意义[10]。

农田钾素长期得不到有效补充，土壤中作物可利用的钾资源日益短缺，不仅严重地影响到作物的产量和品质，同时，降低了作物的抗逆性，从而限制了作物的高产和稳产[7]。而科学施用钾肥对提高和稳定稻麦产量，维持土壤钾素肥力，促进农业可持续发展至关重要。为此，笔者在安徽沿江江南平原区进行了稻麦轮作长期定位试验，试图通过多年田间试验找到既能维持作物高产又能保证农田钾素平衡的适宜钾用量，同时探讨不同钾用量对稻麦产量、钾吸收、土壤钾平衡的影响。现仅就2009—2010年度轮作周期试验结果，对该种植制度下土壤钾素平衡状况和施钾效应进行分析，为钾肥合理利用提供依据。

1　材料与方法

1.1　试验材料

田间试验设在安徽省水稻主产区沿江平原的芜湖县红杨镇永平村杨青松承包田，试验地土壤为河流

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冲积物发育的水稻土，质地砂黏适中。土壤基础农化性状为：pH 5.20，有机质 28.4 g/kg，全氮 1.46 g/kg，速效磷 18.8 mg/kg，速效钾 73.20 mg/kg，缓效钾 374.00 mg/kg。

供试水稻品种为“新香优 80”，小麦品种为“杨麦 11 号”。

供试氮磷钾肥分别为尿素（含 N 46%）、过磷酸钙（含 P_2O_5 12%）、氯化钾（含 K_2O 60%）。

水稻于 2009 年 5 月 11 日播种，密度为 187 500 株/hm^2，6 月 13 日移栽，6 月 28 日追肥，9 月 23 日收获；小麦于 2009 年 10 月 19 日播种，用种量 150 kg/hm^2，播后灌水，3 月 8 日追肥，6 月 1 日收获。

1.2 试验设计和方法

试验设①K0：对照，不施钾；②K1：每季施钾量为 K2 处理的 70%；③K2：当地不同作物的常规用量；④K3：每季施钾量为 K2 处理的 130%；⑤K4：每季施钾量为 K2 处理的 160%共 5 个处理。施肥量见表 1。

表 1 不同处理的水稻和小麦氮磷钾肥用量

Table 1 N, P and K rates for rice-wheat trial (kg/hm^2)

作物	氮肥(N)	磷肥(P_2O_5)	钾肥(K_2O)				
			K0	K1	K2	K3	K4
水稻	200	65	0	84	120	156	192
小麦	180	90	0	63	90	117	144

水稻和小麦氮肥分别基施 70%和 50%，余下适时一次追施。磷钾肥全部作基肥一次性施用，每个处理 4 次重复，随机区组排列，小区面积 20 m^2。

每季作物收获后各处理分别称重，统计生物产量，以计算作物从土壤中带走的养分量。水稻和小麦成熟期随机取地上部植株进行考种，并分析水稻和小麦的秸秆和籽粒中的氮、磷、钾含量。

土壤和植物样品均采用常规分析方法[11]。试验数据采用 DPS7.05 版统计软件，用 LSD 法进行统计分析，并进行多重比较。

2 结果与分析

2.1 施钾量对稻麦生物性状和产量构成的影响

从稻麦生物性状考察结果（见表 2）可以看出，随着施钾量的增加，水稻和小麦株高也随之不同程度增加；但水稻穗长基本稳定不变，小麦穗长和稻麦谷草比也无明显变化趋势。从稻麦产量构成因素统计结果（见表 2）分析，水稻有效穗数无明显变化趋势，而小麦随着施钾量增加，有效穗数呈现上升趋势；各处理的水稻每穗实粒数基本与施钾量增加趋势一致，而小麦无明显变化趋势；稻麦千粒重明显随施钾量增加呈上升趋势。从理论产量看，除水稻最高施钾处理外，随着施钾量增加，稻麦产量也随之提高。

表 2 施钾量对稻麦生物性状和产量构成的影响

Table 2 The effect of K rates on biology characteristics and yield components of rice and wheat

作物	处理	株高 (cm)	穗长 (cm)	有效穗数 (万/hm^2)	穗粒数	千粒重 (g)	理论产量 (kg/hm^2)	谷草比
水稻	K0	131.2a	22.5a	184.0a	155.6b	28.0c	8 027.96cd	1∶0.85
	K1	131.3a	22.7a	177.8a	163.1ab	28.5b	8 250.27bc	1∶0.98
	K2	132.6a	22.6a	182.7a	162.0ab	28.5b	8 447.10b	1∶0.90
	K3	135.0a	22.6a	189.1a	185.7a	28.6b	10 039.63a	1∶0.94
	K4	134.7a	22.6a	185.7a	182.8a	29.0a	9 834.14a	1∶0.92
小麦	K0	90.6b	8.2ab	341.1c	36.3a	46.3c	5 732.83d	1∶1.37
	K1	91.0ab	7.9b	385.5b	33.2c	47.2b	6 040.94c	1∶1.38
	K2	91.6ab	8.0ab	394.8ab	35.2ab	47.4b	6 587.16b	1∶1.44
	K3	91.7ab	8.5a	408.4a	34.3bc	48.2a	6 751.91b	1∶1.36
	K4	92.0a	8.4ab	410.1a	36.1ab	48.4a	7 165.43a	1∶1.43

注：表中同列数据后小写英文字母不同者表示差异显著。

2.2 施钾对稻麦产量的影响

试验实收产量结果(见表3)表明,施用钾肥可明显增加稻麦产量,各施钾处理的水稻较对照增产3.3%～9.6%,小麦增产均超过10%;随着施钾量的增加,稻麦产量也都有不同程度提高,当水稻施钾156 kg/hm²、小麦施钾117 kg/hm²时,稻麦产量最高,分别达到9 144 kg/hm²和4 500 kg/hm²,继续增施钾肥,产量呈现下降趋势。统计分析表明,除水稻K1处理外,各施钾处理均较对照产量差异显著;且除水稻K3较K1处理产量差异显著外,各施钾处理间产量差异均不显著。

表3 施钾量对稻麦产量和经济效益的影响

Table 3 Effect of K rates on yield and economic Benefit of rice and wheat

作物	处理	产量(kg/hm²)	钾肥(K_2O)效率(kg/kg)	钾肥的产量效应		净增收入(元/hm²)	产投比
				增产(kg/hm²)	相对产量		
水稻	K0	8 344c	—	—	100.0	—	—
	K1	8 615bc	3.23	271	103.3	99.90	1.33
	K2	8 830ab	4.05	486	105.8	291.00	1.66
	K3	9 144a	5.13	800	109.6	630.60	2.11
	K4	8 836ab	2.56	491	105.9	37.20	1.05
小麦	K0	3 981b	—	—	100.0	—	—
	K1	4 419a	6.94	438	111.0	559.41	3.05
	K2	4 475a	5.49	494	112.0	548.90	2.41
	K3	4 500a	4.43	519	113.0	479.49	1.95
	K4	4 469a	3.39	488	112.3	303.68	1.49

注:水稻价格1.50元/kg、K_2O 3.65元/kg(2009年);小麦1.90元/kg(2010年)、K_2O 4.33元/kg(2009年)。

由表3还可以看出,随着施钾量的增加,水稻的钾肥效率也随之提高,施钾156 kg/hm²处理(K3)钾肥(K_2O)效率达到5.13 kg/kg,小麦则呈现相反的趋势,而当施钾量达到192 kg/hm²时,水稻的钾肥效率也明显下降。说明在本试验同等钾素肥力状况下,第一季水稻增施一定量钾肥,作物产量增幅高于钾的增量,养分转化为产量的效率也随之提高,但当钾供应量超过一定限度,养分转化为产量的效率滞后,作物产量也转而下降,这也符合报酬递减律;而第二季小麦虽然各处理施钾量不同,但均能满足小麦生长的基本需求,施钾处理间产量差异不足2%(大致在80 kg /hm²以内)。所以,随着施钾量的增加,小麦钾肥效率也随之下降,因为是在不同钾素肥力条件下进行,这种趋势也愈加明显。

2.3 施钾对稻麦经济效益的影响

从施用钾肥的经济效益结果(见表3)分析,不同处理的水稻净增收入中最多的是施钾156 kg/hm²,增收达630.60元/hm²,最少的是施钾192 kg/hm²,仅增收37.20元/hm²;小麦净增收入最多的是最低施钾处理(63 kg/hm²),为559.41元/hm²,最少的是最高施钾处理(144 kg/hm²)。水稻和小麦产投比最高的分别为K3和K1处理,分别为2.11和3.05,最低的均为最高施钾处理,且都未超过1.50。可以看出,稻麦施钾收益差异与钾肥效率变化趋势一致。说明施用钾肥虽然可以增产,但不是施得越多越好,增产也不一定增收,当生产资料和产品价格在相对合理区间时,只有在提高养分效率的前提下,才能确保稳定的高收益。

从稻麦总体统计,K1、K2和K3(2.14～2.01)处理的产投比相差无几,只有K4(1.25)相对较低;而合计净增收入K1、K2、K3和K4处理分别为659.31元/hm²、839.90元/hm²、1 110.09元/hm²和340.88元/hm²。比较分析表明,K3处理(施钾水稻156 kg/hm²、小麦117 kg/hm²)综合经济效益最佳。

2.4 施钾量对稻麦氮磷钾吸收的影响

从水稻和小麦不同部位N、P、K吸收量(见图1、图2)可以看出,各处理间籽粒P、K和秸秆N、P吸收量无明显差异,籽粒N和秸秆K吸收量随着施钾量增加相应提高,而籽粒N、P吸收量均高于秸秆。水稻秸秆K吸收量明显高于籽粒,也明显高于各部位N、P吸收量;小麦籽粒N和秸秆K吸收量明显高于籽粒K和秸秆N以及P吸收量,且随着施钾量的增加而相应提高,说明K、N交互作用促进了稻麦N的吸收,这也一定程度验证了相关研究结果[12-14]。当施钾量达最高(144 kg/hm²)时,秸秆K吸收量超过籽粒N吸收量,由于产量呈现下降,因而可视为小麦钾的无效吸收。以上结果还表明,稻麦K吸收运转主要集中并积累于秸秆部位,这与相关研究结果[8, 15-17]一致。

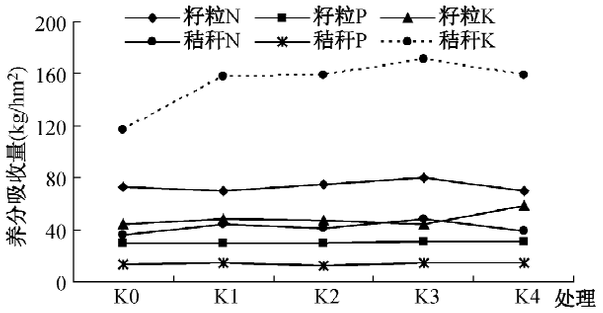

图 1　水稻不同部位 N、P、K 吸收量

Fig. 1　N, P, K uptake in different parts of rice

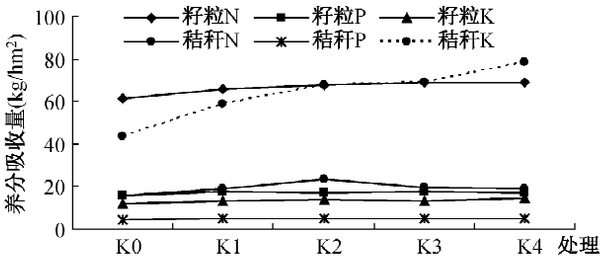

图 2　小麦不同部位 N、P、K 吸收量

Fig. 2　N, P, K uptake in different parts of wheet

从水稻和小麦地上部分 N、P、K 吸收量(见图 3)可以看出,水稻地上部分 N、P、K 吸收量均高于小麦,这主要与产量差异有关;地上部分各处理间水稻 P 和小麦 N、P 吸收量无明显差异;而随着施钾量的增加,水稻和小麦地上部分 K 吸收量也呈上升趋势。

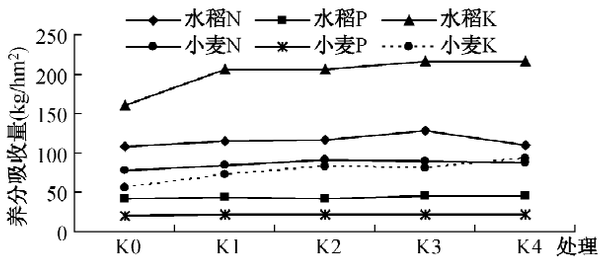

图 3　水稻和小麦地上部分 N、P、K 吸收量

Fig. 3　N, P, K uptake in above plant of rice and wheat

从表 4 可知,水稻和小麦籽粒吸 K 量虽无明显的变化趋势,但基本是随着施钾量的增加总体呈上升趋势,而秸秆以及地上部分总吸 K 量的这种上升趋势尤为明显。由此得到的稻麦两季累计吸 K 量更可以说明这一点。虽然稻麦并没有随着施钾量增加而持续增产,但由于增施钾肥后,大幅提高的根际范围钾离子浓度,吸收动力学作用诱导了钾的被动吸收,也促进了稻麦对钾的奢侈吸收。

表 4　施钾量对稻麦钾吸收的影响

Table 4　Effect of K rates on K uptake in rice and wheat (K kg/hm²)

处理.	水稻			小麦			稻麦合计
	籽粒	秸秆	合计	籽粒	秸秆	秸秆	
K0	43.64	116.53	160.17	11.90	43.80	55.70	215.87
K1	48.24	157.63	205.87	13.21	58.85	72.06	277.93
K2	46.80	159.02	205.82	14.23	67.92	82.15	287.97
K3	44.53	171.74	216.27	13.10	68.73	81.83	298.10
K4	58.05	158.76	216.81	14.43	78.48	92.91	309.72

2.5　施钾量对稻麦轮作制钾表观平衡和钾肥利用率的影响

不同处理的钾表观平衡结果(见表 5)表明,随着钾肥投入的增加,水稻和小麦吸收产出的钾量也明显呈上升趋势;由此得到水稻收获后的土壤钾素均出现亏缺,但随着施钾量的提高,土壤钾素亏缺程度减轻,由不施钾(K_2O)对照的 192.94 kg/hm² 减少到最高施钾(K_2O)量的 69.17 kg/hm²;当施钾(K_2O)量在 120 kg/hm²(当地常规用量)以下时,小麦收获后的土壤钾素同样出现亏缺,而增加 30%～60%钾肥投入后,土壤钾素开始相应盈余。一个轮作周期过后,稻麦累计 K 吸收产出仍是随着施钾量增加而加大;由于水稻产量明显高于小麦,因而,小麦高钾处理土壤钾素赢余不足以填补水稻试验后土壤钾素的亏缺,但可在一定程度上缓解土壤钾素的负平衡。

从应用差减法计算得出的稻麦钾肥利用率结果(见表 5)可知,水稻钾肥利用率随着施钾量增多呈明显下降趋势(65.54%→35.54%),而小麦无明显升降趋势;即便如此,稻麦两季合计,钾肥利用率仍随着施钾量增多呈明显下降趋势(50.85%→33.65%),这与水稻产出生物量和钾摄入量明显多于小麦,占累计数量权重大,在轮作系统中起主导作用有关。

表 5　不同处理稻麦轮作周期钾表观平衡和钾肥利用率

Table 5　K apparent balance and K fertilizer utilization efficiency in different treatments under rice-wheat rotation

处理	钾(K_2O)表观平衡(kg/hm²)									钾肥利用率(%)		
	水稻			小麦			稻麦合计			水稻	小麦	稻麦合计
	投入	产出	平衡	投入	产出	平衡	投入	产出	平衡			
K0	0	192.94	−192.94	0	67.10	−67.10	0	260.04	−260.04	—	—	—
K1	84	247.99	−163.99	63	86.80	−23.80	147	334.79	−187.79	65.54	31.27	50.85
K2	120	247.93	−127.93	90	98.96	−18.96	210	346.89	−136.89	45.83	35.40	41.36
K3	156	260.52	−104.52	117	98.57	+11.76	273	359.09	−85.77	43.32	26.90	36.28
K4	192	261.17	−69.17	144	111.92	+32.08	336	373.09	−37.09	35.54	31.13	33.65

3　讨论与结论

(1) 施用钾肥可明显增加稻麦产量,各施钾处理的水稻较对照增产 3.3%～9.6%,小麦增产均超过 10%;随着施钾量的增加,稻麦产量也都有不同程度提高,当水稻施钾 156 kg/hm²、小麦施钾 117 kg/hm² 时,稻麦产量最高,继续增施钾肥,产量呈现下降。从稻麦产量构成因素统计结果分析,各处理的水稻每穗实粒数基本与施钾量增加趋势一致,而随着施钾量增加,小麦有效穗数呈现上升趋势;稻麦千粒重明显随施钾量增加呈上升趋势。

(2) 随着施钾量的增加,水稻的钾肥效率也随之提高,施钾 156 kg/hm² 达到 5.13 kg/kg K_2O,小麦则呈现相反的趋势;而当施钾量达到 192 kg/hm² 时,水稻的钾肥效率也明显下降。虽然各处理施钾量不同,但均能满足小麦生长的基本需求,施钾处理间产量差异不足 2%。随着施钾量的增加,小麦钾肥效率也随之下降,因为是在不同钾素肥力条件下进行,这种趋势也愈加明显。

(3) 从施用钾肥的经济效益结果分析,不同处理水稻净增收入最多的是施钾 156 kg/hm²,达 630.60 元/hm²;小麦净增收入最多的是最低施钾处理(63 kg/hm²),为 559.41 元/hm²。水稻和小麦产投比最高的分别为 K3 和 K1 处理,最低的均为最高施钾处理。从稻麦总体比较分析表明,K3 处理(施钾水稻 156 kg/hm²、小麦 117 kg/hm²)综合经济效益最佳。稻麦施钾收益差异与钾肥效率变化趋势一致,说明施用钾肥虽然可以增产,但不是施得越多越好,增产也不一定增收,当生产资料和产品价格在相对合理区间时,只有在提高养分效率的前提下,才能确保稳定的高收益。

(4) 水稻地上部分 N、P、K 吸收量均高于小麦,主要与产量差异有关。随着施钾量的增加,水稻和小麦地上部分 K 吸收量也呈上升趋势。水稻和小麦的籽粒 N 和秸秆 K 吸收量随着施钾量增加相应提高,且籽粒 N、P 吸收量均高于秸秆。水稻秸秆 K 吸收量明显高于籽粒,也明显高于各部位 N、P 吸收量;小麦籽粒 N 和秸秆 K 吸收量明显高于籽粒 K 和秸秆 N 以及 P 吸收量,且随着施钾量的增加而相应提高。说明稻麦 K 吸收运转主要集中并积累于秸秆部位。

水稻和小麦籽粒吸 K 量虽无明显的变化趋势,但基本是随着施钾量的增加总体呈上升趋势,而秸秆以及地上部分总吸 K 量的这种上升趋势尤为明显。由此得到的稻麦两季累计吸 K 量更可以说明这一点。虽然稻麦产量并没有随着施钾量增加而持续增产,但由于增施钾肥后,大幅提高了根际范围钾离子浓度,吸收动力学作用诱导了钾的被动吸收,也促进了稻麦对钾的奢侈吸收。

(5) 随着钾肥投入的增加,水稻和小麦吸收产出的钾量也明显呈上升趋势;水稻收获后的土壤钾素均出现亏缺,但随着施钾量的提高,土壤钾素亏缺程度减轻,由不施钾(K_2O)对照的 192.94 kg/hm² 减少到最高施钾(K_2O)量的 69.17 kg/hm²;当施钾(K_2O)量在 120 kg/hm²(当地常规用量)以下时,小麦收获后的土壤钾素同样出现亏缺,而增加 30%～60%钾肥投入后,土壤钾素开始相应盈余。稻麦累计 K 吸收产出也随着施钾量增加而加大。水稻钾肥利用率随着施钾量增多呈明显下降趋势,而小麦无明显升降趋势;稻麦两季合计,钾肥利用率仍随着施钾量增多呈明显下降趋势。

综上所述,在本试验基础肥力条件下,从保证稻麦高产、稳产和高效,维持土壤钾素肥力等考虑,水稻施钾 156 kg/hm²、小麦施钾 117 kg/hm² 的处理效果最佳,可作为类似生产条件农区的钾肥推荐用量。

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Study on potassium strategy to maintain crop high yield and potassium balance in cropland under rice-wheat rotation systems

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Abstract: A field experiment under the rice-wheat rotation was conducted in Plain along the Yangtze River in Anhui. The results indicated that the yields of rice and wheat were enhanced with the increasing of potassium rate, whereas the yields decreased with excessive potassium fertilizer application. Except for the highest potassium rate treatment, potassium fertilizer efficiency of rice was also enhanced with the increase of potassium fertilizer, while there was an opposite trend for wheat compared with rice. Moreover, the difference of potassium fertilizer income exhibited a similar trend in potassium fertilizer efficiency under the rice-wheat rotation system. K absorption in aerial part increased with the improvement of potassium fertilizer rate. N and P absorption in grain for all the treatments under the rice-wheat rotation system was significantly higher than the straw whereas there was higher K absorption in straw compared with grain. With the improvement of potassium fertilizer, the absorption of straw and grain for rice and wheat exhibited a significantly increasing trend. In addition, potassium for all treatments in the farmland system showed a deficit after rice harvesting. However, the deficit was mitigated with the increasing of potassium rate. Moreover, potassium in the farmland exhibited a surplus pattern in the wheat growing season when the application rate of potassium was more than 117 kg/hm^2. The potassium fertilizer efficiency showed an obvious decreasing trend with the increase of potassium rate. Therefore, it was preliminarily concluded that the application rate of potassium 156 kg/hm^2 and 117 kg/hm^2 for rice and wheat respectively was a prefer choice for fertilization strategy in order to guarantee high yield and maintain soil potassium fertility in the similar regions.

Key words: Rice, wheat, yield, potassium efficiency, potassium balance

五年定位试验钾肥用量对双季稻产量和施钾效应的影响[①②]

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摘　要：通过 5 年定位试验（2008—2012 年）研究不同钾肥施用量对水稻产量、植株钾素含量、钾素积累量、钾肥利用率、土壤钾素含量、钾素平衡和钾肥经济效益的影响。试验施钾量（K_2O）从低到高设 K0（不施钾）、K1（早稻 84 kg/hm²、晚稻 105 kg/hm²）、K2（早稻 120 kg/hm²、晚稻 150 kg/hm²）、K3（早稻 156 kg/hm²、晚稻 195 kg/hm²）和 K4（早稻 192 kg/hm²、晚稻 240 kg/hm²）5 个处理。5 年的试验结果表明，施钾能显著提高早、晚稻产量，在一定施钾量范围内，水稻产量随施钾量的增加而增加；施钾能促进水稻植株对钾素的吸收和积累，尤其是稻草对钾素的吸收和积累；早、晚稻的钾肥农学效应均以 K2 处理最高（早稻 3.12 kg grain/kg K_2O、晚稻 3.70 kg grain/kg K_2O）；钾肥利用率以 K1 处理最高（早稻 41.2%、晚稻 76.4%），并随施钾量提高而降低；不同施钾量对土壤钾素含量有明显影响，土壤速效钾、缓效钾和土壤全钾含量均随施钾量的增加而增加，且不同处理间土壤速效钾含量差异达极显著水平（$p<0.01$）；连续种植 5 年 10 季水稻后，K0、K1 和 K2 处理的土壤钾素亏缺（127.1、58.3、10.8 kg/hm²），亏缺量随施钾量的增加而降低；K3 和 K4 处理的土壤钾素盈余（48.0、109.2 kg/hm²），盈余量随施钾量的增加而增加。在经济效益上，早、晚稻产投比均以 K2 处理最高（早稻 1.04、晚稻 1.27）。综合考虑施钾的增产效应、经济效益和土壤钾素养分平衡等因素，建议该双季稻区早稻施钾（K_2O）量在 120～156 kg/hm²、晚稻施钾（K_2O）量在 150～195 kg/hm² 范围内较为适宜。

关键词：钾肥用量；双季稻；产量；施钾效应；定位试验

湖南省是中国水稻的主要产区之一，双季稻是当地最重要的水稻种植模式，其面积占水稻总种植面积的 70%[1]。钾素是实现水稻稳产增产的重要营养元素，在水稻产量形成和稻米品质提升等方面起着极其重要的作用，且水稻对钾素的吸收量较大，甚至高于氮素，因此，合理施用钾肥是实现水稻持续高产的重要措施。然而，在传统水稻生产中，农民往往重视氮肥而忽略磷、钾肥，特别是钾肥的施用[2]。近年来，由于高产杂交水稻和具有高产潜力常规水稻品种的大面积推广，传统的钾肥施用技术无法满足高产水稻对钾素的需求，导致水稻从土壤中带走的钾逐年增加，从而加速了水稻土中钾素的消耗[3-4]。目前有关钾肥施用量和施用方式在湖南省双季稻种植模式中的产量效应、钾素利用效率等方面的研究较多，其主要目标是针对钾对当季作物的效应[5-6]，很少考虑土壤钾素平衡的维持或提高土壤钾素含量。通常推荐的最佳或最经济钾肥施用量，不一定能维持稻田土壤钾素平衡。在湖南省双季稻区，农民传统的施钾技术往往导致水稻吸收的钾量大于最佳施肥量，从而导致土壤有效钾库的耗竭；在部分区域，存在某一年份水稻吸收的钾量小于最佳施肥量而导致土壤钾素肥力的上升现象，然而这种钾肥最佳用量会因其后续水稻生产的经济效益变化而不具有持续性。面对当前我国水稻土缺钾问题，如何在达到水稻稳产高产的同时维持和提高稻田土壤的钾素就显得极为重要。本研究选择湖南典型双季稻地区，通过 5 年田间定位试验，分析了水稻产量、水稻植株钾素含量和吸收量、钾肥利用率、土壤钾素状况、钾素表观平衡以及施钾经济效益等，以寻求一种既能保障水稻高产稳产又能维持农田土壤钾素平衡的钾肥推荐施用方法，同时也揭示土壤钾素肥力变化的基本规律及其影响因素，为双季稻田合理施用钾肥和土壤钾素培肥提供新的思路。

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1 材料与方法

1.1 试验区概况

2008—2012 年定位试验设在长沙县干杉镇(N 28°08′,E 113°12′),试验期间的年平均降雨量 1 378 mm,年平均气温 17 ℃,年平均无霜期约 300 d,属中亚热带季风湿润气候区。供试土壤为第四纪红色黏土发育的水稻土(粉质轻黏土),土壤分类为普通简育水耕人为土。试验开始前 0～20 cm 耕层土壤的基本性状为:pH 值 5.5,土壤有机质 37.9 g/kg,全氮 2.14 g/kg,碱解氮 238 mg/kg,全磷 0.83 g/kg,速效磷 9.2 mg/kg,全钾 9.20 g/kg,缓效钾 107.5 mg/kg,速效钾 62.0 mg/kg。

1.2 试验设计

试验共设 5 个处理,分别为:K0(不施钾肥)、K1(早稻施 K_2O 84 kg/hm^2、晚稻施 K_2O 105 kg/hm^2)、K2(早稻施 K_2O 120 kg/hm^2、晚稻施 K_2O 150 kg/hm^2)、K3(早稻施 K_2O 156 kg/hm^2、晚稻施 K_2O 195 kg/hm^2)和 K4(早稻施 K_2O 192 kg/hm^2、晚稻施 K_2O 240 kg/hm^2)处理。氮、磷和钾化肥品种分别是尿素、过磷酸钙和氯化钾。在试验期间,氮肥(N)按早稻 150 kg/hm^2、晚稻 180 kg/hm^{2}施入;磷肥(P_2O_5)按早稻 75 kg/hm^2、晚稻 45 kg/hm^{2}施入。全部磷肥和钾肥作基肥于插秧前一天施入,氮肥分两次施入:70%做基肥在插秧前一天施入,30%在分蘖期做追肥施入。每个处理 4 次重复,小区面积 20 m^2,随机区组排列。小区间筑田埂并覆盖农用薄膜隔离,以避免小区间水分窜灌或漫灌。供试早稻和晚稻品种(组合)分别为“湘早籼 24”和“丰源优 272”。试验田管理措施与当地农民的大田管理一致。

1.3 采样与分析

试验前采集 0～20 cm 耕层基础土壤样品。每季水稻成熟后多点混合采集植株样品,每小区单打单收称计实产。2012 年晚稻收获后从各小区采集 0～20 cm 耕层土壤样品,用于土壤全钾、缓效钾和速效钾测定。灌溉水样品是在灌溉来水的上游方向取 5 个点的水样混合而成。

植株全钾用 H_2SO_4-H_2O_2 消煮,采用火焰光度计法测定[7];土壤全钾用 NaOH 熔融,采用火焰光度计法测定[7];土壤缓效钾用 1 mol/L 热 HNO_3 浸提,采用火焰光度计法测定[7];土壤速效钾用 1 mol/L 中性 NH_4OAc 浸提,采用火焰光度计法测定[7];土壤有机质、全氮、碱解氮、全磷、速效磷的含量和土壤 pH 均按文献[7]中的方法测定。

1.4 计算与统计方法

钾肥农学效应(Agronomy efficiency, AE, kg/kg)=(施肥区子粒产量—对照区子粒产量)/施钾量

植株吸钾量(K uptake in rice plant, K kg/(hm^2 · a))=稻草产量×稻草钾含量+子粒产量×子粒钾含量

钾肥利用率(K use efficiency, %)=(施肥区植株吸钾量—对照区子植株吸钾量)/施钾量×100

土壤钾素表观平衡按下式计算:

$$K_{ap} = K_{inp} - (K_{up} - K_{rec})$$

式中:K_{ap}是钾素表观平衡(kg/(hm^2 · a)),K_{inp}是通过化肥、秧苗、雨水和灌溉水输入的钾素量(kg/(hm^2 · a)),K_{up}是水稻植株吸收的钾素量(kg/(hm^2 · a)),K_{rec}是通过稻桩和根茬残留循环的钾素量(kg/(hm^2 · a))。

秧苗、雨水、灌溉水及稻桩和根茬残留循环的输入钾素量为试验期间 5 年的平均测定值。

试验数据用 SPSS 13.0 系统软件进行统计分析。

2 结果与分析

2.1 施钾量对水稻产量的影响

不同施钾量对早、晚稻水稻产量的影响表现不同。从表 1 可以看出,各处理水稻产量之间存在差异,施钾处理与不施钾处理之间的差异均达极显著水平($p < 0.01$);连续 5 年施用钾肥的早稻平均产量随钾肥施用量的增加呈先增加后下降的变化趋势,与不施钾肥的对照处理相比,K1、K2、K3 和 K4 处理分别增加 4.82%、7.25%、8.01%和 7.37%;5 季晚稻平均产量随钾肥施用量的增加而增加,K1、K2、K3 和 K4 处理较 K0 处理分别增加 4.93%、8.61%、9.07%和 10.25%。其中早稻平均产量最高的是 K3 处理,晚稻最高的是 K4 处理。早、晚稻农学效应均以 K2 处理最高,施钾量高于 K2 处理,农学效应随施钾量的增加而降低。

表 1　连续 5 年不同施钾肥量对早、晚稻平均产量及钾肥农学效应的影响

Table 1　Effect of K fertilization on the rice grain yields and K agronomic efficiency in 2008—2012

处理 Treatment	早稻产量(kg/hm²) Early rice yield	晚稻产量(kg/hm²) Late rice yield	农学效应 Agronomic efficiency(kg grain/kg K_2O)	
			早稻 Early rice	晚稻 Late rice
K0	5 169.0 cB	6 438.5 cC	—	—
K1	5 418.0 bA	6 755.9 bB	2.96	3.02
K2	5 543.6abA	6 993.1aAB	3.12	3.70
K3	5 583.1aA	7 022.4 aA	2.65	2.99
K4	5 550.1abA	7 098.3 aA	1.98	2.75

注：不同大小写字母表示差异达 1%和 5%显著水平。

2.2　施钾量对水稻植株钾素含量的影响

从表 2 可以看出，施钾量不同，钾素在水稻植株体内的分配不同。施用钾肥能显著提高水稻子粒和稻草中的钾素含量，特别是稻草中的钾含量，早、晚稻施钾处理与不施钾处理之间子粒中的钾素含量差异达显著水平（$p < 0.05$）；稻草中的钾素含量差异达极显著水平（$p < 0.01$）。早、晚稻子粒和稻草中的钾素含量均随着施钾量的增加而增加。K1、K2、K3 和 K4 处理的早稻子粒钾含量分别比对照处理增加 6.25%、9.37%、12.50%和 15.63%，晚稻增加 11.54%、15.38%、19.23%和 23.08%；K1、K2、K3 和 K4 处理的早稻稻草钾含量分别比对照处理增加 41.77%、54.43%、66.46%和 69.62%；晚稻增加 77.69%、92.56%、102.48%和 112.40%。

表 2　连续 5 年不同施钾量对子粒和稻草钾素含量的影响（g/kg）

Table 2　Effect of K fertilization on potassium concentrations in rice plant in 2008—2012 (g/kg)

处理 Treat	早稻 Early rice		晚稻 Late rice	
	籽粒 Grain	稻草 Straws	籽粒 Grain grains	稻草 Straws
K0	3.2±0.23 cC	15.8±1.7 dC	2.6±0.35 bB	12.1±1.5 dC
K1	3.4±0.25 bBC	22.4±1.4 cB	2.9±0.54 aAB	21.5±1.0 cB
K2	3.5±0.31 bAB	24.4±2.1 bcAB	3.0±0.61 aAB	23.3±0.7 bcAB
K3	3.6a±0.32bAB	26.3±1.6 abA	3.0±0.65 aA	24.5±0.7 abA
K4	3.7±0.37 aA	26.8±2.0 aA	3.2±0.67 aA	25.7±2.0 aA

注：不同大小写字母表示差异达 1%和 5%显著水平。

2.3　施钾量对水稻植株吸钾量和钾肥利用率的影响

植株吸钾量和钾肥利用率见表 3。施钾可显著增加早、晚稻水稻植株的吸钾量（$p < 0.01$），植株钾素积累量随施钾量的增加而增加，但早、晚稻表现有所不同，早稻不同施钾处理之间的植株吸钾量存在显著差异，而晚稻不同施钾处理之间的差异不明显。与不施钾肥的 K0 处理相比，K1、K2、K3 和 K4 处理的早稻植株吸钾量分别增加 36.51%、49.62%、59.67%和 65.14%，晚稻增加 76.88%、89.83%、91.33%和 94.22%。钾肥利用率随钾肥施用量的增加而降低，早稻钾肥利用率范围为 32.1%～41.2%，晚稻钾肥利用率范围为 41.0%～76.4%；早稻相近施钾处理间钾肥利用率的差异不明显，晚稻除 K3 和 K4 之间的差异不明显外，其他相近施钾处理间差异均达到极显著水平（$p < 0.01$）。

表 3　不同施钾处理的水稻年吸钾量和钾肥利用率

Table 3　Potassium contents in rice plant and use efficiency of K fertilizer in 2008—2012

处理 Treatment	早稻 Early rice		晚稻 Late rice	
	植株年吸钾量 (kg/(hm²·a))plant K uptake	钾肥利用率（%） K efficiency	植株年吸钾量 (kg/(hm²·a))plant K uptake	钾利用率(%) K efficiency
K0	78.6±7.5 dC	—	86.5±11.4 bB	—
K1	107.3±4.3 cB	41.2±15.8 aA	153.0±18.7 aA	76.4±9.5 aA
K2	117.6±10.1 bAB	39.1±16.0 aAB	164.2±15.3 aA	62.4±6.2 bB
K3	125.5±6.4 abA	36.2±9.7 abAB	165.5±13.4 aA	48.8±8.2 cC
K4	129.8±10.2 aA	32.1±10.6 bB	168.0±15.9 aA	41.0±10.9 cC

注：不同大小写字母表示差异达 1%和 5%显著水平。

2.4 施钾量对钾素养分平衡的影响

通过化肥、秧苗、灌溉水和雨水输入的K量、水稻植株吸收输出的K量及稻桩和根茬残留归还的K量来确定所有处理的表观K平衡(见表4)。从表4可以看出,钾素的输入项中各施钾处理主要是通过钾肥施入的钾,占总输入量的75%以上;其次,水稻稻桩和根茬的钾素(循环钾)对钾输入量也有较大影响,各施钾处理明显高于对照处理,但不同施钾处理间差异较小。钾的输出主要是水稻植株吸收的钾,施钾处理植株吸钾量明显高于对照处理,且随钾肥施用量的增加而增加,说明施钾量越高,作物从土壤中带走的钾素越多,但同时施钾量越高,通过钾肥投入和稻桩根茬残留钾素输入量也越高。5年10季水稻年平均钾素表观平衡结果表明,K0、K1和K2处理处于钾素亏缺状态,钾素亏缺量随施钾量的增加而有较大幅度降低,K0处理的钾素亏缺量为127.1 kg/hm^2,K1处理的钾素亏缺量为58.3 kg/hm^2,而K2处理的钾素亏缺量仅为10.8 kg/hm^2;K3和K4处理处于钾素盈余状态,钾素盈余量随施钾量的增加急剧增加,K3处理的钾素盈余量为48.0 kg/hm^2,K4处理的钾素盈余量为109.2 kg/hm^2。

表4 连续5年施钾钾素平衡状况(kg/hm^2)

Table 4 Estimates of soil potassium balance in the 5-year continued application K fertilizer (kg/hm^2)

处理 Treatment	输入钾 Potassium input				植株吸收 Plant uptake	循环钾* Recycled K	钾表观平衡 Apparent balance
	肥料 Fertilizer	秧苗 seedling	灌溉水 irrigation	降雨 rainfall			
K0	0	2.5	14.5	6.7	165.2	14.4	−127.1
K1	156.8	2.5	14.5	6.7	260.4	21.6	−58.3
K2	224.0	2.5	14.5	6.7	281.8	23.3	−10.8
K3	291.3	2.5	14.5	6.7	291.1	24.1	48.0
K4	358.5	2.5	14.5	6.7	297.9	24.9	109.2

注:*表示残留在水稻根系和稻茬中的钾素量。

2.5 施钾量对土壤钾素状况的影响

从5年10季水稻种植后的土壤钾素状况来看(见表5),不同施钾量对耕层土壤中的钾素含量有明显影响,土壤速效钾、缓效钾和全钾含量均随施钾量的增加而提高。不同处理间土壤速效钾含量达到极显著差异($p<0.01$),其值的变化范围为46.8～90.3 mg/kg;除不施钾肥的K0处理较初始土壤降低外,各施钾肥处理的土壤速效钾含量均较试验前有所提高,K1、K2、K3和K4处理分别提高4.84%、15.81%、30.16%和45.65%。土壤缓效钾的变化趋势与土壤速效钾变化趋势相似,其值在104.25～121.50 mg/kg范围内变化,除K0处理较试验前降低,各施钾处理的土壤缓效钾含量均提高,K1、K2、K3和K4处理的提高幅度分别为1.21%、3.26%、5.86%和13.02%。土壤全钾含量也随施钾量的增加而增加,但除施高量钾肥的K4处理外,其他处理土壤中的全钾含量较试验前均有所降低。

表5 连续5年不同施钾量对红壤性水稻土钾含量的影响

Table 5 Effect of the 5-year continued K application on the K contents of reddish paddy soil

处理 Treat	速效钾 Av. K (mg/kg)	缓效钾 Slowly av. K (mg/kg)	全钾 Total K (g/kg)
K0	46.8±0.9eE	104.3±2.2dD	9.03±0.05cC
K1	65.0±3.0dD	108.8±3.7cC	9.08±0.05bcC
K2	71.8±3.1cC	111.0±3.3bcBC	9.10±0.05bBC
K3	80.7±6.4bB	113.8±3.7bB	9.18±0.05aAB
K4	90.3±5.6aA	121.5±6.0aA	9.23±0.05aA

注:不同大小写字母表示差异达1%和5%显著水平。

2.6 施钾量对水稻经济效益的影响

从经济效益来看(见表6),早稻施钾(K_2O)量在0～156 kg/hm^{2}范围内,稻谷产值和增产值随施钾量

的增加而提高；但当施钾(K_2O)量高于 156 kg/hm²时，稻谷产值和增产值反而降低；晚稻的稻谷产值和增产值随施钾量的增加而提高；早、晚稻稻谷产值和增产值主要与产量水平有关。从产投比来看，早、晚稻均以 K2 处理的最大，当施钾量高于 K2 处理时，产投比随施钾量增加而降低，说明早晚稻均以 K2 处理的经济效益较好。

表 6　连续 5 年施钾对水稻经济效益的影响（元）

Table 6　Economic profits of K fertilization on rice from 2008 to 2012

处理 Treat	早稻 Early rice				晚稻 Late rice			
	产值 Output	肥料投入 Fertilizer input	增产值 increase	产投比 Output/input	产值 Output	肥料投入 Fertilizer input	增产值 Increase	产投比 Output/input
K0	11 569	1 120	—	—	14 968	1 063	—	—
K1	12 125	1 685	556	0.98	15 704	1 770	736	1.04
K2	12 408	1 928	839	1.04	16 255	2 073	1 287	1.27
K3	12 486	2 170	917	0.87	16 306	2 376	1 338	1.02
K4	12 418	2 413	849	0.66	16 471	2 679	1 503	0.93

注：2008、2009、2010、2011 和 2012 年稻谷价格分别为：早稻 1.84、2.10、2.16、2.34、2.76 元/kg，晚稻 1.88、2.14、2.24、2.44、2.86 元/kg；肥料 N 3.48、3.91、4.35、4.78、5.22 元/kg；P_2O_5 5.33、5.83、6.33、6.67、7.00 元/kg；K_2O 5.67、6.00、7.67、7.33、7.00 元/kg。

3　讨论与结论

生物量积累是水稻产量形成的基础，而生物量积累又与其体内的营养状况密切相关。钾是水稻生长必需的大量营养元素之一，充足的钾素营养对于提高水稻产量、改善稻米品质具有重要意义，钾素供应不足将限制水稻产量的提高。大量研究表明，施钾能够显著提高水稻产量[8-9]，且晚稻施钾增产效果好于早稻[10]。王强盛等研究发现，在一定的钾肥施用量范围内，水稻产量随施钾量的增加而增加，当钾肥施用量继续增加，水稻产量呈现下降的趋势[11]。本研究连续 5 年定位研究的结果也表明，钾肥(K_2O)施用量在 0～156 kg/hm²范围内，5 年早稻平均产量随施钾量增加而增加，当钾肥 K_2O 施用量高于 156 kg/hm²时，早稻平均产量随施钾量增加而下降；晚稻产量随钾肥施用量的增加而增加，但随钾肥施用量的增加，不同施钾处理的产量差异变化不明显。由此可见，追求水稻高产稳产并不意味着无限度地增加钾肥施用量，合理施钾才是双季稻增产稳产的关键。同时，在考虑钾肥增加水稻产量时还应考虑钾肥投入的经济效益。在本试验中，早、晚稻所有处理中均以 K2 处理的产投比最大，均大于 1，同时早晚稻施钾水平高于 K2 处理时，水稻产量没有显著差异。因此，综合产量和经济效益因素，湖南双季稻生产中按早稻 120 kg/hm² 和晚稻 150 kg/hm² 施入 K_2O，不仅可以提高水稻产量，还可增加经济效益。

钾是作物正常生长必不可少的肥料三要素之一，其吸收、积累、转移和分配对水稻生产和产量形成至关重要[12]。本试验结果表明，施钾显著增加早、晚稻植株吸钾量，尤其是增加稻草中的钾素含量，这与前人的研究结果一致[13-15]。已有对 NPK 在水稻地上部分分布的研究结果表明水稻吸收的 K 主要集中在稻草中[15]，本试验结果表现出同样的趋势。同时，从本试验结果还可发现，施用钾肥增加了稻草吸钾量占水稻植株总钾吸收量的比例。K0 处理的 5 年平均早、晚稻稻草中钾吸收量占早稻总钾吸收量的 83.2%和 82.3%，而施钾处理的稻草钾吸收量占总钾吸收量的 86%以上。这一结果说明水稻吸收的 K 主要集中在营养器官（稻草）中，增施钾肥导致稻草中 K 的分配率提高。钾肥施用后稻草中钾含量和积累量的提高对于稻草还田中钾的循环利用具有十分重要的意义，如何发挥稻草中的钾在水稻生产中的作用值得进一步深入研究。

长期不施钾肥，土壤中的钾素含量呈明显下降趋势，施钾肥或钾肥与有机肥配施对土壤钾素下降有一定的延缓作用[16-17]。国内外研究表明，长期施用钾肥有利于土壤全钾和速效钾的积累[18-19]。范钦桢和谢建昌通过对我国 18 个长期定位试验中土壤速效钾和缓效钾含量的演变规律研究发现，长期施用钾肥有利于提高土壤中的速效钾和缓效钾含量[20]。本研究结果表明，连续定位 5 年 10 季水稻不施钾肥处理的土壤全钾、速效钾和缓效钾含量均较试验开始前有所降低；施钾处理的土壤缓效钾和速效钾含量均高于试验

前，土壤全钾含量除 K4 处理外其他处理均低于试验。这一结果说明施钾能提高土壤速效钾和缓效钾的含量，并对土壤全钾含量的下降有延缓作用。

大量试验结果表明，在目前施肥情况下，农田钾素一般处于亏缺状态，有的还严重亏缺[2, 21-24]。姚源喜[25]等人研究分析了 22 年肥料定位试验土壤中钾素收支平衡状况，发现长期只施用磷肥和钾肥情况下土壤中钾素出现盈余，而氮、磷、钾肥同时施用则土壤中钾素呈现亏缺。中国农业科学院衡阳红壤试验站的多年水稻-水稻-紫云英（作绿肥）的轮作定位试验表明[26]，每季肥料用量为 84 kg/hm^2 K_2O 时，NPK 处理 K_2O 年亏缺量为 42.6 kg/hm^2。对于目前钾素较为丰富的土壤，若仅靠自身的循环，在作物带走的钾素得不到补充的情况下，即使目前作物不缺钾，这种情况也不能持续；对于供钾潜力较低的土壤，由于土壤本身提供的钾素有限，若作物消耗的钾长期得不到补充，将会严重影响其他营养元素如氮、磷的效应[22]。因此，为了维持或提高土壤钾素肥力，使作物高产、稳产，应充分注意土壤钾素的平衡问题。在本试验条件下，K2 处理的钾素略有亏缺，亏缺量为 10.8 kg/hm^2，当低于该施钾水平时则钾素亏缺量增大；K3 处理的钾素盈余量为 48.0 kg/hm^2，当高于 K3 处理的施钾水平时，钾素盈余量有较大增长。因此，考虑土壤钾素表观平衡，在本试验条件下，早稻施 K_2O 120～156 kg/hm^2 和晚稻施 K_2O 150～195 kg /hm^2 较为适宜。

在目前水稻种植条件下，只有坚持合理施用钾肥，才能提高水稻产量，或维持水稻稳产，促进钾素养分循环，保持农田钾素平衡，提高土壤钾素肥力。本文仅在红壤双季稻种植制度下，研究水稻产量、吸钾量和土壤钾素含量状况与施钾量之间的关系，探讨施钾量对水稻经济效益的影响，揭示不同钾肥投入情况下土壤钾素肥力变化的基本规律及其受各种因素影响的规律，并对土壤钾素状况及钾素平衡进行初步探讨，对黏促进南方双季稻区科学合理施用钾肥具有一定的现实意义。但径流量和淋失量对钾素损失量的影响，冬闲期间处理间土壤钾素的不同损失量，耕层土壤（0～20 cm）以下土层的供钾情况，不同处理中土壤的固钾能力和含钾黏土矿物的变化等均有待今后做进一步研究。同时，由于钾肥施用后稻草中的钾含量和积累量大幅度提升，因此，其稻草的循环利用对于土壤钾素和钾肥效应的影响亟待更深入的研究。

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Effect of potassium rates on rice yields and potassium application efficiency in double-rice cropping system under a 5-year located experiment

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Abstract: Effects of potassium fertilizer application on rice yield, K content in plant, K uptake, K-fertilizer use efficiency, potassium balance and economic benefit were studied by using a five-year (2008—2012) located experiment in double-rice cropping system. There were five treatments, K0 (non potassium fertilizer), K1 (84 kg K_2O /hm^2 in early rice and 105 kg K_2O /hm^2 in late rice), K2 (120 kg K_2O /hm^2 in early rice and 150 kg K_2O /hm^2 in late rice), K3 (156 kg K_2O /hm^2 in early rice and 195 kg K_2O /hm^2 in late rice) and K4 (192 kg K_2O /hm^2 in early rice and 240 kg K_2O /hm^2 in late rice). The results show that the K fertilizer application could obviously increase grain yields of early rice and late rice, and under a certain K fertilizer application range, the yield is increased with the increase of potassium application rate. The potassium uptook by rice plant, especially by rice straw is obviously increased with the increase of K fertilizer application amount. The K agronomy efficiency of the K2 treatment is the highest in both early rice (3.12 kg grain/kg K_2O) and late rice (3.70 kg grain/kg K_2O) among all the treatments, and the K recovery efficiency of K1 treatment is the highest in both early rice (41.2%) and late rice (76.4%) and the K recovery efficiency is decreased with the increase of K application amount. K fertilizer application could significantly affect K contents in soils, and the contents of available K, slowly available K and total K in soils are increased with the increase of K fertilizer application amount and the differences of available K among treatments are significant ($p < 0.01$). The apparent K balance in the soil-crop system is negative in the K0, K1 and K2 treatments (127.1 K kg/hm^2, 58.3 K kg/hm^2 and 10.8 K kg/hm^2) after the five-year rice-cropping and the potassium deficient amount is decreased with the increase of K fertilizer application amount, while the apparent K balance is positive in the K3 and K4 treatments (48.0 K kg/hm^2 and 109.2 K kg/hm^2) and potassium surplus amount is increased with the increase of K fertilizer application amount. The ratios of output to input of K fertilizer of the K2 treatment in both of early rice (1.04) and late rice (1.27) are the highest. The overall results suggest that the appropriate potassium application rates are 120 kg K_2O/hm^2～156 kg K_2O/hm^2 in early rice and 150 kg K_2O/hm^2～195 kg K_2O/hm^2 in late rice in this double-rice cropping area.

Key words: Potassium rate, double-rice, rice yield, potassium application efficiency, located experiment

Field-scale K and P fluxes in the bioenergy crop switchgrass: Theoretical energy yields and management implications[§]

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Abstract: Our understanding of how mineral nutrition affects productivity and composition of bioenergy crops grown on marginal lands remains fragmented and incomplete despite world-wide interest in using herbaceous biomass as an energy feedstock. Our aim was to determine switchgrass (*Panicum virgatum* L.) biomass production and maize (*Zea mays* L.) grain yield on marginal soils used previously to evaluate the effect of soil phosphorus (P) and potassium (K) fertility on alfalfa (*Medicago sativa* L.) forage production. Grain yield of maize was reduced on P- and/or K-limited plots that also impaired alfalfa forage yield, whereas switchgrass biomass yields were high even in plots possessing very low available P (4 mg kg^{-1}) and K (<70 mg kg^{-1}) levels. Linear-plateau regression models effectively described the relationship of soil test P and K to tissue P and K concentrations, and tissue P and K concentrations accurately predicted removal of P and K in harvest biomass. However, neither soil test P and K, nor tissue P and K concentrations were effective as diagnostics for predicting switchgrass biomass yield nor could soil tests and their change with cropping predict nutrient removal. Concentrations of cellulose, hemicellulose, lignin and ash were not influenced by P and K nutrition. Predicted bio-ethanol production was closely associated with biomass yield whereas high biomass K concentrations reduced estimated bio-oil production per hectare by as much as 50%. Additional research is needed to identify diagnostics and managements to meet the bioenergy production co-objectives of having high yield of biomass with very low mineral nutrient concentrations (especially K) while sustaining and improving the fertility of marginal soils.

Key words: Bio-ethanol, biomass, bio-oil, *Panicum virgatum* L., phosphorus nutrition, potassium nutrition

1 Introduction

World-wide there is a need to double the amount of land dedicated to agriculture by 2050 if we are going to meet the competing demands for food and bioenergy with projected population increases (*Field* et al., 2008). Current U. S. plans for energy security rely on the conversion of large acreages from food crop production to the production of cellulosic biomass and/or expansion of intensive crop production onto marginal lands. Graminaceous perennials including the improved native species switchgrass (*Panicum virgatum* L.), and low-input native prairies may offer key advantages over use of annuals for biomass production (*Samson* et al., 2005). Farmers can use existing farm equipment and these systems are expected to require far fewer energy and financial inputs than annual row crops. *Heaton* et al. (2004) identified C_4 graminaceous perennials as ideal in terms of multiple ecosystem services while providing high biomass yields with minimal nutrient input. With theoretically more resource-efficient crops, lands currently considered too marginal for intensive food production may be considered suitable for dedicated, bioenergy crops.

At present, limited research on bioenergy crop production on marginal lands has been reported, but biomass production potential of different landscapes and soils remains largely unknown (*Debolt* et al., 2009), and information on nutrient cycling of candidate biomass systems is fragmented and incomplete across all soil types (*Christian* et al., 1997); this represents a critical barrier to profitable, sustainable, and environmentally

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benign on-farm implementation of a global biofuel agenda. Estimates vary widely but suggest that there are 400 Mha of abandoned land available worldwide for biomass production (*Field* et al., 2008). In the U.S., the targeted marginal lands include those currently set aside in conservation programs with highly erodible and nutrient-poor soils where realized productivity potential may be much lower than is used in most modeling analyses forecasting national bioenergy production potential. For example, *Boe* et al. (2009) reported yields of prairie cordgrass (*Spartina pectinata* Link) on marginal soils to be only 17% that obtained on prime soils in South Dakota, USA. Biomass species often react differently as soil quality changes indicating that field research is necessary to quantify species × soils × management interactions. *Lee* at al. (2009) reported that biomass yield rankings of big bluestem (*Andropogon gerardii* Vitman), switchgrass and western wheatgrass (*Pascopyrum smithii* (Rydb.) Á. Löve) varied with year (and rainfall) on the backslope (marginal) site, whereas yield of the latter two species was consistently superior to that of big bluestem on the footslope (better) site. Similar interactions occurred in a seven-year study on marginal soils in Kentucky USA, where yield of eastern gamagrass (*Tripsicum dactyloides L.*), switchgrass, and big bluestem varied with year and stand age (*Stork* et al., 2009). Marginal sites will present both agronomic (e.g., establishment, yield, persistence) and environmental (e.g., nutrient-use efficiency, water-use efficiency, erosion) challenges that need to be quantified for candidate species in order to conduct accurate and meaningful economic analyses and life cycle assessments.

The perennial nature of switchgrass and its low management intensity coupled with its low consumption of energy and agrochemicals are thought to make it the ideal cellulosic bioenergy crop (*McLaughlin and Kszos*, 2005). Switchgrass fertility research historically has focused on N management because of its positive impact on both growth/yield and forage protein when used as hay/pasture for ruminant livestock, with little or no positive effect of K or P on forage production or quality generally observed (*Morris* et al., 1982; *Jung* et al., 1988; *Hall* et al., 1982; *Bredja*, 2000; *Muir* et al., 2001; *Parish and Fike*, 2005; *Haque* et al., 2009). Few tissue-testing diagnostics exist for switchgrass although *Kroth* and *Mattas* (1982) recommended a tissue P concentration of >1 mg kg^{-1} at heading when the crop was to be used for hay or pasture. However, when switchgrass is to be used for biomass, high yield and very low mineral nutrient concentrations are often co-objectives, and the science underpinning strategies to achieve high biomass yield with minimal tissue mineral concentration, including K, is poorly understood. Low mineral concentrations, especially K, Mg, Ca, and Na, are especially critical if the intent is to convert biomass to liquid fuels using thermo-chemical processes because these elements interfere with the efficiency of conversion (*Brown*, 2003; *Madakadze et al.*, 1998), or when used for biomass combustion and electricity generation, increase slagging and fouling of boilers (*Smith and Slater*, 2011).

Previously we studied how P and K nutrition influenced yield, persistence, and forage composition of alfalfa (*Medicago sativa* L.), a forage species known for having a high K requirement (*Berg* et al., 2005; 2007; *Lissbrant* et al., 2009; 2010). Upon completion of this 8-year study, maize was grown for 1 year, then switchgrass was established on these plots in order to inform our understanding of P and K nutrition of switchgrass on marginal soils. The aim of this work was to characterize switchgrass biomass and maize grain yield on soils previously characterized for differential alfalfa forage productivity potential linked to soil P and K fertility. Specific objectives included (i) the quantification of relationships among surface-soil P and K availability, above-ground tissue P and K concentrations, total biomass, P and K accumulation and cell-wall components determining yield quality, and (ii) the evaluation of standard diagnostics for estimating nutrient removal and guiding fertilizer management. The interactive effects of soil P and K fertility on theoretical ethanol and bio-oil yields were also investigated.

2 Material and

Located in west central Indiana, USA, this experiment was overlaid on existing plots from a

recently terminated, long-term (1997 to 2005) alfalfa study on the effect of P and K nutrition on agronomic performance (*Berg* et al., 2005, 2007, 2009; *Lissbrant* et al., 2009, 2010). The site selection for the original alfalfa study was based on poor soil fertility including low concentrations of extractable P (9 to 15 mg kg^{-1}) and low to moderate levels of exchangeable K (108 to 138 mg kg^{-1} exchangeable K) at the onset of the alfalfa nutrition study (*Berg* et al., 2005, 2007). The historic alfalfa plots were 5 m × 10 m and original treatments included four P (0, 25, 50, and 75 kg P ha^{-1} yr^{-1} as triple superphosphate) and five K (0, 100, 200, 300, and 400 kg ha^{-1} yr^{-1} as KCl) rates applied in split applications (half in May, half in September) from autumn 1997 to autumn 2004. Treatments were blocked into four replicates with replicates evenly divided onto the field site's two soil-map units, a Drummer silty clay loam (fine-silty, mixed, superactive, mesic Typic Endoaquoll) and a Lauramie silt loam (fine-loamy, mixed, active, mesic, Mollic Hapludalf). The alfalfa experiment was monitored through the 2004 harvests (four annually) and then grown without measurement in 2005 although plant herbage was removed in summer and again in the autumn. Glyphosate herbicide [N-(phosphonomethyl) glycine; 1.68 kg acid equivalent ha^{-1}] terminated all herbage growth in early spring 2006. To facilitate conversion to switchgrass, maize was planted mid-May 2006 at 71 000 seeds ha^{-1} into the alfalfa residue without tillage. The crop was fertilized with a high N rate (291 kg N ha^{-1} as urea-ammonium nitrate applied in two applications) to overwhelm treatment plot differences in mineralizable N associated with differential alfalfa growth resulting from the P and K treatments. The original treatment plot boundaries for the alfalfa study were maintained. On October 24, 2006 5.3 m of the center two maize rows of each plot were hand-harvested, shelled and analyzed for grain moisture content. Maize stover was dried to constant moisture (65℃); grain and stover are reported on a dry-weight basis.

In spring 2007, the historic alfalfa plot boundaries were reconfirmed and on May 22nd, 2007, an upland ecotype of switchgrass (*Panicum virgatum* L.; Shawnee) was no-till seeded at a rate of 18 kg ha^{-1}. No additional fertilizers were applied and throughout the 2007 growing season the establishing switchgrass plots were mowed twice to leave a 10 cm stubble and hand-weeded as needed to control weeds. No biomass was collected in the autumn of 2007. Starting in the 2nd year of the study, all plots were fertilized with 84 kg N ha^{-1} yr^{-1} in May as Agrotain™-treated urea. Forage was harvested on August 14 and 15, 2008, using a Carter flail-type chopper (Carter Manufacturing Co., Brookston, IN) and on August 27, 2009, and October 30, 2010, with a Wintersteiger biomass harvester (Wintersteiger, Inc., Salt Lake City UT USA). The harvesters sampled a 1 m wide swath through the center of each 10 m long plot. A subsample of the harvested biomass was weighed, and dried at 65℃ for 48 h. The dried sample was re-weighed and percent dry matter of the forage used to calculate yield per plot; biomass is reported on a dry-weight basis.

To monitor soil P and K levels, soil samples were obtained following the maize harvest in 2006 and after each switchgrass biomass harvest in 2008—2010. A 12-core composite was collected using 2.5 cm hand probes from each historic treatment plot in two discrete depth increments (0 to 10 cm and 10 to 20 cm). Samples were air-dried in a greenhouse. Soil samples were crushed to pass a 2 mm mesh and plant-available P and K levels were determinedusing the Mehlich III extraction method (*Mehlich*, 1984). Extractable K concentrations were quantified using a single-channel flame photometer (Model EW-02655-00; Cole Palmer, Vernon Hills IL USA), while P concentrations were assessed following a modified phospho-molybdate colorimetric procedure (*Murphy* and *Riley*, 1962) using a Perkin Elmer Lambda XLS+spectrophotometer (Perkin Elmer, Waltham MA USA). Plant tissues were ground to pass a 1 mm screen and digested (200 mg tissue) in 5 mL 15.8 M sulfuric acid following a modified micro-Kjeldahl digestion protocol (*Nelson* and *Sommers*, 1973) using a BD "s" Series Block Digestion System (SEAL Analytical Inc., Mequon, WI USA). Potassium and P concentrations in digests were analyzed as described for soils (above).

Potassium and P removals by switchgrass stands in each plot were quantified directly by year as the

product of harvest dry weight and concentration and indirectly for the 3 yr experiment as the measured change in soil test levels between autumn 2006 and autumn 2010 (sum of 0 – 10 and 10 – 20 cm depth increments). The indirect, soil-based estimate used bulk density values of 1.39 and 1.45 g cm^{-3} for 0 – 10 and 10 – 20 cm layers, respectively, data previously reported by *Fernandez* et al. (2008) for the same site.

Biomass composition was analyzed using the detergent fiber analysis system (*Van Soest* et al., 1991) modified as follows. Dried and ground (1 mm) switchgrass forage samples for each plot were weighed (0.5 g) and placed into pre-weighed F57 filter bags (ANKOM Corp., Fairport NY). Samples were analyzed for neutral detergent fiber (NDF) and acid detergent fiber (ADF) using an ANKOM 2000 Fiber Analyzer (ANKOM Corp., Fairport NY USA; *ANKOM* 2005, 2006; *Vogel* et al., 1999). Acid detergent lignin (ADL) was determined using a Daisy II wheel incubator (ANKOM Corp., Fairport NY USA). Samples in fiber bags were extracted with NDF solution as described above, then placed in Daisy II incubator jars and covered with 72% (v/v) H_2SO_4. The samples were rotated in the incubator for 3 h at room temperature. After rotation, the samples were washed eight times in hot water to remove H_2SO_4, rinsed in acetone for 10 min, and dried at 102℃ for 12 h. The fiber bags were weighed, placed in crucibles, and combusted in a muffle furnace at 525℃ for four hours to determine residual ash. Crucibles with ash were weighed and ADL was calculated, while accounting for the ash correction factor. Hemicellulose concentration was calculated by subtracting the ADF concentration from the NDF concentration. The cellulose concentration was calculated by subtracting the ADL concentration from the ADF concentration (*Lemus* et al., 2002). Total ash was determined by placing 1 g of plant tissue into pre-weighed crucibles, combusting the samples in a muffle furnace at 600℃ for 4 h, and weighing the remaining residue (Method 942.05, *AOAC* 2005).

A combination of continuous and categorical variable approaches was used to understand relationships among crops and soils. Simple correlations (*Minitab*, 2000; Minitab Inc., State College, PA USA) compared biomass yields among alfalfa in the last year of the study (2004), maize (grain, stover and total aboveground dry matter, 2006), and switchgrass (2008, 2009, 2010). Linear regression (SigmaStat, Systat Software, Inc., Chicago, IL) characterized switchgrass yield as a function of soil and tissue P and K concentrations and P and K removals as a function of dry matter yield. A linear-plateau model characterized relationships between maize yield and the 2004 alfalfa yield, P and K concentration in tissue and that in the surface soil (*SigmaPlot*, 2007; Systat Software, Inc., Chicago, IL USA).

For the categorical analysis, previous, related work at the experimental site had classified the historic treatment plots according to stand performance in the last year (2004) of the alfalfa study. As described by *Lissbrant* et al. (2010), the May 2004 harvest was selected as a reference harvest reflecting the long-term treatment evolution; nonhierarchical clustering using the *K*-means approach classified the 80 plots into six different performance clusters that differed significantly in yield. Variance reduction analysis after *Brock* et al. (2005) verified the number of clusters as appropriate as minimal additional variance reduction was achieved when observations were divided into seven or more clusters. The numbers of plots in each performance cluster were 17 to 20 for Medium-High, Medium, and Low performing clusters (MH, M, L, respectively), 11 for High and Medium-Low performing clusters (H, ML, respectively) and 3 for the Very Low performing cluster (VL) where the alfalfa stand had effectively died prior to the last study year. The switchgrass plots were assigned to the same clusters used to analyze alfalfa performance (High, Medium High, Medium, Medium Low, Low, and Very Low) as previously reported (*Lissbrant* et al., 2010). Performance of the maize transition crop and switchgrass stands among these previously identified clusters was compared within years for numerous attributes measured in experiment years 2008 to 2010. Classifying switchgrass data into these pre-existing clusters permitted evaluation of the similarity between alfalfa, maize and switchgrass responses

to fertility-limited soil conditions reflecting both fertilizer additions and extreme, micro-scale soil P and K variability that predated any fertilizer additions. Data were analyzed using unpaired t-tests (*Minitab*, 2000; Minitab Inc., State College PA) to determine differences in yield as well as herbage P and K, soil test P and K, and cell wall fiber concentrations among clusters within a year.

Finally, theoretical ethanol yields were estimated for each plot year as the product of above-ground biomass and the species-specific conversion factor for the Shawnee cultivar of 412 L t^{-1} identified by *Vogel* et al. (2011). Theoretical bio-oil yields were estimated using the following formula:

$$\text{bio-oil yield (L ha}^{-1}) = [(\text{DM}) \times (\text{bio-oil yield (wt. \%)})] / \text{bio-oil density} \quad [1]$$

where DM was the above-ground dry matter measured at harvest, bio-oil density was assumed constant at 1.2. kg L^{-1} after (*Rogers* and *Brammer*, 2012) and bio-oil yield as wt % was estimated from tissue K concentration following *Coulson* (2006) where

$$\text{bio-oil yield as wt. \%} = 62.5 - (24 \times \%\text{K}) \quad [2]$$

For this calculation we assumed that sodium (Na) concentrations were negligible and that K was the only alkali metal present in switchgrass biomass. Previous Na analysis of alfalfa grown on these plots in 2004 (n=320) revealed that average forage Na concentration (0.21 g kg^{-1}) represented 1.1% of the sum of Na+K in tissues (mean K concentration of 19.73 g kg^{-1}). The interactive P/K effects on theoretical energy production were examined for a subset of plots (n=24) within each year. A two-sample t-test was used to compare dry matter and estimated ethanol and bio-oil yields between treatments with highest and lowest (15 % or 12 plots for each class) tissue K concentrations within each year. Likewise, K concentrations and theoretical energy yields were compared for treatments with highest and lowest tissue P concentrations.

3 Results

3.1 Maize and switchgrass yields within historic alfalfa clusters

The historic P/K fertility regimes previously identified as important for alfalfa productivity affected maize productivity but had little to no influence on switchgrass productivity in any study year. In 2006, maize grain yields in plots previously identified as highest (H) and medium highest (MH) yielding for alfalfa averaged 12.80 and 13.03 t dry matter ha^{-1}, respectively, and were not significantly different from each other; the individual plot yields from these two clusters were distributed around a plateau of 12.00 t ha^{-1}(Fig 1a). In contrast, the H cluster average yield for alfalfa in 2004 was 4.39 t ha^{-1}, 15% higher than the yields in the MH cluster.

Non-linear regression of individual maize plot yields on 2004 alfalfa yields identified a linear and plateau relationship with a break point at an alfalfa yield of 2.88 t ha^{-1} and alfalfa yields from plots in the medium (M), medium low (ML), low (L) and very low (VL) were predominately below the break-point value. Maize yields corresponding to alfalfa yields below the break point decreased 1.89 kg grain ha^{-1} for every 1 kg ha^{-1} decrease in alfalfa herbage yield. However, the mean maize yield in the ML cluster was not significantly different than maize yields in H and MH clusters. The VL cluster averaged only 6.53 t maize grain ha^{-1}, significantly lower than all other clusters. Maize stover dry matter yields followed grain yields with a harvest index of 0.64 kg grain kg^{-1} total biomass (exclusive of cobs) in all clusters save the VL where an index of only 0.55 kg kg^{-1} was observed (stover data not shown).

In contrast to maize, alfalfa cluster identity had little effect on switchgrass yields with no significant yield differences observed among clusters after stand establishment. In 2008, the first-year yields were evaluated following planting in 2007, switchgrass yields averaged 11.75 t ha^{-1} across clusters and yields were significantly lower in M and VL clusters when compared to H and L clusters (Fig. 1b). However, in the 3rd growth season (2009) when stands were considered fully established, yields averaged 12.25 kg

ha^{-1} and no differences were observed among clusters. Likewise in 2010, yields were similar among clusters although they were significantly ($p < 0.1\%$) lower (9.89 kg ha^{-1} averaged across clusters) when compared to earlier years. Irrespective of cluster, simple correlations of individual plot yields of switchgrass with the 2004 plot yields for alfalfa found a weak but significant correlation in 2008 but no relation in 2009 and 2010 (Fig. 1b inset). Correlations among plot-level switchgrass yields in successive years were not significant.

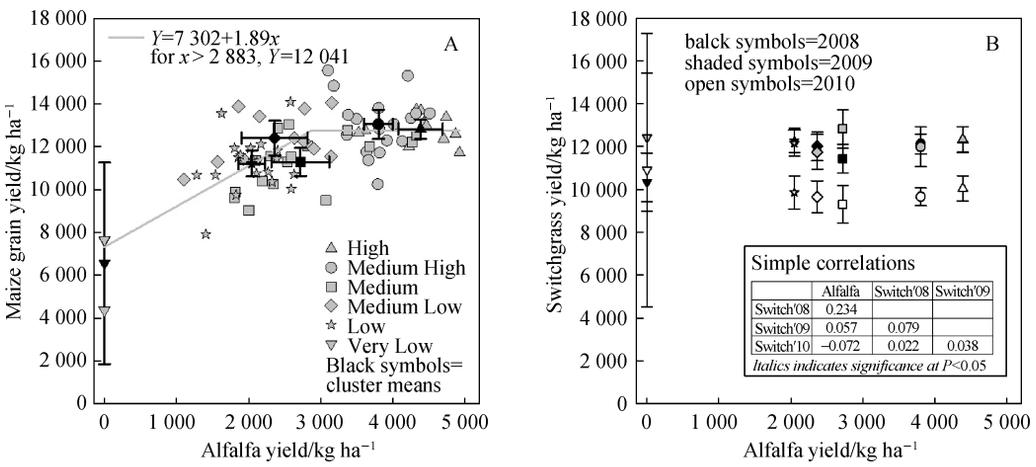

Figure 1 Relationship between alfalfa forage yield in 2004 and maize grain yield in 2006 (A) and switchgrass biomass yield in 2008 to 2010 (B). The high, medium high, medium, medium low, low and very low yielding clusters of plots were assigned in the alfalfa experiment (*Lissbrant* et al., 2010). Cluster means and standard errors are provided. The linear-plateau regression of maize grain yield on alfalfa forage yield was significant (A). Switchgrass biomass yield was weakly correlated with alfalfa forage yield in 2008, but not in 2009 and 2010, and switchgrass biomass yields were not correlated across years (B).

It should be noted that overall lower switchgrass yields in 2010 as compared to previous years likely reflected the comparatively later harvest (October versus August) as well as growth-season weather-conditions. In 2010, substantial lodging was observed with the delayed harvest. Further, growing season (April — Oct.) mean daily air temperatures averaged 18.0 and 17.3℃ in 2008 and 2009, respectively, and approximated the 30 yr mean of 17.4℃. In contrast, the 2010 growing season was an average 2.3℃ warmer (weather data not shown). These warmer temperatures may have advanced maturity and thus reduced the timeframe for biomass accumulation.

3.2 Linkages among soil and switchgrass biomass P and K status

Analysis of variance using the factorial structure of the original P and K fertilizer treatments applied to alfalfa from 1997 and 2004 revealed that soil test P and K levels remained significantly different in 2008 to 2010 during switchgrass sampling. Averaged over years, soil test P (0 – 10 cm depth) increased from 5.1 to 8.7, 18.8, and 42.6 mg kg^{-1} as fertilizer-P application to alfalfa increased from 0, to 25, 50, and 75 kg ha^{-1}, respectively, while soil test K (0 – 10 cm depth) increased from 85 to 94, 121, 158, and 223 mg kg^{-1} as fertilizer K applications to alfalfa increased from 0 to 100, 200, 300, and 400 kg ha^{-1}, respectively. In general, estimates of available soil P identified marked stratification between 0 – 10 and 10 – 20 cm soil layers; within layers, mean cluster values declined in each successive year (Tab. 1). The plots previously identified as highest yielding for alfalfa (H) were characterized by comparatively high Mehlich-3 P concentrations in surface soils. Initial values observed in 2006 at 0 to 10 cm were approximately 33 mg kg^{-1} declining by 50% by 2010. Within any experimental year, H cluster P values in the 0 – 10 cm layer were not significantly different from those observed in any other cluster except the M cluster where values declined from >10 to <5 mg P kg^{-1} soil during the course of the experiment. Soil P values observed in the 10 – 20 cm layer tended to be only a third or a quarter of the values in the surface layer; again, the exception was the M cluster where soil P values at 10 to 20 cm averaged about 75% of surface soil values. For a given layer within any year, the cluster identified as

VL yielding for alfalfa tended not to differ significantly from any other cluster.

Table 1 Phosphorus concentrations of the surface 0 – 10 cm and 10 – 20 cm soil depths in 2006 (maize cropping year) and 2008 to 2010 (switchgrass cropping). The arithmetic mean of the soil depth increments also is provided. The H, MH, M, ML, L, and VL are high, medium high, medium, medium low, low and very low yielding clusters of plots, respectively, as identified in the preceding alfalfa experiment (*Lissbrant* et al., 2010).

Soil depth (cm)	Year	Cluster					
		H*	MH	M	ML	L	VL
		---------- mg kg^{-1} ----------					
0 – 10	2006	32.6a[a]	25.7a	10.8b	33.7a	23.5a	37.3ab
	2008	29.4a	26.5a	7.1b	31.6a	22.7a	44.5ab
	2009	23.6a	21.9a	4.9b	27.6a	17.3a	34.5ab
	2010	16.6a	15.7a	4.8b	22.4a	15.3a	24.1ab
10 – 20	2006	8.5ab	8.3ab	7.2b	11.9a	8.7ab	18.0ab
	2008	6.2a	5.8a	5.9a	7.9a	5.8a	7.4a
	2009	5.5a	5.7a	3.3b	7.5a	5.9a	6.6ab
	2010	4.5a	5.1a	2.7b	5.4a	5.0a	4.5ab
Arithmetic mean	2006	20.5a	17.0a	9.0b	22.8a	16.1a	27.7ab
	2008	17.8a	16.2a	6.5b	19.8a	14.2a	25.9ab
	2009	14.6a	13.8a	4.1b	17.6a	11.6a	20.5ab
	2010	10.6a	10.4a	3.8b	13.9a	10.2ab	14.3ab

[a]Means within rows followed by the same letter are not significantly different ($p < 5\%$)

Likewise, extractable soil K values were notably stratified with higher values observed for the surface-most layer (Tab. 2). However, value changes over the course of the experiment were not apparent in all treatment clusters. Soil K values were greatest in the M cluster where surface soils declined from 236 to 139 mg K kg^{-1} between 2006 and 2010, respectively; values at 10 – 20 cm were relatively stable across experimental years and averaged 102 mg K kg^{-1}. The H, MH, ML, and L clusters exhibited more moderate K levels ranging from 103 to 187 mg kg^{-1} at 0 – 10 cm and from 63 to 86 mg kg^{-1} at 10 – 20 cm across experimental years. The VL cluster averaged 80 and 58 mg kg^{-1} in surface and subsurface layers, respectively. Within years, VL surface soil and arithmetic mean values tended to be significantly lower than the values of all other clusters save those of the L cluster in 2006.

Table 2 Potassium concentrations of the surface 0 – 10 cm and 10 – 20 cm soil depths in 2006 (maize cropping year) and 2008 to 2010 (switchgrass cropping). The arithmetic mean of the soil depth increments also is provided. The H, MH, M, ML, L, and VL are high, medium high, medium, medium low, low and very low yielding clusters of plots, respectively, as identified in the preceding alfalfa experiment (*Lissbrant* et al., 2010).

Soil depth (cm)	Year	Cluster					
		H*	MH	M	ML	L	VL
		---------- mg kg^{-1} ----------					
0 – 10	2006	145bc[a]	187ab	236a	127c	133cd	78d
	2008	157ac	166a	186a	118bc	124c	75d
	2009	131abc	144ac	160a	103bc	113c	74d
	2010	130ab	148a	139ab	117b	119b	91c
10 – 20	2006	65b	74b	107a	65b	66b	53b
	2008	85b	86ab	112a	73c	82bc	61d
	2009	69ab	72ab	89a	63b	72abc	53c
	2010	85abc	84ac	98a	69bc	83abc	65c
Arithmetic mean	2006	105bc	131ab	172a	96c	89cd	65d
	2008	121a	126a	149a	96b	103a	68c
	2009	100a	108a	125a	85b	93a	64c
	2010	108a	116a	119a	93b	101a	77c

[a] Means within rows followed by the same letter are not significantly different ($p < 5\%$)

Among clusters, tissue P values reflected the gross differences in soil P status with relatively higher

concentrations occurring in H, ML and L clusters when compared to the M cluster where the 3 yr averaged 0.86 mg g^{-1} (Tab. 3). Across years, plant P concentrations in the M cluster varied from 48 to 65% of the concentrations measured in VL cluster tissues. Nonlinear regression of individual plot tissue P values assessed as a function of soil P identified linear-plateau relationships with breakpoints and plateaus varying with year and soil layer (Fig. 2a and b). Tissue values increased linearly with surface soil-P to a break point of 23, 15 and 10 mg P kg^{-1} soil in 2008, 2009 and 2010, respectively; these breakpoints were significantly different from each other and corresponded to plateaus in tissue P concentration of 1.6, 1.3 and 1.2 g kg^{-1} (2008, 2009, and 2010, respectively). Among years, relationships between tissue concentrations and soil P measured at 10 - 20 cm were less distinct than relationship with 0 - 10 cm soil test values; break points ranged from 5 (2008) to 8 (2009) mg P kg^{-1} soil.

Table 3 Phosphorus (P) and potassium (K) concentrations of switchgrass biomass sampled in 2008 through 2010. The H, MH, M, ML, L, and VL are high, medium high, medium, medium low, low and very low yielding clusters of plots, respectively, as identified in the preceding alfalfa experiment (*Lissbrant* et al., 2010).

Nutrient	Year	Cluster					
		H*	MH	M	ML	L	VL
		---------- mg g^{-1} ----------					
P	2008	1.50a[a]	1.40b	1.10c	1.60a	1.40b	1.70a
	2009	1.14b	1.10b	0.76d	1.40c	1.10b	1.60a
	2010	1.30a	0.99b	0.72c	1.10ab	1.10ab	1.50ab
K	2008	10.3ac	10.4a	10.0ac	9.20c	7.80d	6.20e
	2009	7.30ab	8.00a	7.70a	6.70b	6.30b	4.20c
	2010	3.30ab	3.80a	3.30ac	2.76bc	2.70c	1.60d

[a] Means within rows followed by the same letter are not significantly different ($p < 5\%$)

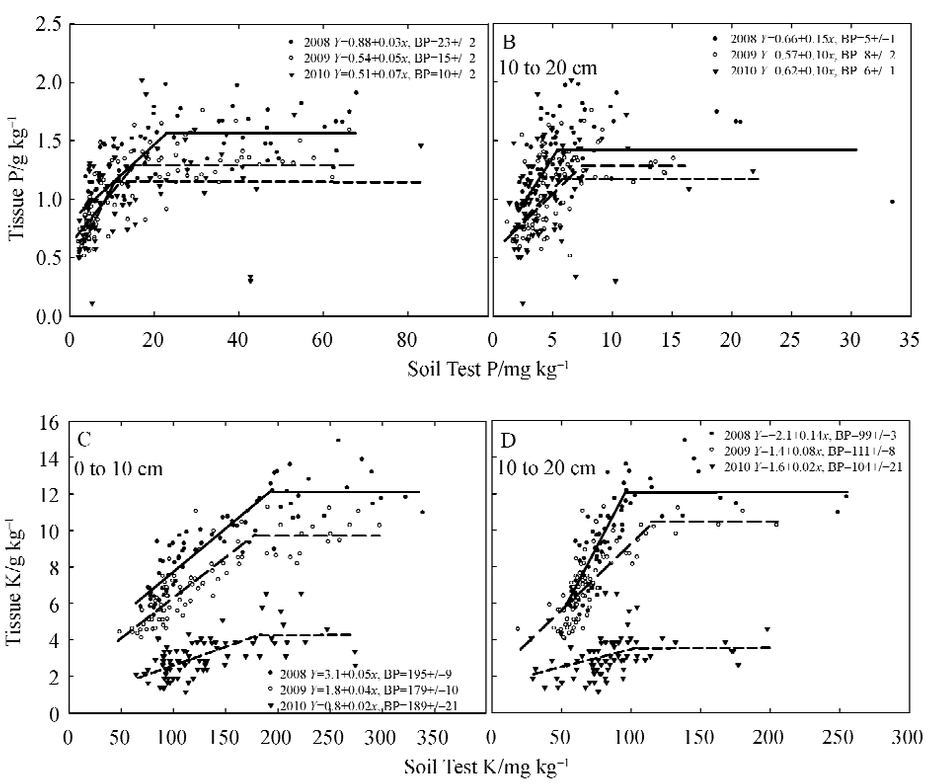

Figure 2 Linear-plateau regressions of soil-test phosphorus (P) and potassium (K) on tissue P (A, B) and K (C, D) concentrations in 2008 to 2010. Analyses were conducted separately for the 0 - 10 cm (A, C) and 10 - 20 cm (B, D) soil depth increments. Break points (BP, ± standard error) identify the transition from the linear response of tissue P or K to increasing soil P or K, respectively, and the non-responsive plateau.

As observed for tissue P concentrations, tissue K concentrations generally tracked the soil test K levels with highest tissue concentrations observed in H, MH, and M clusters, intermediate concentrations in ML and L clusters, and lowest concentrations in the VL cluster (Tab. 3). Likewise, non-linear regression identified linear and plateau relationships between individual plot tissue K concentrations and corresponding soil test K values. For a given soil layer, relationships of tissue K to soil test K revealed similar break-point values for the three experimental years. Tissue K concentrations were maximized at just under 200 mg K kg^{-1} soil and approximately 100 mg K kg^{-1} soil for 0 - 10 (Fig. 2c) and 10 - 20 (Fig. 2d) cm soil layers, respectively. However, tissue concentrations in the delayed 2010 harvest were markedly reduced when compared to other years; tissue concentrations plateaued at approximately 4 g kg^{-1} in 2010 as compared to 12 g kg^{-1} in 2008.

Within and among years, correlation and regression analyses found no significant relationship between individual plot yield and i) either soil (both depths and arithmetic mean) or tissue P concentrations (data not shown) and ii) either soil (both depths and arithmetic mean) or tissue K concentrations (data not shown).

3.3 Best predictors of P and K removal in biomass

Annual K removal ranged from 15 to 165 kg ha^{-1}, while annual P removal ranged from 2 to 25 kg ha^{-1} (Fig. 3). Evaluation of yield and plant nutrient concentration as predictors of nutrient removal identified the latter as the better predictor for both P and K. Across all study years, both P and K removal were a significant linear function of yield but yield explained only 26 and 35% of variation in P (Fig. 3a) and K (Fig. 3c) removal, respectively. In contrast, tissue P concentration explained 84% of P removal variation (Fig. 3b) while tissue K concentration explained 94% of the variation in K removal (Fig. 3d) among all plot-year observations.

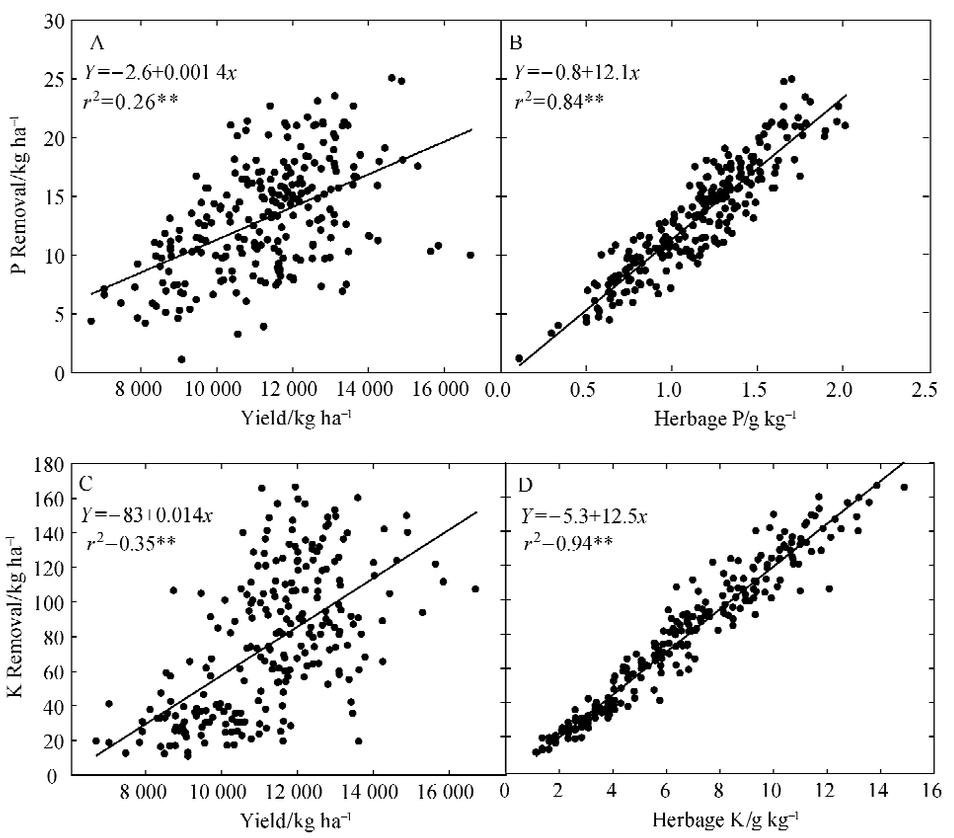

Figure 3 Linear regressions of phosphorus (P) and potassium (K) removal in switchgrass biomass versus biomass yield (A, C) and plant P and K concentrations (B, D). Plots include data from 2008 to 2010. Regressions are significant at $p < 1\%$, however, coefficients of determination (r^2) were lower for the removal-yield relationships.

Cumulatively over the 3 yr study up to 43 and 215 kg ha^{-1} of P and K, respectively, were removed with the harvested biomass (Fig. 4). Summed changes in the P and K contents of the 0－10 and 10－20 cm soil layers between the beginning (autumn 2006) and the end (autumn 2010) of the switchgrass experiment were significant but relatively poor predictors of cumulative nutrient removal by the 3 successive years of switchgrass cropping (R^2 of 0.14 and 0.29 for P (Fig. 4a) and K (Fig. 4b), respectively). On a land-area basis, slopes from regression of cumulative crop removal as a function of net change in soil nutrient content suggest a 1 kg change in soil P content corresponded to only 187 g P removal by the crop while a 1 kg change in soil K content reflected net K removal of 268 g. However, for both nutrients, soil changes under- rather than over-estimated nutrient removal as the majority of observations fell well to the left of a one-to-one relationship between removal by the crop and net loss from the soil.

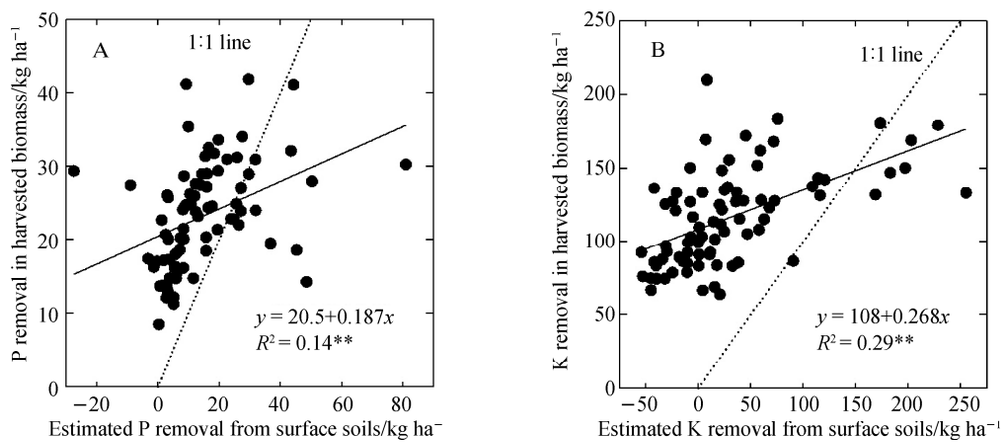

Figure 4 Linear regression of phosphorus (P) and potassium (K) removal in switchgrass biomass versus estimated P and K removal from the surface soils based on changes in soil test P and K concentrations. Regressions were significant at $p < 1\%$. Coefficients of determination (R^2) are provided. The fine-dotted line represents the 1 : 1 relationship between actual and estimated nutrient removal.

3.4 P/K influences on biomass fiber composition and estimated energy yields

Across years, P and K fertility regimes had almost no effect on any aspect of biomass fiber composition. Among years and clusters, hemicellulose concentration varied from 281 g kg^{-1} (M cluster in 2008) to 307 k kg^{-1} (VL cluster in 2010; Tab. 4). A significant difference among clusters was only observed in one year (2010) where the concentration mean of the lowest cluster (MH) was 98% of the value observed in the highest cluster (VL). Cluster cellulose concentrations ranged from 299 to 351 g kg^{-1} (2009 ML and VL clusters, respectively); small but significant differences occurred in 2008 when ML and MH averaged 333 g kg^{-1}, 12 g kg^{-1} higher than concentrations in the M cluster. Lignin values varied among years and significant differences among clusters were observed in the year with the greatest lignin concentrations (2010) reflecting the delayed harvest in that year. Lignin concentrations in the VL

Table 4 Hemicellulose, cellulose, acid detergent lignin (ADL) and total ash concentrations in switchgrass biomass from 2008 to 2010. The H, MH, M, ML, L, and VL are high, medium high, medium, medium low, low and very low yielding clusters of plots, respectively, as identified in the preceding alfalfa experiment (*Lissbrant* et al., 2010).

Cell-wall component	Year	Cluster					
		H*	MH	M	ML	L	VL
		g kg^{-1}					
Hemicellulose	2008	293bc[a]	294abc	297ab	300ac	290bc	297abc
	2009	284	283	281	286	284	291
	2010	299ab	300b	304ab	303ab	300ab	307a

续 表

Cell-wall component	Year	Cluster					
		H*	MH	M	ML	L	VL
Cellulose	2008	330ab	332a	321b	334a	333a	348ab
	2009	328	356	334	299	349	351
	2010	343	323	339	330	337	310
ADL	2008	68.4	67.1	74.6	65.6	67.6	70.26
	2009	84.5	89.2	88.8	89.6	90.9	90.5
	2010	111a	112a	109a	118a	112a	75.0b
Ash	2008	39.1	38.9	41.5	38.8	38.5	39.4
	2009	39.1ab	38.6b	39.9a	38.8ab	40.5ab	39.3ab
	2010	38.6	37.9	38.9	38.3	37.9	39.0

[a]Means within rows followed by the same letter are not significantly different ($p < 5\%$)

cluster (75 g kg^{-1}) were reduced by approximately one third when compared to means of all other clusters. Ash ranged from 37.9 (MH and L, 2010) to 41.5 (M, 2008) g kg^{-1} but the only significant difference was a 3% difference (1.3 g kg^{-1}) between MH and M clusters in 2009.

The interactive P/K effects and implications for theoretical energy production are illustrated by the within-year comparison of yields for a subset ($n=24$) of plots corresponding to the highest and lowest 15% of observed K concentrations and the highest and lowest 15% of observed P concentrations. Subsetting of highest and lowest 15% of tissue K concentrations within a year illustrated that higher K concentrations tended to correspond to lower P concentrations although tissue P concentrations between the highest and lowest K concentration plots were not always significant (Tab. 5). Trends in associated dry matter yield showed that the high K (low P) plots corresponded to numerically lower mean yields as compared to the low K (high P) plots (within-year yield differences were significant at $p<10\%$ in 2008 and 2009) suggesting P-limited growth in high K (low P) plots. Likewise, the subset of plots selected for contrasting highest and lowest P concentration exhibited lower K concentrations in association with high P concentrations (K concentration differences for high/low P concentration plots significant in 2009

Table 5 Means (±standard error) for tissue potassium (K), phosphorus (P), biomass yield, and predicted ethanol and bio-oil production. Plots with the highest 15% ($n=12$) and lowest 15% ($n=12$) tissue K or P concentrations were identified within each year and means compared using a two-sample t-test. Ethanol production values were not analyzed statistically because they are simply calculated from yield as described[a].

Nutrient	Year	Group	Tissue K	Tissue P	Yield	Predicted ethanol[a]	Predicted bio-oil[b]
			---- g kg^{-1} ----		kg ha^{-1}	---- L ha^{-1} ----	
K	2008	High	13.0±0.3**	1.22±0.17	11 299±270	4 655	2 949±85
		Low	6.0±0.1	1.31±0.30	12 157±40±	5 009	5 297±156**
	2009	High	10.4±0.5**	0.73±0.26	11 696±353	4 819	3 645±115
		Low	4.5±0.2	1.26±0.27**	12 510±29±	5 154	5 399±133**
	2010	High	5.0±0.9**	0.96±0.35	9 331±393	3 844	3 936±179
		Low	1.6±0.3	1.22±0.30±	9 805±480	4 040	4 790±237**
P	2008	High	8.4±0.3	1.80±0.03**	12 082±30±	4 978	4 267±158±
		Low	9.3±0.8	0.92±0.03	11 185±336	4 608	3 756±240
	2009	High	6.5±0.6	1.55±0.03**	11 850±362	4 882	4 657±232
		Low	9.2±0.5**	0.62±0.02	12 387±583	5 103	4 197±284
	2010	High	2.8±0.2	1.58±0.06**	10 433±43±	4 298	4 852±173*
		Low	3.8±0.4*	0.49±0.05	9 386±501	3 867	4 166±234

** Indicates high versus low group means differ within a year for that nutrient at $p < 1\%$

* Indicates high versus low group means differ within a year for that nutrient at $p < 5\%$

± Indicates high versus low group means differ within a year for that nutrient at $p<10\%$

[a] Ethanol per ha was calculated using 0.412 L/kg dry matter yield as reported by Vogel et al. (2011).

[b] Bio-oil per ha was calculated using Equations 1 and 2 described in Material and methods.

and 2010). In this case, however, trends in yields were reversed with higher yields in high P (low K) plots when compared to low P (high K) plots suggesting this contrasting set of observations exhibited tissue K dilution associated with P-driven growth (yield differences significant in $p<10\%$ in 2008 and 2010).

Given the minimal effects of P/K regime on biomass fiber composition (Tab. 4)—justification for using a single, species/cultivar-specific conversion value of 0.412 L kg^{-1} for theoretical ethanol yield estimation—any trend toward dry matter yield differences among plots with contrasting P or K concentrations are translated directly into ethanol yields. Thus, a minimal effect of plant P/K status on output of energy via biochemical processing was observed as significant differences in yield corresponded to a differential ethanol yield of only <431 L ha^{-1} ($<10\%$ reductions). In contrast, a high K concentration negatively affected estimated bio-oil yields from a thermochemical processing pathway. Significant bio-oil reductions of 18 (854 L ha^{-1}, 2010) to 44% (2 348 L ha^{-1}, 2008) were observed in plots selected for high K (low P and P-limited growth) as compared to low K (high P) plots. Conversely, high P (low K and P-driven growth) tended to produce substantially more bio-oil than the low P (high K) plots with significant differences of 12 and 14% in 2008 and 2010, respectively. It should be noted that the lower K concentrations observed in 2010 associated with the delayed harvest improved the biomass conversion such that bio-oil yield was comparable across years.

4 Discussion

A general consensus for viable biomass enterprises stipulates use of agriculturally marginal lands with minimal fertilizer, pesticide, and fossil fuel inputs—agro-ecosystems where perennials are likely to outperform high-input annuals including maize (*Hill* et al., 2006; *Lewandowski* and *Schmidt*, 2006). Switchgrass, a warm-season perennial native to the U.S., has been much touted for its ability to produce high yields with low soil fertility making it suitable for use on U.S. farmlands otherwise considered marginal for crop production (e.g. *Parrish* and *Fike*, 2005; *Sanderson* and *Adler*, 2008; *Schmer* et al., 2008; *Walsh* et al., 2003; *McLaughin* and *Kszos*, 2005). However, to date, few if any studies have tested the switchgrass marginal land concept directly with respect to classifications of interacting P/K limitations and the production potential of switchgrass as compared to the predominant and high value forage legume (alfalfa) and row crop (maize). Our results suggest that classifying soils as P/K marginal for alfalfa was useful for predicting maize productivity but largely unimportant for switchgrass.

In the original alfalfa work, *Lissbrant* et al. (2010) applied the clustering approach because P and K fertilizer treatments were confounded by strong plot-to-plot variability in native soil P and K availability that were not adequately addressed by the randomized complete block experimental design. Each cluster contained a variety of the P/K fertilizer treatments but the analysis of alfalfa performance and surface soil and herbage P and K concentrations identified the M cluster as moderately P-limited, the ML cluster as moderately K-limited, the L cluster as slightly P- and moderately K-limited and the VL cluster as extremely K-limited. With the exception of the moderately K-limited cluster (ML cluster), the P/K restrictions to alfalfa productivity were reflected in reduced maize grain yields (Fig. 1a). Note, the 12 t ha^{-1} plateau identified in non-linear regression of maize yield as a function of alfalfa yield typifies regional yields for well-managed maize with no fertility restrictions suggesting our results are relevant even though maize data comprised a single experimental year. In contrast, during establishment only minimal yield reductions were observed for switchgrass with moderate P (M cluster) and extreme K (VL cluster) limitations. In subsequent years when stands were established switchgrass biomass yield was insensitive across the array of P/K conditions at the experimental site (Fig. 1) despite continued nutrient extraction (Tabs. 1 and 2).

Fertilizer management guides for the U. S. Midwest identify critical levels for P in the 0 – 20 cm soil layer of 15 mg kg^{-1} for alfalfa and wheat and 25 mg kg^{-1} for maize and soybean (*Vitosh* et al. , 1995) but offer no guidance on switchgrass despite its use as a forage. However, several recent studies on low-fertility soils have addressed the historic dearth in P management for switchgrass. *Brejda* (2000) reviewed the literature from the forage management perspective and suggested applying P fertilizer to soils falling below 20 or 25 mg kg^{-1} depending on location but *Lemus* et al. (2009) characterized soil P levels of 2 to 15 mg kg^{-1} as adequate for producing high biomass yields. Further, *Kering* et al. (2012) found the higher-yielding, lowland ecotype Alamo responded to P applications (45 kg ha^{-1} yr^{-1}) in the 2nd through 4th year of growth in only one of two experiments established on soils testing below 3. 5 mg P kg^{-1} (extraction protocol not specified). Our results provide further confirmation of a P critical value for biomass switchgrass in the range of 2 or 3 mg P kg^{-1} as lowest soil P values observed in the M cluster averaged 3. 8 mg kg^{-1} in the last year of the experiment which was not limiting to productivity of the established stand. However, establishment in the same cluster at 6. 5 mg P kg^{-1} was somewhat inhibited (Tab. 1; Fig. 1b).

As with P, soil K levels in this study were not sufficiently low to result in pronounced switchgrass growth reductions even in establishment although maize grain yields were halved and alfalfa stands failed completely in the VL cluster (Fig. 1 a) where soil K levels averaged 69 mg kg^{-1} across depths and years (Tab. 2). At present, existing studies are generally too sparse to provide a rigorous foundation for switchgrass K recommendations (*Brejda*, 2000) although scientists in Iowa, USA, recommend K fertilization at $<$60 mg K kg^{-1}. Further, while clear linear and plateau relationships characterizing tissue K (and P) concentration as a function of soil tests were observed in our study (Fig. 2), relationships between yield and tissue concentration showed no trend. Linear-plateau regressions are often used to identify the break point above which the system becomes nonresponsive, and allows us to calculate a standard error of the break point that can be used to estimate a confidence interval. Some interpret this break point as a starting point for determining a "critical value", and this has practical value in soil/tissue test recommendations. However, the break point identified for tissue-soil concentration relationships either for K or P cannot be interpreted as a critical soil test level but rather a generous sufficiency level beyond which K and P do not luxuriously accumulate under normal growth conditions or concentrate under growth-limiting conditions.

It is important to note, however, that tissue K concentrations may have strong implications for energy yields in thermal conversion processing (Tab. 5). Analyses of thermal conversion in prototype systems report that tissues with higher alkali metal concentrations have reduced organic liquid yields and must be processed at lower temperatures (*Coulson*, 2006; *Fahmi* et al. , 2007). Our work demonstrates that both harvest date and soil fertility may represent economically important considerations for thermal processing as earlier harvests (2008 and 2009 vs 2010; Fig. 1b) and higher soil fertility (Fig. 2c, d) increase tissue K concentrations; the preliminary estimates presented here suggest bio-oil yields could be reduced by $>$ 40% on high-K fertility soils when harvests are taken early before nutrients can be translocated to roots or leached from above-ground biomass (Tab. 5).

In contrast to bio-oil production, recent literature and our results suggest optimizing dry matter yield will be the main concern for bioethanol yield (Tab. 5). Although ethanol yields can vary almost two-fold among the array of crops currently considered for lignocellulosic biomass (*Kim* and *Dale*, 2004), *Vogel* et al. (2011) documented only small differences (21. 5 L t^{-1} or 5%) in theoretical ethanol yields among switchgrass cultivars including Shawnee. Further, in a subsequent, multi-location study, *Schmer* et al. (2012) found only slightly higher Shawnee-specific values (421 to 430 L t^{-1} versus 412 L t^{-1}) despite some differences in lignin concentration when compared to the earlier study. In our study, harvest date drove most differences in lignin composition (Tab. 4). However, the magnitude of the differences across clusters was less than the magnitude of difference in Shawnee lignin concentrations

between the *Vogel* et al. (2011: 150 and 53 g kg^{-1} Klason lignin and ADL, respectively) and *Schmer* et al. (2012: 99 to 107 g kg^{-1} Klason lignin only) studies and thus justifies our use of a single conversion across our experimental conditions.

Some forecasts for bioenergy production from biomass have been extremely optimistic regarding the potential for low-input management on marginal lands. For example, *Tilman* et al. (2006) used results from an existing long-term experiment as a foundation for postulating the high-diversity grasslands would require only inputs of P to consistently outperform higher input monocultures including switchgrass. However, *Russelle* et al. (2007) noted serious flaws in the *Tilman* et al. (2006) argument and highlighted cation removal/replacement as a critical, but overlooked attribute of any productive system. In our study, total annual K removal was significant even on low K testing soils (>70 kg ha^{-1} over 3 years). In comparison, maize in the highest yield cluster removed 50 kg ha^{-1} yr^{-1} (assumes 3.9 g K kg^{-1} grain after *Brouder* and *Volenec*, 2008). This removal was not predicted by either change in soil test (Fig. 4b) or yield (Fig. 3c), the standard diagnostics for predicting K and P removal. Further, use of the plateau value from the linear and plateau relationship between tissue concentration and soil nutrient availability as a book value for estimating removals would ensure replacement but would overestimate fertilizer needs and, in the case of K, have negative impacts on energy yields from thermal conversion. In sum, more research is needed on low fertility soils to adequately characterize input needs and develop the diagnostic tools and fertility recommendations for sustainable P and K management of switchgrass used for biomass.

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生物能源作物柳枝稷田间尺度的钾磷通量：理论能源产量及管理措施

摘　要：尽管全世界都有意以草本物质作为能源原料，但我们对于矿质养分如何影响边际耕地上生物能源作物的生产力和组成等方面的了解还不够全面。本文主要目的是研究边际耕地上柳枝稷的生物产量和玉米的籽粒产量，这些曾被用来评估土壤磷钾肥力对苜蓿生长的影响。缺磷或缺钾田块中玉米籽粒产量会减少，苜蓿产量也有所降低，然而柳枝稷即使在有效磷(4 mg/kg)和有效钾(<70 mg/kg) 含量较低的田块中生物量仍然很高。线性-平稳回归模型有效描述了土壤磷钾含量与作物组织中磷钾浓度的关系，根据作物组织中的磷钾浓度可以准确推算作物收获时从土壤中移走的磷钾量。但

是对于柳枝稷来说，土壤磷钾测定值和植物体磷钾含量均不能有效诊断其生物产量及其从土壤中带走的养分量。纤维素、半纤维素、木质素和灰分等指标与磷钾养分没有显著的相关性。生物乙醇的生产力与生物产量关系密切，但植物体钾浓度较高会降低生物原油的产量，估计降幅可达 50%。在诊断指标和管理措施方面还需要有更多的研究，以满足生物能源生产的需求，同时要关注养分浓度较低的情况下（尤其是钾元素）生物能源作物的高产及维持和提高边际耕地的土壤肥力水平。

关键词：生物乙醇；生物量；柳枝稷；磷素营养；钾素营养

湖北省莲藕钾肥合理用量与运筹方式研究①②

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摘　要：采用田间小区试验研究了莲藕钾肥合理用量与运筹方式，结果表明：用线性＋平台模型确定莲藕 K_2O 临界用量为 232～422 kg/hm²，根据湖北莲藕生产和施肥现状，以及藕田土壤钾素含量状况，提出湖北莲藕钾肥（K_2O）合理用量为 225～300 kg/hm²；钾肥运筹可采用“7-0-3-0”和“5-2-3-0”2 种分配方式，前者适用于土壤质地比较黏重的藕田，后者适用于土壤质地比较轻的藕田。

关键词：莲藕；钾肥；用量；运筹方式

中图分类号：S147.5

钾在作物生理生化过程中有着特殊功能，一直被誉为“品质元素”和对作物健康影响最大的元素[1, 2]。钾素不仅是作物“肥料三要素”之一，而且对农田生态系统养分的迁移与转化有重要影响。从全国范围来看，我国耕地土壤氮、磷养分盈余，钾素亏缺严重[3]；中国南方地区大约有 2/3 的水稻土和 1/2 的旱地土壤缺钾，长江以南地区缺钾面积约占全国缺钾面积的 80%[4]。以地下膨大根状茎为收获物的藕莲（习惯上仍称为莲藕）是我国种植面积最大、产量最高的水生蔬菜，湖北省是全国莲藕生产第一大省[5]。研究证实，影响湖北莲藕产量的土壤养分限制因子主要为氮、钾、磷和锌[6]，但关于莲藕肥料用量与运筹方式研究的报道较少。本研究通过田间小区试验探讨莲藕钾肥的合理用量和运筹方式，为莲藕生产中科学、高效施钾提供理论依据。

1　材料与方法

1.1　供试土壤与莲藕品种

本研究所有田间试验均安排在武汉市洪山区南湖试验农场，供试土壤为长江冲积物母质发育的潮土性水稻土，用常规方法[7]分析其属性和养分状况（见表 1）。试验莲藕为早中熟品种“鄂莲五号”，由武汉市东西湖区柏泉农场提供。

表 1　供试土壤属性和养分状况

Table 1　property and available nutrients status of soils tested

年份	试验名称	层次（cm）	pH	质地	有机质（g/kg）	碱解氮（mg/kg）	速效磷（mg/kg）	速效钾（mg/kg）	有效硼（mg/kg）	有效锌（mg/kg）
2003	钾肥用量试验 1	0～30	7.1	重壤	30.7	165.0	11.2	127.0	0.33	0.85
2008	钾肥用量试验 2	0～20	6.4	重壤	33.3	115.5	31.7	152.5	0.41	1.88
2008	钾肥用量试验 2	20～40	7.5	重壤	28.5	96.0	23.1	122.5	0.31	1.68
2009	钾肥用量试验 3—高钾	0～20	6.2	重壤	33.7	145.9	31.3	227.9	0.45	1.75
2009	钾肥用量试验 3—高钾	20～40	7.5	重壤	29.4	113.3	19.6	208.3	0.38	1.64
2009	钾肥用量试验 4—低钾	0～20	6.6	重壤	31.6	122.2	18.6	115.5	0.49	1.71
2009	钾肥用量试验 4—低钾	20～40	7.4	重壤	27.9	102.8	13.6	106.7	0.41	1.61
2007	钾肥运筹方式试验	0～20	6.7	重壤	36.8	131.1	9.58	137.5	0.45	1.35
2007	钾肥运筹方式试验	20～40	6.9	重壤	33.6	59.6	3.98	100.0	0.39	1.17

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1.2 试验设计

1.2.1 莲藕钾肥用量试验

本研究共开展了4个钾肥用量试验，2003年1个试验，处理为：①K0，②K90，③K180，④K270，⑤K360；2008—2009年共3个试验，处理均为：①K0，②K180，③K360，④K450，⑤K540。其中K=K_2O，字母“K”后的数字代表每公顷施用K_2O的公斤数（钾肥运筹方式试验同）。2003年每处理再施300 kg/hm^2 N和120 kg/hm^2 P_2O_5；2008—2009年每处理再施360 kg/hm^2 N、120 kg/hm^2 P_2O_5和22.5 kg/hm^2一水硫酸锌。

1.2.2 莲藕钾肥运筹方式试验

钾肥运筹方式试验安排1个，于2007年度进行，设6个处理：①K0，②K450（10-0-0-0），③K450（7-0-3-0），④K450（3-0-7-0），⑤K450（5-2-3-0），⑥K450（0-4-6-0）。其中②括号内数字“10-0-0-0”依次代表钾肥基肥（4月中旬），第一次（6月上旬）、第二次（6月下旬）和第三次（7月中旬）追肥的分配比例，其他处理以此类推，下同。此外，每处理再施450 kg/hm^2 N、150 kg/hm^2 P_2O_5和22.5 kg/hm^2一水硫酸锌。

以上试验中氮肥品种用尿素（N 46%），2003年和2007年试验的氮肥运筹采用“6-2-2-0”的方式，2008—2009年采用“4-2-4-0”的分配方式；磷肥用过磷酸钙（P_2O_5 12%），100%基施；钾肥用氯化钾（K_2O 60%），用量试验采用“7-0-3-0”的分配方式；锌肥在移栽后一周内分小区化水施入。施肥前关注天气变化情况，浅水或湿润施肥，2 d后再灌水，避免施肥后3～5 d内下大雨。

试验每小区30 m^2，钾肥用量试验每处理重复3次，钾肥运筹方式试验重复4次，随机区组排列，种植密度为5 000 kg/hm^2，各小区之间作田埂并用厚塑料布隔离，防止串水串肥串藕。及时“转藕”、灌水和防治病虫草害。在当年4月中旬移栽，11—12月收获记录莲藕实产（鲜重），并进行经济效益分析；收获的同时，在每小区采取代表性藕6～8支，制备代表性分析样品，用常规方法[7]分析其全钾含量，计算莲藕收获物吸收带走的钾素总量。

1.3 参数计算与数据分析

1.3.1 参数计算

参考张福锁[8]和邹娟[9]的方法，用以下参数来表征钾肥的利用效率：

钾肥偏生产力（partial factor productivity from applied K，PFP_K，kg/kg K_2O）=施钾区产量/施钾量；

钾肥农学利用率（agronomic efficiency of applied K，AE_K，kg/kg K_2O）=（施钾区产量－无钾区产量）/施钾量；

钾肥表观利用率（apparent recovery efficiency of applied K，ARE_K，%）=（施钾区作物吸钾量－无钾区作物吸钾量）/施钾量100；

钾肥贡献率（fertilizer contribution rate of applied K，FCR_K，%）=（施钾区产量－无钾区产量）/施钾区产量100。

1.3.2 莲藕推荐施钾量模型选择

运用SAS8.1软件进行线性＋平台模型函数式（L＋P）拟合钾肥用量与莲藕产量之间的关系：

$$y = b_0 + b_1 x (x < c),\ y = y_p (x \geqslant c)$$

式中：y为莲藕产量（kg/hm^2），x为钾肥用量（kg/hm^2），b_0为基础产量（不施钾肥时产量），b_1为线性系数，c为钾肥用量临界值（由直线和平台的交点求得），y_p为平台产量。

1.3.3 数据统计分析

试验数据采用DPS软件的单因素LSD检验法进行统计分析。用Microsoft-Excel 2007进行其他数据的处理和计算。

2 结果与讨论

2.1 藕田土壤钾肥合理用量研究

2.1.1 钾肥用量对莲藕产量和钾素利用效率的影响

从表2中结果可见：在2003、2008和2009年度低钾田试验中，当K_2O用量在360 kg/hm^2以内时，莲藕产量随钾肥用量增加而显著增加，超过360 kg/hm^2之后莲藕产量则趋于平稳；K_2O用量在360 kg/hm^2

时，莲藕产量比不施钾肥处理增产 4 370～10 005 kg/hm²，增产幅度为 19.7%～44.1%，净增收 4 956～13 690元/hm²，钾肥产投比 2.73～7.53，钾肥的偏生产力为 73.7～90.8 kg/kg K_2O，农学效率为 12.1～27.8 kg/kg K_2O，钾肥当季表观利用率为 6.24%～12.0%，钾肥产量贡献率为 16.5%～30.6%。在 2009 年度高钾田试验中，当 K_2O 用量在 180 kg/hm² 以内时，莲藕产量随钾肥用量增加而显著增加，超过 180 kg/hm² 之后莲藕产量趋于平稳；K_2O 用量在 180 kg/hm² 时，莲藕产量比不施钾肥处理增产 4 685 kg/hm²，增产幅度为 19.7%，净增收 6 352 元/hm²，钾肥产投比为 6.99，钾肥的偏生产力和农学效率分别为 158.3 kg/kg K_2O 和 26.0 kg/kg K_2O，钾肥当季表观利用率和产量贡献率分别为 17.2%和 16.4%。

钾肥用量对莲藕产量及钾肥经济效益的影响符合报酬递减律。在肥料经济学研究中通常认为，只有当肥料产投比 VCR 值大于 2.0 时，施用化肥才有意义[10]。根据这个原则和钾肥在莲藕上的产量效应，并结合试验土壤的分析结果，可以初步认为，当土壤速效钾含量较低时(100～150 mg/kg)，钾肥用量在 360 kg/hm² 左右比较合适；而当土壤速效钾含量相对较高时(200～250 mg/kg)，钾肥用量在 180 kg/hm² 左右比较合适。

表 1 和表 2 中结果还表明，当土壤速效钾含量较低时(100～150 mg/kg)，莲藕钾吸收量随钾肥用量增加而增加，并逐渐趋于稳定；当土壤速效钾含量较高时(200 mg/kg 以上)，莲藕钾吸收量随钾肥用量增加而增加，K_2O 施用量超过 360 kg/hm² 后，莲藕钾吸收量并没有同步增加。莲藕钾肥的偏生产力和农学效率较一般大田作物高[8, 9]，与其收获指数较高和产量以鲜重量表示有关。总体上看，莲藕钾肥的偏生产力、农学效率和当季表观利用率均随钾肥用量的增加而降低，钾肥的产量贡献率则随钾肥用量的增加而增加。

表 2　钾肥用量对莲藕产量和钾素利用效率的影响

Table 2　Effect of potash application rate on yield and potassium use efficiency of rhizome lotus

年份	处理	产量 (kg/hm²)	钾增产 (kg/hm²)	钾增幅 (%)	钾净增收 (元/hm²)	钾产投比	PFPK(kg/kg K_2O)	AEK(kg/kg K_2O)	K 吸收量 (kg/hm²)	AREK (%)	FCRK (%)
2003	①K0	22 678 e	—	—	—	—	—	—	96.2	—	—
	②K90	24 790 d	2 112	9.3	2 819	6.20	275.4	23.5	100.8	6.17	8.52
	③K180	27 792 c	5 114	22.5	7 017	7.72	154.4	28.4	116.5	13.5	18.4
	④K270	30 571 b	7 893	34.8	10 870	7.97	113.2	29.2	118.3	9.81	25.8
	⑤K360	32 683 a	10 005	44.1	13 690	7.53	90.8	27.8	120.8	8.19	30.6
2008	①K0	22 176 b	—	—	—	—	—	—	83.9	—	—
	②K180	23 649 b	1 473	6.6	1 374	1.51	131.4	8.2	93.5	6.39	6.23
	③K360	26 546 a	4 370	19.7	4 956	2.73	73.7	12.1	102.6	6.24	16.5
	④K450	27 019 a	4 843	21.8	5 234	2.30	60.0	10.8	107.2	6.20	17.9
	⑤K540	27 097 a	4 921	22.2	4 901	1.80	50.2	9.1	107.2	5.18	18.2
2009	①K0	23 805 b	—	—	—	—	—	—	85.8	—	—
-高	②K180	28 490 a	4 685	19.7	6 352	6.99	158.3	26.0	111.6	17.2	16.4
	③K360	29 589 a	5 784	24.3	7 148	3.93	82.2	16.1	129.5	14.6	19.6
	④K450	30 115 a	6 310	26.5	7 508	3.30	66.9	14.0	117.8	8.54	21.0
	⑤K540	29 889 a	6 084	25.6	6 703	2.46	55.4	11.3	126.3	9.01	20.4
2009	①K0	21 891 c	—	—	—	—	—	—	88.9	—	—
-低	②K180	26 057 b	4 166	19.0	5 548	6.10	144.8	23.1	116.3	18.3	16.0
	③K360	28 737 ab	6 846	31.3	8 793	4.84	79.8	19.0	124.9	12.0	23.8
	④K450	29 520 ab	7 629	34.8	9 552	4.20	65.6	17.0	126.6	10.0	25.8
	⑤K540	29 734 a	7 843	35.8	9 430	3.46	55.1	14.5	129.9	9.12	26.4

注：按当地同期市场均价，K_2O、莲藕和收获劳务价格分别为 5.05、1.90、0.35 元/kg，同一试验各处理其他投入视同相等。价格下同。

2.1.2　用线性＋平台模型确定莲藕适宜钾肥用量

从上述结果可以发现，当钾肥用量增加到一定程度之后，莲藕产量在较大的钾肥用量范围内趋于稳定，与施钾量的关系很难符合常见的二次抛物线关系。为进一步明确莲藕的适宜施钾量，采用线性＋平台模型拟合莲藕钾肥用量与产量之间的关系(见图 1，2003 年试验由于钾肥用量范围较窄，未出现“平台”，故未进行拟合)。结果表明：2008 年试验基础产量21 939 kg/hm²，平台产量 27 058 kg/hm²，K_2O 临界用量为 421.7 kg/hm²；当 K_2O 用量低于 421.7 kg/hm²时，莲藕产量用方程 $y = 12.139x + 21\,939$ 来确定。2009 年高钾田(土壤速效钾含量 208～228 mg/kg)试验基础产量 23 805 kg/hm²，平台产量

29 864 kg/hm^2，K_2O临界用量为 232.8 kg/hm^2；当 K_2O 用量低于 232.8 kg/hm^{2}时，莲藕产量用方程 $y=26.027x+23\,805$ 来确定。2009 年低钾田（土壤速效钾含量 106～116 mg/kg）试验基础产量 22 139 kg/hm^2，平台产量 29 627 kg/hm^2，K_2O 临界用量为 393.8 kg/hm^2；当 K_2O 用量低于 393.8 kg/hm^{2}时，莲藕产量用方程 $y=19.015x+22\,139$ 来确定。由此可见，在本试验条件下，用线性＋平台模型确定的莲藕钾肥合理用量在 232～422 kg/hm^{2}之间。

从 2009 年度 2 个不同土壤钾水平试验结果来看，在高钾土壤上，莲藕基础产量比低钾田高出 7.53%，K_2O 临界用量比低钾田低 161 kg/hm^2，而平台产量两者大致相当，可能与莲藕对钾营养比较敏感、需要较高的钾浓度来促进莲藕产量形成有关。另外，与 2008 年度试验相比较，2009 年度低钾田试验土壤速效钾含量略低，其 K_2O 临界用量也略低，平台产量则高出 9.5%，可能与年度气候和土壤微环境差异有关。

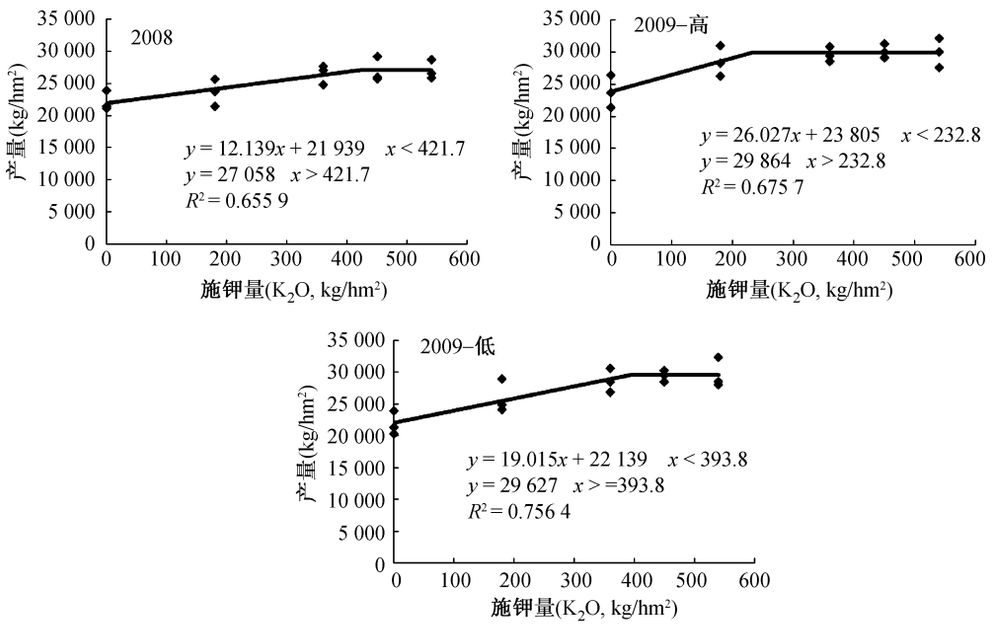

图 1　钾肥用量与莲藕产量之间的线性＋平台函数模型

Fig. 1　linear＋plateau model between potash application rate and rhizome lotus yield

2.2　莲藕钾肥合理运筹方式研究

从表 3 中结果可见，当 K_2O 用量在 360 kg/hm^{2}时，5 种不同钾肥运筹方式下莲藕产量比不施钾肥处理增产 2 116～4 770 kg/hm^2，增产幅度为 8.45%～19.0%，净增收 1 007～5 120 元/hm^2，钾肥产投比 0.44～2.25，钾肥的偏生产力为 60.4～66.3 kg/kg K_2O，农学效率为 4.70～10.6 kg/kg K_2O，钾肥当季表观利用率为 4.76%～8.90%，钾肥产量贡献率为 7.79%～16.0%。对莲藕产量的影响，5 种不同钾肥运筹方式之间的差异没有达到显著性水平，可能与田间试验重复之间差异较大有关；但从钾肥的增产绝对量和增产幅度、施钾净增收、钾肥产投比、钾肥农学效率、当季表观利用率和产量贡献率等指标来看，钾肥运筹方式以“7-0-3-0”和“5-2-3-0”2 种方式较好，且 2 种方式之间的效果基本相当。

表 3　钾肥运筹方式对莲藕产量和钾素利用效率的影响

Table 2　Effect of potash assignment on yield and potassium use efficiency of rhizome lotus

处理	产量 (kg/hm^2)	钾增产 (kg/hm^2)	钾增幅 (%)	钾净增收 (元/hm^2)	钾产投比	PFPK (kg/kg K_2O)	AEK (kg/kg K_2O)	K 吸收量 (kg/hm^2)	ARE_K (%)	FCR_K (%)
①K0	25 046 b	—	—	—	—	—	—	97.7	—	—
②K10-0-0-0	28 336 a	3 290	13.1	2 827	1.24	63.0	7.31	123.2	6.80	11.6
③K7-0-3-0	29 551 a	4 505	18.0	4 710	2.07	65.7	10.0	128.5	8.20	15.2
④K3-0-7-0	27 162 a	2 116	8.45	1 007	0.44	60.4	4.70	120.8	6.15	7.79
⑤K5-2-3-0	29 816 a	4 770	19.0	5 120	2.25	66.3	10.6	131.1	8.90	16.0
⑥K0-4-6-0	27 358 a	2 312	9.23	1 312	0.58	60.8	5.14	115.6	4.76	8.45

3 问题与讨论

3.1 莲藕钾肥合理用量与运筹方式

过去对莲藕钾肥用量方面的研究并不多，偶有零星报道，且多采用池栽试验研究方法[11,12]。近几年来，随着国家测土配方施肥补贴项目的全面开展，全国一些莲藕主产县（市）开展了相关研究。宋江春等[13]研究提出，在每公顷施用 270～360 kg N、90 kg P_2O_5 的基础上，莲藕最佳钾肥（K_2O）用量以 180 kg 最好；刘逊忠等[14]在广西灵山县潴育性杂沙泥肉田和钦州市潴育性沙泥肉田上的莲藕钾肥用量试验结果表明，广西横县莲藕品种在施用 15 000 kg/hm^2 经生物发酵腐熟的优质有机肥、600 kg/hm^2 N 和 150 kg/hm^2 P_2O_5 的基础上，K_2O 用量以 225 kg/hm^2 增产增收效果最好；曾广巧等[15]在广西柳江县石灰性水稻土上通过“3414”肥料回归试验，研究得出“鄂莲 5 号”的合理施肥量为：400～500 kg/hm^2 N、130～200 kg/hm^2 P_2O_5 和 200～300 kg/hm^2 K_2O；在武汉市蔡甸区，对成熟莲藕和青荷藕也有过类似研究[16,17]。在本项研究中，用线性＋平台模型确定莲藕钾肥合理用量在 232～422 kg/hm^2 之间。根据湖北省莲藕主产区莲藕的生产水平和施肥现状[18]，以及藕田土壤钾素含量状况（未发表资料），推荐莲藕钾肥用量为 225～300 kg/hm^2 K_2O 比较合适。由于钾肥当季利用率较低，如果连年施用，钾肥用量还需逐年酌情递减。

肥料的合理运筹除了考虑作物自身的营养特性和当地气候特征之外，另一个重要因素就是肥料养分在土壤中的化学行为。文献调研结果表明，与肥料合理用量方面的研究相比较，对作物肥料合理运筹方式的研究要少得多，对莲藕肥料合理运筹方式的研究则未见报道。参考其他作物肥料合理运筹方面的研究结果，并根据湖北省莲藕产区的气候特点，建议在质地比较黏重的藕田，钾肥采用“7-0-3-0”的分配方式，以降低劳力成本；在土壤质地比较轻的藕田，钾肥采用“5-2-3-0”的分配方式与氮肥一起施用，以充分发挥钾肥的增产效果、减少流失、提高钾素的当季利用率。此外，针对湖北省莲藕产区农户施肥习惯[18]，以复混肥作为莲藕的钾源时，提倡将复混肥作基肥施用。

3.2 莲藕钾肥利用效率

肥料偏生产力（PFP）、农学效率（AE）、表观利用率（ARE）以及肥料贡献率（FCR）都从不同的角度描述了作物对肥料养分的利用效率，其内涵及应用对象常常不同[9]。ARE 能很好地反映作物对化肥养分的吸收状况，是我国学术界和政府关注的焦点[8,9]。莲藕（Nelumbo nucifera Gaertn）是睡莲科莲属多年生宿根大型水生草本植物，也是我国目前种植面积最大、经济价值最高的水生蔬菜。在本研究中，莲藕钾肥的当季表观利用率随其用量的增加而降低，在适宜用钾量附近为 6.24%～17.2%。刘佐等[19]在天津市土壤钾素含量中等偏下的菜园潮土露地、中小拱棚和日光温室内，研究了钾肥对 27 种蔬菜钾素吸收特性和当季表观利用率的影响，结果表明钾肥当季表观利用率为果菜类（30.18%）＞瓜菜类（28.81%）＞根茎类（25.83%）＞叶菜类（22.91%），平均为 26.93%。由此可见，莲藕钾肥的当季利用率比一般蔬菜要低，可能与其生长周期较长、喜高温和大肥大水等特性有关。对蔬菜类作物肥料养分当季利用率和累积利用率的研究不多，值得深入探讨。

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A study of rational potash application rate and assignment on rhizomes lotus in Hubei Province

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Abstract: Rational potash application rate and assignment on rhizomes lotus was studied by field experiments. Results showed that, the critical value of K_2O application rate determined by linear + plateau model was 232～422 kg/hm^2. Taken the present status of rhizome lotus production, farmer practice fertilization and lotus field soil potassium fertility into consideration, rational potash application rate on lotus rhizomes in Hubei province was suggested to be 225～300 kg/hm^2 K_2O. "7-0-3-0" and "5-2-3-0" were two rational potash assignments, the former was suitable for a lotus field with heavy soil texture, and the latter was suitable for a lotus field with light soil texture.

Key words: Rhizome, potash, application rate, assignment

贵州马铃薯钾肥施用研究与应用状况回顾与展望①

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摘　要：阐述了国内钾肥研究与使用的历程，重点回顾国内外马铃薯使用钾肥的历史，评述氯化钾、硫酸钾在马铃薯种植过程中的施用条件和效果；分析贵州马铃薯施用钾肥试验结果，指出不同海拔地区马铃薯品种、熟期不同，对氮磷钾需求有差异，进一步分析马铃薯大面积生产上钾肥施用不足的原因；提出今后应加强马铃薯钾肥高效利用技术、有机钾肥替代化学钾肥技术、提高钾肥利用率的土壤环境协调技术等方面的研究。

关键词：马铃薯；钾肥；研究；应用

中图分类号：S532；S143.3

钾在1838年由Sprengel等确定为植物必需营养元素，在Liebig提出矿质营养学说后就有施钾试验之说，1861年德国开始钾肥（氯化钾）的商业化生产[1]。1935年，钾肥生产商在美国华盛顿特区筹组了美国钾肥研究所（API），至1960年，由于加拿大钾肥厂商的加盟，API更名为北美钾肥研究所。1952年，欧洲钾肥生产商在瑞士成立国际钾肥研究所（IPI），其目的是优化土壤、植物和农业生态系统中的钾及其他作物营养元素施用。但从有关植物钾营养研究的文献来看，20世纪60年代以前有关钾肥施用的研究较少，植物钾含量丰缺结果多见于60—70年代发表的文献[2]。此后有关钾肥施用的研究迅速增多，这里仅就国内及贵州省钾肥研究状况和马铃薯钾肥使用简略回顾，以供进一步的研究参考。

1　国内及贵州省钾肥施用研究状况

我国化肥（含钾肥）的研究在20世纪80年代中期进行过3次全国规模的肥效试验。1935—1941年前中央农业实验所进行第一次全国范围的化肥肥效试验，在14个省、7个区、68个试验点、68种植物上共完成氮、磷、钾肥田间试验156个，得出全国地力概况，氮肥的需要程度为80%左右，磷肥为40%左右，钾肥仅为10%左右。1957年农业部组织全国化肥试验网，于1958—1962年进行第二次全国范围的化肥肥效试验，1958年在25个省、自治区、直辖市的157个点上以粮棉为主实施351个田间试验。1958年后扩大到油料、烟草、蔬菜、果树等植物上，结果是氮、钾肥效与20年前相同，磷肥肥效比20年前有提高。1981—1983年进行第三次全国范围的化肥肥效试验，在29个省、自治区、直辖市的18种作物上布置5 334个田间试验。对其中4 943个试验数据整理分析，结果为氮肥肥效大于磷肥，磷肥肥效大于钾肥的趋势没变，氮肥效果有下降，但不同地区、不同作物程度不一样。磷肥效果在南方水稻上下降，在北方小麦、玉米上有上升。钾肥的效果在南方趋于明显，在北方大部分地区的粮食作物仍未显效[3]。

20世纪80年代中后期，我国钾方面的科研和推广工作较为活跃。1984年起，中国农科院土肥所和有关单位先后与PPI/PPIC、加拿大钾肥公司协作，PPI/PPIC在我国先后设立4个办事处。南京土壤所和有关单位与IMC、SCPA和以色列死海公司等组织进行了合作。近年来，农业部全国农技推广中心与UNDP协作开展平衡施肥研究与推广工作。60年代我国基本上没有钾肥供应。南京土壤所与建材部门协作，于60年代中期在粤西用水泥窑灰进行大量试验，70年代初继续在广东、湖南、江西和江苏进行示范推广。进入80年代以后，我国土壤缺钾程度加剧，在土壤含钾相对较丰富的北方地区，缺钾面积也逐渐增大。80年代初，农业部在全国推行配方施肥。在“八五”和“九五”期间，平衡施肥技术列入全国重点推广

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的十大农业技术之一[4]。

贵州钾肥施用研究始于20世纪50年代，省内科研单位曾作过20多次钾肥肥效试验，其中大部分效果不显著，少数略有增产。1981—1984年，贵州参加全国化肥试验网协作研究，在水稻、玉米、油菜、小麦四种作物上进行了172个田间试验。结果为每kg氧化钾增产3.0 kg稻谷(n=110)的试验63个，增产3.5 kg玉米(n=49)的试验49个，增产1.2 kg油菜籽(n=10)的试验10个，增产2.2 kg小麦(n=3)的试验1个，钾肥增产效果在旱地显现，明显高于稻田[5]。

进入21世纪后，我国钾方面的科研和推广工作进一步深入。由于我国矿物钾资源有限，钾肥的高效利用和替代技术就成为我国肥料科研工作者关注的问题。

2 马铃薯使用钾肥历史回顾

马铃薯是喜钾作物。美国曾进行了大量的两种钾源对马铃薯产量、品质、抗病性等方面的影响研究。如Panique，E等曾于1992—1995年在美国威斯康星州三个地点进行硫酸钾和氯化钾的5种处理试验，发现氯化钾和硫酸钾对产量和品质的影响并无大的区别，与硫酸钾相比，氯化钾会轻微地降低薯块的比重，即轻微地降低淀粉的含量，而硫酸钾在施肥量较大的情况下会引起减产。因此在美国主产区爱达荷州、科罗拉多州等州的州立大学制定的马铃薯栽培指导中，均建议农民可以使用氯化钾[6]。

国内关于马铃薯施用钾肥的研究比白俄罗斯晚十多年。田蕴德等(1984)报道甘肃省马铃薯施用钾肥的试验结果，合理施用化学钾肥对马铃薯的产量、品质、抗病性均呈明显的有利影响。块茎的产量比对照提高44.4%，NP基础上配合施钾块茎产量提高13.8%，淀粉含量、晒丝率有一定程度的提高，抗病性亦有所增强。在两种钾肥的增产、优质作用中硫酸钾明显优于氯化钾，平均每kg硫酸钾增产块茎13.70～19.26 kg，平均16.48 kg，每kg氯化钾增产块茎3.8 kg[7]。马国瑞等(1988)的室内及田间试验结果表明，在浙江省定海、象山县的气候、土壤条件下，马铃薯施氯离子9.5 kg/667 m^2，对品质无不良影响。金安世等(1992)把马铃薯划为中等耐氯作物，其安全值、临界值、毒害值和致死值分别为为200、500、900和2 600 mg/L。并明确指出，对于马铃薯等所谓忌氯作物，在200 mg/L低氯情况下，薯块中淀粉和可溶性糖含量基本不受影响，而达800 mg/L高氯后则影响较大，品质有所下降[8]。李济宸等(1997)进一步指出，在河北省施用含氯化肥使土壤含氯浓度在570 mg/kg以下时，促进马铃薯生长发育，提高产量，不影响品质。连续使用含氯化肥，土壤中没有明显的氯积累，马铃薯生产施用含氯化肥，特别是氯化钾，安全有效，不存在“忌氯”问题，可大力推广使用氯化钾，以进一步提高马铃薯的产量[9]。李玉影等(1997，1998)试验表明，在黑龙江，施钾肥对马铃薯块茎有极显著的增产作用。增产的主要原因是钾促进了马铃薯的生长发育，促进了干物质的积累和块茎膨大，增加了大薯比例，减少了小薯比例。在海伦黑土钾肥增产幅度6.8%～17.6%。在等钾量情况下，氯化钾和硫酸钾对块茎产量的影响差异不大。从增产效果和经济施肥两方面考虑，在该土壤上马铃薯钾肥适宜用量为K_2O 90 kg/hm^2。富锦黑黏土钾肥增产幅度6.5%～20.0%。在该土壤上马铃薯钾肥适宜用量为K_2O 60 kg/hm^2。薄层黑土钾肥增产幅度12.6%～22.4%。在该土壤上马铃薯钾肥适宜用量为K_2O 90 kg/hm^2[10，11]。刘效瑞等(2001)研究认为在半干旱定西地区，施用钾肥均有一定的增产作用，硝酸钾、硫酸钾、磷酸二氢钾效果较好，氯化钾、草木灰效果较差[12]。

3 贵州马铃薯生产与钾肥施用状况

贵州马铃薯种植已有100多年历史[13]，但钾肥施用研究比甘肃省晚15年。李裕荣等(2000)报道在贵州威宁马铃薯主产区，在施用有机肥18.7 t/hm^2、N 104 kg/hm^2、P_2O_5 60 kg/hm^{2}基础上，施K_2O 100 kg/hm^2、150 kg/hm^2，马铃薯产量分别比对照(19.04 t/hm^2)增加3.54 t/hm^{2}和6.63 t /hm^2，增产率分别为18.59%和34.82%[14]。陆引罡(2003)指出在贵州高海拔地区施18 t/hm^{2}有机肥基础上，高产高效施肥的N∶K_2O为100∶(95～140)为宜，即施氮(N)105 kg/hm^2，施钾(K_2O) 100～150 kg/hm^{2}为宜[15]。阎献芳等(2005)研究表明，在土壤养分较缺乏的贵州高寒地区栽种马铃薯以N∶P_2O_5∶K_2O=1∶0.9∶2.1为最佳配比，在N 100 kg/hm^2、P_2O_5 90 kg/hm^2、K_2O 210 kg/hm^{2}的施肥水平下可得到最高产量32.79t/hm^{2}和最佳经济效益3 032元/hm^{2}的收益[16]。肖厚军等(2011)试验表明，在贵州低海拔

的黄平县和高海拔的水城县，不同海拔马铃薯熟期、品种不同，对氮磷钾肥需求有差异；中低海拔地区种植早熟马铃薯（费乌瑞它）的氮、磷、钾用量为 N 150 kg/hm²、P_2O_5 135 kg/hm²、K_2O 270 kg/hm²；高海拔地区种植晚熟马铃薯（威芋 3 号）的氮、磷、钾用量为 N 240 kg/hm²、P_2O_5 135 kg/hm²、K_2O 240 kg/hm²，按此推荐量施肥，可获得较高的产量（低海拔区 28.0 t/hm² 和高海拔区 21.0 t/hm²）和较好的经济效益[17]。纵观贵州不同时期马铃薯施钾试验结果，可以看出贵州马铃薯主产区近年来钾肥用量增加，但增产效果下降，其原因需深入研究。

据 2008 年测土配方施肥农户调查，贵州马铃薯主要种植区的农民习惯施肥水平（含有机肥）每 hm² 氮（N）174 kg、磷（P_2O_5）80 kg、钾（K_2O）115 kg，该施肥水平氮、磷用量与 PPI/PPIC 的技术资料中马铃薯产量达 40 t/ hm² 的氮、磷带走量相当，而钾用量只相当于带走量的 1/3 左右。如表 1 所示，贵州马铃薯单产 2001 年与全国接近，以后都低于全国水平，钾肥施用量不足可能是贵州马铃薯产量长期处于徘徊甚至下降的重要原因之一。

马铃薯种植钾肥施用量不足的原因，一是对钾肥作用的宣传力度不够，缺少示范，农民对钾肥的重要性认识不足；二是我国钾资源不足，长期依靠进口，价格偏高，而马铃薯种植一般在海拔较高的冷凉地区，农民比较贫困，购买力低，习惯选用价格比较低廉的碳酸氢铵、普通过磷酸钙以及其功效被广大农民认可的尿素等，由此造成了钾肥用量严重不足；三是与国内对马铃薯与钾肥关系的认识有关，即认为马铃薯是忌氯作物，不能使用价格便宜含钾量高的氯化钾，而只能使用价格较高且含钾量稍低的硫酸钾，近来这种认识有所改变，但农民仍认为施用量稍高即会引起“氯害”。

表 1　2001—2008 年全国以及贵州省的马铃薯公顷单产情况（t）

Table 1　Potato yield from 2001 to 2008 in China especially in Guizhou Province

年份 Year	全国平均单产 Average yield in China	贵州平均单产 Average yield in Guizhou
2001	13.68	13.47
2002	16.12	13.46
2003	15.06	13.04
2004	15.71	12.89
2005	14.52	9.81
2006	14.83	13.04
2007	14.62	12.62
2008	15.18	12.41

4　贵州马铃薯钾肥施用研究展望

据孙爱文等（2009）的统计，中国已成为世界主要的钾肥消费国。2001—2007 年，我国钾肥的表观消费量以 10.7% 的速度增长，2007 年达到历史最高峰，为 750 万 t（折纯 K_2O，下同）。虽然钾肥生产量以 9.7%的速度增长，到 2007 年我国钾肥的生产量达到了 226 万 t，但是我国钾肥自给率只有 30%，进口依赖度达到 70%左右，钾肥进口量从 2001 年的 381 万 t 增长到了 2007 年的 574 万 t。我国钾肥需求和进口量的过快增长导致国际钾肥价格飞速攀升。2008 年我国氯化钾价格达到 700 美元/t 左右，比 2005 年增长 470 美元/t，其中 2007 年底以来暴涨了 400 美元/t。钾肥价格过快增长已经成为农业生产成本增长的主要原因，而进口量不断增长已经成为限制农业持续发展的重要问题。我国钾肥面临的问题：一是国际钾肥供应商统一对外贸易，国际钾资源形成了高度垄断；二是我国不仅钾资源探明储量少，而且资源开采能力有限；三是钾肥施用不尽合理，在追求经济效益时忽视钾肥利用率，已存在局部过量施用的问题[18]。

针对我国钾肥面临的问题，贵州应从以下三方面进一步深化马铃薯钾肥施用研究。一是马铃薯施钾高效利用技术研究，如开展贵州主要土壤钾素状况与供钾能力调查，进一步明确氯化钾对贵州马铃薯种植的安全施用量，研究提高钾肥利用率的钾肥施用技术，马铃薯缺钾诊断技术等；二是水溶性钾肥以外的钾肥资源开发利用技术，如作物秸秆、有机肥、绿肥等含钾物料对化学钾肥的替代技术，难溶性低含量矿物钾资源利用技术等；三是钾肥高效利用的土壤外部环境协调技术，如钾肥与其他肥料的配合施用和部分代偿

技术，钾肥与土壤改良剂的配合施用技术，吸钾缓释材料的研发等。

显然，提高钾肥利用率，减少钾肥消耗，增加农作物产量和农民收入是需要全社会关注的问题。除农业科技人员和农民的自身努力外，地方政府应该以测土配方施肥等项目为契机，加强相应的研究和技术推广工作。农田增施有机肥及秸秆还田是提高有机资源中钾还田的重要措施，需要依赖政策、机械、技术领域的大力支持，建议政府加大秸秆还田、有机肥施用的政府补贴，加强秸秆还田和有机肥施用机械的研发和推广支持。

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Research status and perspective of potash fertilization application of potato production in Guizhou Province

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Abstract: Research progress and application status of potash (K) fertilization are reviewed in China, especially in potato planting. After analyzing results of experiments of applying potash fertilization in potato planting in Guizhou Province, there was a difference in the requirement of N, P and K fertilizers between the different maturity periods of potato varieties planted in areas at different elevations. The reasons for deficiency of applying potash fertilizer in potato planting areas are looked into further. The techniques for efficient potash fertilization, substituting organic K fertilizer for inorganic K fertilizer, and improving use efficiency of K in soil should be strengthened in future.

Key Words: Potato, potash fertilizer, research, application

不同类型紫色土含钾量及对烤烟钾分布规律的影响①

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摘　要：于 2009 年在江西紫色土烟区点对点采集土壤样与烟叶样进行化验，分析不同类型紫色土含钾量特征及其对烤烟钾分布规律的影响，得出结果如下：江西紫色土含钾量较高，全钾 17.7 g/kg，速效钾 152.2 mg/kg；全钾含量分布中≥16 g/kg 占 68.3%，速效钾含量分布中≥100 mg/kg 占 75.6%；烟叶含钾量较高，平均含量为 37.5 g/kg，其中碱性紫色土更能促进烟叶对钾的吸收；不同类型紫色土烤烟其不同叶位的烟叶含钾量差异不大。江西紫色土钾素资源丰富，是烟叶含钾量高与质量好的物质基础。

关键词：紫色土；烤烟；烟叶含钾量；全钾；速效钾；叶位

中图分类号：Q938；S572

钾是植物生长必需的大量营养元素之一，烟草吸收钾素的量比其他任何元素都高，一般是氮素的 1.4 倍，磷素的 3.5 倍[1-2]。钾可以促进烟株光合作用，提高烟株的呼吸效率，参与糖类、脂类和蛋白质的代谢过程[3-4]。钾含量的高低是衡量烤烟品质高低的重要指标之一。含钾量高的烟叶色泽呈深桔黄色，香气足，吃味好，有弹性和韧性，填充性强，持火力和燃烧性好；施用钾肥可改善烟气品质，降低烟气中总微粒物和尼古丁含量[4-6]。在烟株生育时期，烟株内含钾量高还可能增强烟株抗旱、抗病虫等抗逆能力[7]。美国烤烟烟叶含钾量（质量分数）一般为 4%～6%，有的高达 8%～10%；而我国烟叶含钾量一般在 2%以下。较低的含钾量制约着我国烟叶质量的进一步提高[8]。土壤是烟草生长的重要生态条件之一，土壤钾素的供应状况是影响烤烟含钾量的重要因子。目前，关于土壤对烟草钾营养的影响和提高烟叶含钾量的技术措施[9-14]等方面的研究报道较多，烟草对钾素的吸收、运输和分配规律亦有报道[15-19]；但是针对不同类型紫色土含钾量对烤烟含钾量分布规律的研究较少。

江西紫色土以生产优质烤烟而闻名。紫色土在中国土壤系统分类（CST）中名为紫色正常新成土（Purpli-Orthic Primosols）[20-21]。由于紫色土通气性能比较好，质地上轻下重，保水保肥性能比较强，钾与硼含量较高，有机质与氮素含量中等，其土壤理化性状适宜于烤烟的生长，故江西省浓香型特色优质烟叶的开发主要集中在紫色土上。据统计，江西省紫色土面积为 20.1 万 hm^2，占江西土壤总面积的 1.35%，目前种植烤烟的紫色土有 0.8 万 hm^2，占江西烤烟种植面积的 25%。随着种烟年限的递增，紫色土土壤结构及养分状况发生了一系列的变化，为了查明江西烟区紫色土养分供应现状与烤烟养分分布规律，故于 2009 年在江西省紫色土烟区点对点采集土样与烟样进行化验分析，通过探讨江西不同类型紫色土含钾量差异，摸清不同类型紫色土烤烟含钾量的分布规律，为江西紫色土烤烟平衡施肥提供科学依据。

1　材料与方法

1.1　样品采集

1.1.1　土壤样品采集

2009 年在江西采集了 41 个植烟紫色土，其中酸性紫色土（pH＜6.5）10 个、中性紫色土（6.5＜pH＜7.5）27 个、碱性紫色土（pH＞7.5）4 个。土壤样品采集是根据具体采样地块的形状和大小，确定适当的采样路线和方法。取样时间均统一在烟草尚未施用底肥和移栽以前，以反映采样地块的真实养分状况和供

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肥能力，同时注意避开雨季。采样深度为 20 cm，每个地块一般取 10～15 个小样点（即一钻土样）土壤，制成一个混合样。采集的各小样点土壤要在田间用“四分法”弃去多余部分，最后保留 0.5 kg，经登记编号后进行预处理，经过风干、磨细、过筛、混匀、装袋后备测定分析之用。

紫色土一般长期处于幼年发育阶段，且大多富含碳酸盐，但碳酸盐含量差异大，由1 g/kg至 180 g/kg 不等，其含量差异与母岩性状相关，也是判定土壤类型分异的重要依据[21]。在降雨量与日照丰富的亚热带江西地区，紫色土以酸性和中性土壤为主，碱性紫色土偏少。这也是本次采样过程中碱性紫色土样品偏少的原因。

1.1.2 烟叶样品采集

烟叶样品采集是在土壤样品采集对应的地块，烟叶取样点同土壤采样范围保持一致，共采集了 41 套烟叶样品。烟叶等级按照“GB 2635-92 烤烟标准”进行分级，其中每套烟叶样品包括下部叶（X2F）、中部叶（C3F）、上部叶（B2F）三个等级。每个样品取 1.5 kg 烟叶。烟叶样品为同一烤烟品种 K326。

1.2 测定与方法

土壤样品测定的项目：全钾、速效钾，测定方法按常规方法统一进行[22]。

烟叶样品测定的项目：钾，测定方法为常规方法[23]。

2 结果与分析

2.1 不同类型紫色土含钾量状况

江西紫色土土壤全钾含量较高（见表 1），平均为 17.7 g/kg，在 12.5～25.1 g/kg 之间变化，不同类型紫色土之间全钾含量差异不大。紫色土速效钾平均含量为 152.2 mg/kg，以碱性紫色土速效钾含量最低，为 135.1 mg/kg。

表 1 不同类型紫色土中有效钾含量状况

Table 1 Soil available K content in different types of purple soils

	数值 value	紫色土 Purple soils	酸性紫色土 Acid purple soil	中性紫色土 Neutral purple soil	碱性紫色土 Alkaline purple soil
全钾 Total K	平均值 Mean (mg/kg)	17.7	17.7	17.8	17.3
	最大值 Max(mg/kg)	25.1	19.3	25.1	21.8
	最小值 Min(mg/kg)	12.5	13.8	12.5	13.0
	标准方差 Std. Deviation	3.3	1.9	3.6	3.8
速效钾 available K	平均值 Mean (mg/kg)	152.2	152.1	154.8	135.1
	最大值 Max(mg/kg)	299.6	289.5	299.6	210.3
	最小值 Min(mg/kg)	37.9	59.9	37.9	56.4
	标准方差 Std. Deviation	67.3	68.7	69.4	62.9

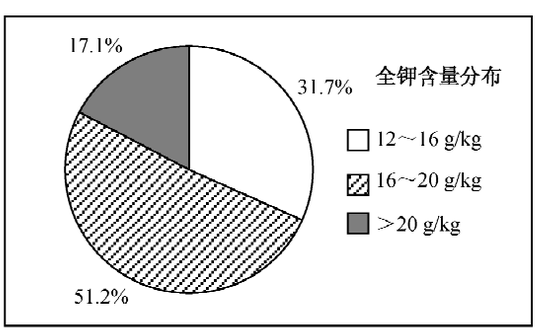

图 1 紫色土全钾含量分布

Fig. 1 Distribution of total K content in purple soils

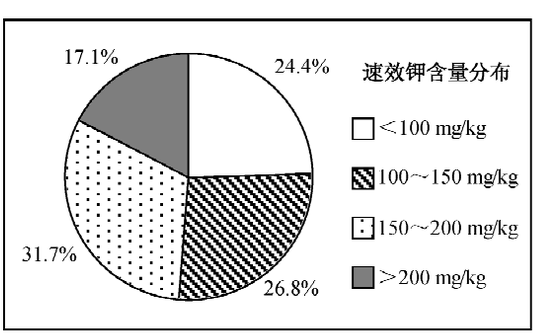

图 2 紫色土速效钾含量分布

Fig. 2 Distribution of available K content in purple soils

在紫色土土壤全钾分布中(见图 1),含量适中(12～16 g/kg)占 31.7%,含量高(16～20 g/kg)占 51.2%,含量丰富(＞20 g/kg)占 17.1%。在紫色土速效钾分布中(见图 2),小于 100 mg/kg 仅占 24.4%,速效钾含量高(100～200 mg/kg)占 58.5%,速效钾含量丰富(＞200 mg/kg)占 17.1%。由于烤烟对钾的需求特别强烈,故在烤烟种植中,钾比任何其他养分的施用量都大,而紫色土速效钾含量丰富,完全可以提供充足的钾来供给烤烟以满足优质烤烟生产的需求。

2.2 不同类型紫色土烟叶中钾的含量与分布

紫色土烟叶含钾量较高,平均含量为 37.5 g/kg,最高含量可达到 48.9 g/kg,紫色土烟叶含钾量较高与紫色土土壤含钾量较高有关。从不同类型紫色土烟叶含钾量结果可以看出(见图 3):碱性紫色土烟叶含钾量(38.4 g/kg)与酸性紫色土(38.9 g/kg)差异不大,但碱性紫色土烟叶含钾量显著高于中性紫色土(36.3 g/kg),而碱性紫色土土壤速效钾含量比中性与酸性紫色土低 13%,故表明碱性紫色土更能促进烟叶对钾的吸收。

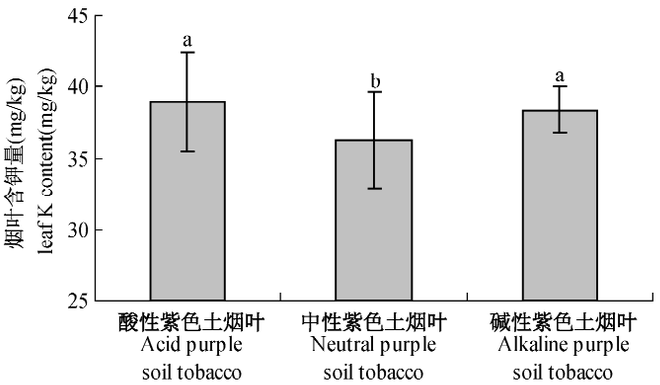

图 3 不同类型紫色土烟叶钾素含量

注:图中不同字母表示差异达到 0.05 的显著水平

不同类型紫色土烤烟其不同叶位的烟叶含钾量没有显著性差异(见表 3),这一结果与传统认为老叶中钾由于要不断向新叶转移,上部叶含钾量应高于下部叶的观点不同。这是因为紫色土速效钾含量非常丰富,使得烤烟吸收的钾量比较充足,因此不需要过多老叶中的钾再向新叶分配,仅根部所吸收的钾即可满足新叶对钾的需求,故紫色土烤烟不同叶位的含钾量差异不大,这也是紫色土优质烟叶的特色之一。

表 3 不同类型紫色土烤烟其不同叶位的烟叶含钾量

Table 3 Difference position leaf K content tobacco planted in different types of purple soil

数值 value	酸性紫色土烤烟 Acid purple soil tobacco			中性紫色土烤烟 Neutral purple soil tobacco			碱性紫色土烤烟 Alkaline purple soil tobacco		
	上部烟 B2F	中部叶 C3F	下部叶 X2F	上部烟 B2F	中部叶 C3F	下部叶 X2F	上部烟 B2F	中部叶 C3F	下部叶 X2F
平均值 Mean (g/kg)	38.62 a	39.97 a	38.16 a	36.11 a	36.60 a	36.09 a	38.79 a	37.30 a	39.07 a
最大值 Max (g/kg)	44.18	46.23	44.35	46.43	48.85	44.92	40.49	39.61	41.39
最小值 Min (g/kg)	34.08	35.29	33.97	31.12	29.39	31.59	37.44	36.15	37.87
标准方差 Std. Deviation	3.56	3.72	3.46	3.35	3.71	3.20	1.47	1.58	1.58

注:表中不同字母表示差异达到 0.05 的显著水平。

3 结论

江西紫色土土壤含钾量较高,全钾 17.7 g/kg,速效钾 152.2 mg/kg;不同紫色土之间全钾含量差异不大,但速效钾含量以碱性紫色土略低。紫色土全钾≥16 g/kg 占 68.3%;速效钾≥100 mg/kg 占 75.6%。紫色土烟叶含钾量较高,平均含量为 37.5 g/kg,最高含量可达到 48.9 g/kg,其中碱性紫色土更能促进烟叶对钾的吸收。由于紫色土钾素资源丰富,故导致紫色土烤烟不同叶位的含钾量差异不大。

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The soil K contents in different types of purple soils and their effects on nutrient K distribution laws of flue-cured tobacco

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Abstract: In order to investigate the contents of soil potassium (K) content in different types of purple soils in Jiangxi and their effects on K distribution laws of flue-cured tobacco, soil and tobacco samples were collected by point to point in purple soil and were determined in 2009. The results showed that soil K content was abundant in the purple soils of Jiangxi Province. Total K and available K was 17.7 g/kg, 152.2 mg/kg, respectively; total K ≥16 g/kg accounted for 68.3% and available K ≥100 mg/kg accounted for 75.6% in the distribution of soil K content. Tobacco leaf K content was high and averaged 48.5 mg/kg and alkaline purple soil was good for the absorption of K. However, there was no significant difference in the position of leaf K content in different types of purple soil tobacco. Therefore, the soil K resource was rich in the purple soils of Jiangxi Province, resulting in the high K content and good quality of tobacco tested.

Keywords: Purple soil, flue-cured tobacco, leaf K content, total K, available K, leaf position

华南蔬菜钾肥推荐施用技术研究[①②]

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摘　要：在不同地点、不同肥力水平的菜园土上进行叶菜、瓜、豆三类主要蔬菜的钾肥田间试验，对149个试验的三类蔬菜相对产量与施钾量、土壤有效钾含量等一系列试验数据进行相关统计分析，建立回归方程，以此建立菜园土有效钾养分丰缺指标和各等级土壤的推荐施钾指标：(1)蔬菜相对产量为＜75%、75%～90%、90%～95%、＞95%的各肥力等级菜园土壤有效钾丰缺指标分别为＜35 mg/kg、35～125 mg/kg、125～190 mg/kg、＞190 mg/kg。(2)各有效钾等级对应的施钾量叶菜分别为8.5～12.5 kg/亩、5.5～8.5 kg/亩、4.5～5.5 kg/亩、＜4.5 kg/亩；瓜类蔬菜分别为15.0～23.0 kg/亩、10.0～15.0 kg/亩、8.5～10.0 kg/亩、＜8.5 kg/亩；豆类蔬菜分别为13.5～21.0 kg/亩、9.0～13.5 kg/亩、7.0～9.0 kg/亩、＜7.0 kg/亩。

关键词：菜园土；钾；肥力分级指标；推荐施肥量；叶菜；瓜；豆

中图分类号：S143.7

蔬菜是人们重要食物资源，钾是植物生长必需的大量营养元素之一，对蔬菜产量形成和品质提升有不可替代的重要作用。土壤肥力指标法是当前全国测土配方施肥工作中主推的方法之一，在20世纪的第二次土壤普查工作中，土壤养分丰缺指标协作组系统地建立了我国主要土壤类型、主要大田作物的土壤肥力分级指标[1-4]，近年来有关单位又应用“3414”试验建立了冬小麦测土配方施肥指标体系[5]。有关蔬菜氮、磷、钾的测土施肥研究也做了不少[6、7]，但主要集中在适于叶菜的营养诊断指标[8-11]和土壤氮、磷的丰缺指标[12、13]上，而适于华南其他蔬菜的土壤钾素诊断指标和推荐施肥技术指标则研究较少。目前在蔬菜集约化生产面积不断扩大的条件下[14、15]，需要明确菜园土有效钾的营养诊断指标，为蔬菜平衡施肥提供科学的施肥指标和推荐依据，以保证蔬菜优质安全生产。本文开展菜园土有效钾丰缺指标和施肥技术指标研究，旨在为本地区蔬菜生产的钾素合理施用提供依据。

1　材料与方法

1.1　试验设计

试验于2008—2011年在广东省的30多个县、区进行。供试的蔬菜中叶菜类以菜心和小白菜为代表、瓜类以苦瓜为代表，豆类以豇豆为代表。供试肥料均为单质肥料：尿素（N 46 %）、过磷酸钙（P_2O_5 12%）、硫酸钾（K_2O 50%）或氯化钾（K_2O 60%）。

在每个田间试验前采集混合的耕层（0～20 cm）基础土壤样品，风干过1 mm筛后进行养分分析。用醋酸铵浸提-火焰光度法测定。

试验方案按农业部的《测土配方施肥技术规范》的“3414”完全实施方案，本文选用了施氮2水平、磷2水平条件下不施钾（K0）和施钾2水平（K2）处理的蔬菜产量数据。

施钾2水平K_2O用量：小白菜和菜心为6.6 kg/亩，苦瓜为12 kg/亩，豇豆为11 kg/亩。施氮2水平N用量：小白菜和菜心为10 kg/亩，苦瓜为12.5 kg/亩，豇豆为12 kg/亩。施磷2水平P_2O_5用量：小白菜和菜心为2 kg/亩，苦瓜为8 kg/亩，豇豆为9 kg/亩。3次重复，随机区组排列。小区面积为20 m^2。株行距：小白菜和菜心0.20 m×0.20 m，苦瓜和豇豆每畦单行、株距分别为0.8 m和0.6 m。收获时按小区测产。每类蔬菜进行40个点或以上的田间试验。

1.2　数据统计方法

1.2.1　土壤有效钾肥力分级指标的建立方法

采用对数方程法，以相对产量作为统计指标，149个试验点的蔬菜相对产量（RY）为不施钾肥区（K0）

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蔬菜产量占施钾肥区(K2)蔬菜产量的百分数,即:RY%=(K0/K2)×100%,以对数方程获得相对产量与土壤有效钾测定值之间的数学关系式,以相对产量为50%、75%、90%、95%计算土壤有效钾含量,根据计算值划分土壤钾丰缺指标。本研究拟定缺钾区相对产量为50%的钾测定值为极低,介于50%至75%范围内的为低,介于75%至90%范围内的为中,介于90%至95%范围内为高,>95%的为极高。

1.2.2 推荐施肥量的计算方法

对于钾的推荐施肥量计算,分叶菜、苦瓜、豇豆三种不同蔬菜品种,用三元二次方程或二元二次方程、或一元二次方程和线性加平台方程[4]获得各个试验点的最佳施肥量,分别将三种蔬菜每个试验点的最佳施肥量与土壤有效钾养分含量进行统计,按上述建立的土壤肥力分级指标分为极低、低、中、高、极高进行汇总统计,确定各等级有效氮、磷、钾水平下的推荐氮、磷、钾施用量[9-13]。

2 结果与分析

2.1 菜园土壤有效钾丰缺指标的建立

根据试验地基础土样的土壤速效钾含量以及"3414"田间试验中的N2P2K0、N2P2K2、2个处理的蔬菜产量计算出缺钾处理小区的相对产量(相对产量即不施钾区叶菜产量占施钾区蔬菜产量的百分数)。首先按叶菜、瓜、豆三个不同种类的蔬菜分别进行计算拟合,将叶菜49个田间试验、苦瓜47个田间试验、豇豆51个田间试验基础土壤样本的速效钾含量与相对应试验的缺钾区蔬菜相对产量作散点图,分别得出三类蔬菜的对数回归方程(见图1(a)、(b)、(c)),然后再把所有蔬菜149样点的田间试验数据用同样方法进行统计获得三种蔬菜合并的对数方程(见图1(d))。统计结果显示,4个方程均达到极显著水平。

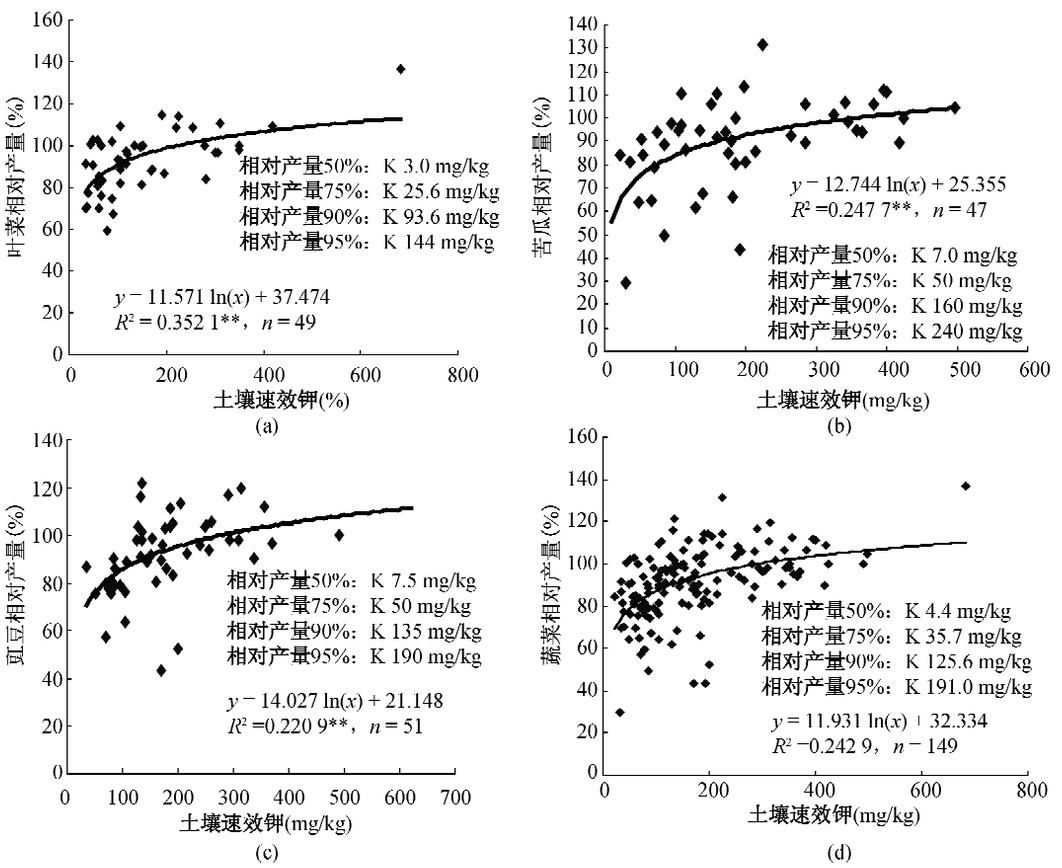

图1 土壤速效钾含量与缺钾区蔬菜相对产量的关系

Fig. 1 The relationship between soil NH_4OAc-K and relative yield of vegetable

分别用图1中土壤有效钾与叶菜、苦瓜、豇豆、合并蔬菜相对产量的4组数学模型,求取相对产量为50%、75%、90%、95%对应的土壤速效钾含量,得出4组土壤有效钾的丰缺指标值:叶菜组分别为3.0、25.6、93.6、144.0 mg/kg;苦瓜组分别为7.0、50.0、160、240 mg/kg;豇豆组分别为7.5、50.0、135.0、190 mg/kg;合并蔬菜组分别为4.4、35.7、125.6、191.0 mg/kg。根据图1,分别将合并蔬菜组与叶菜

组、苦瓜组和豇豆组进行比较，发现相对产量50%的指标范围为3.0～7.5 mg/kg、75%的指标值范围为25.6～50 mg/kg、90%的指标范围为93.6～160 mg/kg、95%的指标值范围为144.0～240 mg/kg。差异最大的指标值是相对产量为95%级的，相对产量在90%以下时的指标值差异均不算大，75%级的苦瓜和豇豆的指标值甚至重合，均为50.0 mg/kg。为了指标体系在生产实际中应用简便和可操作，可将3种蔬菜的土壤有效钾丰缺指标值合并为一套，统一使用合并蔬菜组的。

检查所有试验点(149个)，蔬菜相对产量＜50%的只有5个(占全部试验的3.3%)，其中苦瓜为4个(占苦瓜试验的8.1%)、豇豆为1个(占豇豆试验的1.9%)、叶菜则为零。若将土壤有效钾丰缺指标分为5级时，按相对产量＜50%的钾测定值为极低，50%～75%范围内的为低，75%～90%的为中，90%～95%的为高，＞95%的为极高，根据图1(d)的方程，各级的指标值分别为＜4.4 mg/kg、4.5～35 mg/kg、36～125 mg/kg、126～190 mg/kg、＞191 mg/kg。再检查所有试验点(149个)的土壤速效钾测定值，＜4.4 mg/kg的为0，4.5～125 mg/kg的有5个(占总数的3.3%)，36～125 mg/kg的有55个(占总数的36.92%)，126～190 mg/kg的有39个(占总数的26.2%)，＞191 mg/kg的有50个(占总数的33.6%)。考虑到指标体系在实际应用中的方便性，可将菜田土壤有效钾丰缺指标进一步简化为4级。即蔬菜相对产量＜75%时，土壤有效钾为低等级(35 mg/kg)；在75%～90%时，土壤有效钾为中等级(36～125 mg/kg)；90%～95%时为高等级(126～190 mg/kg)；＞95%时土壤有效钾为极高(＞191 mg/kg)。

2.2 蔬菜钾肥推荐施肥技术指标的建立

分别将三类蔬菜的每个试验进行产量与施肥量的回归分析，建立有关钾的肥料效应函数。根据产量和肥料价格，通过边际分析计算每个试验点的最佳施肥量，以采用一元二次函数和线性加平台方程为主，二元二次和三元二次函数为辅的原则(因三元二次函数的拟合成功率较低，且推荐施肥量过高或容易出现负值)，对拟合成功的方程，根据方程拟合的决定系数选用统计检验显著的方程，求得各个试验点的最佳经济施钾量。分别将三类蔬菜各个点的最佳施钾量结果与相应土壤速效钾含量进行相关分析，并作图和分别求取叶菜、苦瓜和豇豆的相关性模型(见图2)，根据各类蔬菜的模型，按表1的各等级钾肥力水平分别计算出各等级的推荐施钾肥技术指标(见表1)。

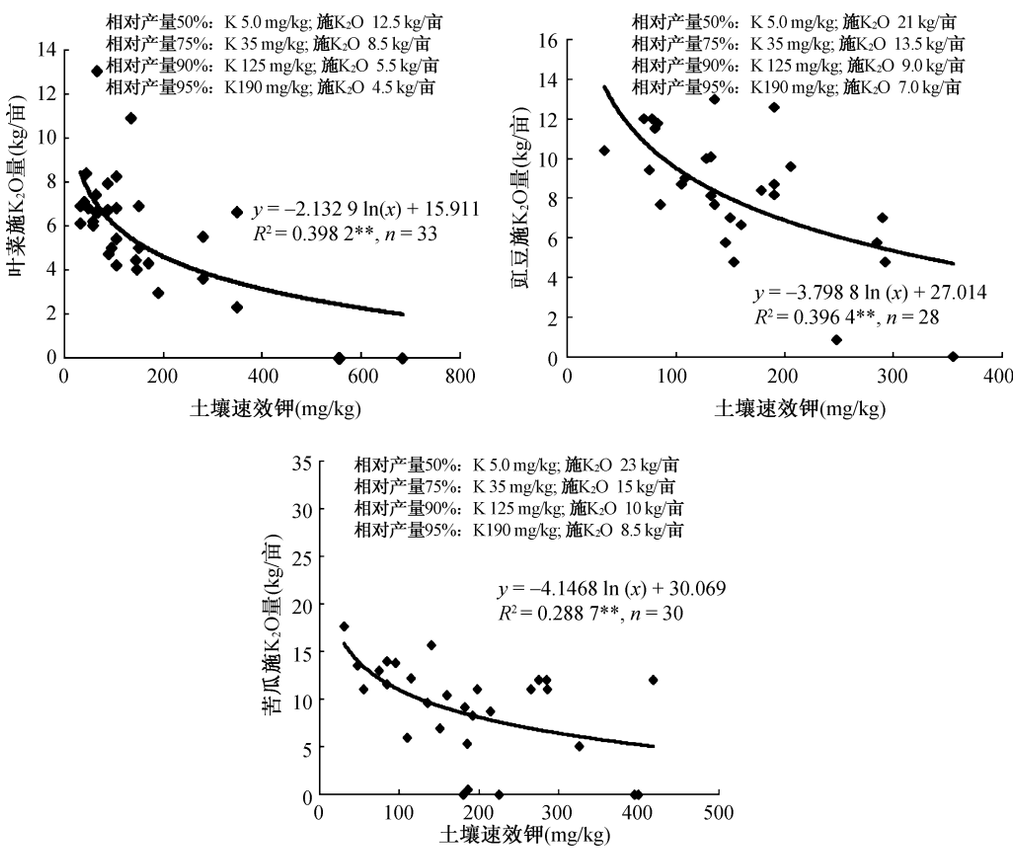

图2 土壤速效钾与蔬菜施钾量的关系

Fig. 2 The relationship between soil NH_4OAc-K and K fertilizer for vegetable

表1 菜田土壤有效钾丰缺指标及蔬菜磷肥推荐施用量表

Table 1 Soil available K grades and K fertilizer recommendation for vegetable

土壤有效钾等级	相对产量(%)	速效钾(mg/kg)	推荐总施 K_2O 量(kg/亩)		
			叶菜	苦瓜	豇豆
低	<75	<35	8.5～12.5	15.0～23.0	13.5～21.0
中	75～90	36～125	5.5～8.5	10.0～15.0	9.0～13.5
高	90～95	126～190	4.5～5.5	8.5～10.0	7.0～9.0
极高	>95	>191	<4.5	<8.5	<7.0

当土壤速效钾含量为低等级(<35 mg/kg)时,推荐每亩总施钾(K_2O)量叶菜为 8.5～12.5 kg、苦瓜为 15～23 kg、豇豆为 13.5～21 kg;土壤速效钾含量在 36～125 mg/kg 时,推荐每亩总施钾量叶菜为 5.5～8.5 kg、苦瓜为 10.0～15.0 kg、豇豆为 9～13.5 kg;土壤速效钾含量在 126～190 mg/kg 时,推荐每亩总施钾量叶菜为 4.5～5.5 kg、苦瓜为 8.5～10.0 kg、豇豆为 7～9 kg;土壤速效钾含量在>191 mg/kg 时,推荐每亩总施钾量叶菜不超过 4.5 kg、苦瓜不超过 8.5 kg、豇豆不超过 7 kg。表 1 所推荐施钾量指标是包括了有机肥中钾素含量的,因此若与有机肥配合施用时,要考虑有机肥所含的钾量而适当低于此施钾量。

3 结论与讨论

3.1 土壤有效钾养分肥力等级的划分

关于土壤有效钾肥力等级划分,周鸣铮[16]在 80 年代建议将其划分为 5 级,即“极低”、“低”、“中”、“高”和“极高”;陆允甫等[17]、金耀青等[18]、林守宗等[19]建议划分为 4 级,章明清[20]等把福建的粮油作物测土配方施肥指标划分为 3 级。本研究 149 个试验点的蔬菜相对产量<50%的只有 5 个,没有找到菜田土壤速效钾含量处于极低水平(<4.4 mg/kg)的。也就是说,在本省菜田土壤有效钾水平极少处于极低水平的情况下,将土壤有效钾肥力划分出极低等级不具实际意义。鉴于此,当蔬菜的相对产量为<75%、75%～90%、90%～95%和>95%时,其所对应的土壤有效磷丰缺等级划分为:“低”、“中”、“高”和“极高”4 个等级。

3.2 土壤有效钾丰缺指标的比较

广东省第二次土壤普查养分分级标准[21]:六级至一级分别为<30 mg/kg、30～50 mg/kg、50～100 mg/kg、100～150 mg/kg、150～200 mg/kg、> 200 mg/kg;陈琼贤等[22]对华南菜心的土壤钾分级:极低为<60 mg/kg、低为 60～80 mg/kg、中为 80～120 mg/kg、高为 120～220 mg/kg、极高为> 200 mg/kg。这与本试验中广东蔬菜当前产量水平下的土壤有效钾含量<35 mg/kg 为低、36～125 mg/kg 为中、126～190 mg/kg 为高、>191 mg/kg 为极高的标准差异不大。

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Study on the technical index value of potassium at soil testing and fertilization for vegetables in South China

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Abstract: Fertilizer K experiments of 138 field trials on leaf vegetable, gourd vegetable and legume vegetable in different locations with different fertility levels were investigated, and the statistical analysis on the relative yield and potassium fertilization and soil available potassium were carried out. The regression equations were also established. They were to determine the soil Rich-Lack index on available potassium and the recommended fertilization of potassium for different fertility levels of soil. Results showed that when the relative yield of vegetable were <75%, 75%-95%, >95%, the soil Rich-Lack index on the available potassium were <50 mg · kg^{-1}, 50-240 mg · kg^{-1}, >240 mg · kg^{-1}, respectively for gourd-vegetable like balsam pear, that was <45 mg · kg^{-1}, 45-195 mg · kg^{-1}, >195 mg · kg^{-1} respectively for legume vegetable like cowpea, that was <20 mg · kg^{-1}, 20-140 mg · kg^{-1}, >140 mg · kg^{-1} respectively for leaf vegetable. The recommended fertilization of potassium for different fertility levels of soil were that the gourd vegetables were 225.0 kg · hm^{-2}, 112.5-225.0 kg · hm^{-2}, <112.5 kg · hm^{-2} respectively, the legume vegetables were 187.5 kg · hm^{-2}, 105.0-187.5 kg · hm^{-2}, <105.0 kg · hm^{-2}, respectively, the leaf vegetables were 142.5 kg · hm^{-2}, 82.5-142.5 kg · hm^{-2}, < 82.5 kg · hm^{-2}, respectively.

Key words: Soil of vegetable garden, potassium, soil fertility grading index, recommended fertilization index, leaf vegetables, gourd vegetables, legume vegetables

第三部分
钾肥效应与功能

Effects and function of potassium fertilization

The effects of potassium fertilization on water-use efficiency in crop plants§ $

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Abstract: The supplies of water and nitrogen to a plant during its critical stages of growth are the main factors that define crop yield. A crop experiences irregular water deficits during its lifecycle in rain-fed agriculture. An effective anti-stress oriented approach therefore ought to focus on increasing the units of water productivity. The main objective of this conceptual review is to confirm that adequate K management can be used as an important tool to alleviate the negative effects of water deficit on plant growth, yield component formation and yield. The French and Schultz approach of using the water-limited yield (WLY) was modified in this review into a graphical form and was used to discriminate between yield fractions that depended on the volume of transpired water from those that were induced by K fertilizer. By using this method, it was possible to demonstrate the extent of several crop (winter wheat, spring triticale, maize, sugar beet) responses to the K supply. Yield increases resulting from K application mostly appeared under conditions of mild water deficit. As described for sugar beet, finding the critical period of crop K sensitivity is a decisive step in understanding its impact on water-use efficiency. It has been shown that an insufficient supply of K during crucial stages in the yield formation of cereals (wheat, spring triticale), maize and sugar beet coincides with a depressed development in the yield components. The application of K fertilizer to plants is a simple agronomic practice used to increase crop tolerance to a temporary water shortage. It may be that the improvement of a plant's access to K during mild water deficiency stress will increase water uptake by the root cells, which in turn increases their osmotic potential and thereby allows extension growth. This growth in turn promotes access to other mineral elements (including nitrogen) and water, which favor plant growth and yield.

Key words: Drought stress, water-limited yield, critical stage, root system

1 Introduction

The yield potential of a particular crop may be defined as the maximum plant productivity in the presence of an ample supply of water and nutrients (*Evans* and *Fisher*, 1999). However, rain-fed crops are subject to intermittent water stress in temperate climate zones, which decreases the yield potential, a trait that is primarily controlled by the genome (*Debaeke* and *Aboudrare*, 2004; *Rabbinge* and *Diepen*, 2000). Actual harvested yields result from the interactions between different growth factors, which are responsible for fulfilling the yield potential of cultivated varieties. As a rule, actual yields are much lower than the attainable maximums and are defined by soil and climatic conditions (*Supit* et al., 2010). On the basis of the degree of yield potential realization, *Rabbinge* (1993) has divided all growth factors into three main groups in descending order of importance: (a) defining (light, CO_2, plant), (b) limiting (water, nutrients), and (c) reducing (weeds, diseases, external toxins). Furthermore, *Lansigan* (1998) has distinguished four levels of production systems: (a) potential, (b) water-limited, (c) nitrogen-limited, (d) other nutrient-limited. The criteria of the production factor's hierarchy have become the basis of the yield gap concept. The yield gap is defined as the lost part of a potentially harvested yield that was achievable at each production level (*Dobermann* and *Cassman*, 2002; *Evans* and

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$ This manuscript is partly based on original data from a PhD thesis as presented in Tables 1 and 2 and Figures 1, 2, and 6.

Fisher, 1999; *Wallace* and *Wallace*, 2003).

The availability of water together with the nitrogen supply is a key factor in plant growth. It is well recognized that only with ample water supply can crop plants effectively exploit soil and fertilizer nitrogen resources. Therefore, the nitrogen supply must be considered as a prime factor of crop plant growth that isa decisive aspect of productivity (*Gonzalez-Dugo* et al., 2010). Even mildwater stress can be detrimental to the harvested yield. Any water deficit significantly disturbs plant function, which negatively impacts plant life processes, both at the molecular and whole-plant levels. Drought stress induces stomatal closure, reducing evapotranspiration (ET_a) and the mass flow of soil solution to the root surface. As a consequence, the rate of mineral element delivery decreases, which limits plant nutrition and growth (*Flexas* and *Medrano*, 2002; *Farooq* et al., 2009; *Gonzalez-Dugo* et al., 2010; *Kuchenbuch* et al., 1986; *Luan*, 2002; *Shao* et al., 2009). The physiological consequence of reduced crop water-supply is a decrease in the rate of growth, which in turn decreases the production of biomass and its partition among plant organs. (*Ågren* and *Franklin*, 2003; *Debaeke* and *Aboudrare*, 2004; *Shao* et al., 2009). However, other growth factors must also be taken into account because both the water and the units of N productivity depend on the uptake and utilization of other plant nutrients (*Cakmak*, 2005; *Fageria*, 2001; *Janssen*, 1998; *Wallace*, 1990).

In modern agriculture, the economically and environmentally sound practice of production requires some insight into processes that increase productivity per water unit. The depletion of soil nutrient reserves is a logical consequence of soil mining-oriented agriculture, which results in soil fertility decline. As reported by *Wood* et al. (2000), K depletion is a major reason for the degradation of arable land in southeast Asia, Latin America, and the Caribbean. Agriculture in Central Europe is orientated towards K mining and is the principal reason for low water-use efficiency, resulting in considerable seasonal variability in yields (*Grzebisz* and *Diatta*, 2012). Thus, the primary objective for farmers is to decrease the year-to-year variability of harvested yields. However, fulfilling this objective depends on the answers to two other urgent questions: (a) How can the water productivity per unit be increased under rain-fed conditions? (b) How can the productivity per unit of nitrogen be increased under limited water conditions? In terms of agricultural policy, the answers to both these questions relate to methods and measures, which could bring the limiting productivity factors of water and nitrogen to the attention of farmers.

In light of this information, it can be proposed that the size of the crop yield gap is a consequence of insufficient nitrogen productivity, which in turn results from inadequate water-use efficiency (WUE). The objectives of this conceptual review are: (a) to describe a quantitative assessment method for K impact on WUE, (b) to define critical stages of crop plant response to K, and (c) to illustrate that adequate potassium management can be used as an important tool for alleviating the negative effects of water deficits on plant growth and yield.

2 Potassium fertilization versus water-use efficiency (WUE)

2.1 A framework for the WUE concept

The physiological functions of water are characterized at three levels: (a) cellular (as a component and medium for biochemical reactions), (b) tissue (as a link to adjacent cells), and (c) whole plant (as a means of mineral nutrient and hormone transport; *Shao* et al., 2009; *Monneveux* and *Belhassen*, 1996). In agronomy, a fourth operational level of water's effect on a crop plant has been developed that summarizes all basic processes at the canopy level. This index is known as the water-use efficiency (WUE) index, and in a broad sense it describes the quantity of biomass produced by a particular crop plant in relation to the volume of water that is evaporated and transpired during its life cycle (*Liu* et al., 2007). The WUE index is calculated as the quantity of the main crop product (Y_a) per unit of water

(ET_a) used (kg per mm or m^3):

$$WUE = \frac{Y_a}{ET_a} \quad [1]$$

Yield (Y_a) is defined as the quantity of actual harvestable or marketable crop parts (seeds, grain, roots, tubers, etc.) per given area during a fixed period of time. Evapotranspiration (ET_a) is a measure of the water that is used (transpired and evaporated water in mm or m^3) by a cultivated crop during its growth period. The ET_a is calculated on the basis of the vapor-pressure deficit and harvest index (*Debaeke* and *Aboudrare*, 2004) as follows:

$$Y_a = k(ET - Es) \times (HI/VPD) \quad [2]$$

whith Y_a, the yield of a particular crop; k, biomass/transformation ratio; ET_a, total water use ($ET_a = T_p + E_s$); T_p, plant transpiration, E_s, soil evaporation; HI, harvest index; VPD, vapor pressure deficit.

As a rule, it is assumed that any increase in crop yield in a particular environment is accompanied by a simultaneous increase in the WUE (*Ritche* and *Basso*, 2008). Therefore, ET_a is frequently considered to be a constant part of the operational index (Liu et al., 2007). However, *Zwart* and *Bastiaanssen* (2004) showed that ET_a is not a constant value. Based on an extended collection of empirical data, these investigators concluded that the coefficient of determination or r^2 for the relationship between the harvested yield (Y_a) and ET_a was low, amounting to 0.35 for wheat and 0.33 for maize. In addition, our findings also show that the r^2 coefficient variability adequately reflects differences in both the climatic conditions and nutrient supply. Therefore, the WUE is a useful index for comparing different crops and regions (*Liu* et al., 2007). Nevertheless, its applicability to discriminating between the growth factors that contribute to yield increases seems to be limited.

Agnus and *Herwaarden* (2001) have proposed another method for a simple and quick assessment of water productivity at the field level, which is known as the French and Schultz approach (FAS). This method considers the problem of imbalanced water use by crop plants. Its major thesis assumes that a plant's water supply is not the dominant factor in determining the quantity of the harvested yield, but accounts for environmental and management factors as well, which limit water-use productivity. These assumptions are seemingly contradictory to the multiple limitation hypothesis, (MLH), which treats water as the main growth factor (*Rubio* et al., 2003). In fact, the FAS concept raises the problem of the efficient crop use of water, which in turn depends on factors that affect its uptake, from soil resources to biophysical processes (*Cakmak*, 2005; *Rengel* and *Damon*, 2008).

The FAS method of water productivity assessment was originally based on wheat research in Australia (*French* and *Schultz*, 1984; *Passioura*, 2006). Operationally speaking, FAS relies on the attainable (water-limited) yield determination. This procedure requires data on the maximum unit water productivity (TE) and amount of water available for transpiration by a crop canopy during the growth season. The algorithms for the water-limited yield (WLY) calculation are as follows:

$$WLY = TE(R - \sum E_S) \quad [3]$$

$$WLY = TE(R - \sum E_S) + WR \quad [4]$$

where: TE, the transpiration efficiency ($TE = k/VPD$); R, the sum of rainfall during the growth period; E_S, the seasonal soil evaporation, equal to 110 mm; and WR, water reserves in the rooted soil volume at the beginning of growth for a particular crop.

The original FAS algorithm was composed of two units, the first of which was the TE index, which was originally estimated to be 20 kg grain ha^{-1} mm^{-1}. This level of unit water productivity can be achieved only under optimum growth conditions, i.e., without disturbances from low soil fertility or attacks by diseases and pathogens (*Turner*, 2004; *Passioura*, 2006). However, even in Australia the

standard value is under discussion, with wider values ranging from 20 to 30 kg grain ha^{-1} mm^{-1} (*Agnus* and *Herwaarden*, 2001). The second component of the equation is the water balance R, which is the total rainfall from the beginning to the end of the vegetative season. Therefore, this method of water productivity calculation relies on the maximally available water supply for the season. In the temperate regions of the world, especially in continental zones, an important source of water is soil water reserves, or WR, which originate from winter precipitation. For the purposes of this study, equation [3] has been extended into equation[4] to include a unit that quantitatively describes internal soil water resources.

However, the FAS approach has another advantage. It can be applied to evaluate the fractional effect of any particular factor that limits water-unit productivity, that is to say, any factor that impacts its use efficiency. It has been assumed that each growth factor affects water uptake by the crop from the soil and that its biophysical processes are critical for increasing water unit productivity. The graphical interpretation of this method that is proposed in this review allows for the discrimination between effects that result from the action of transpired water and the tested factor. Operationally, the harvested yield is divided into two parts. The first part, i. e. , the WLY results from the amount of transpired water, is considered to be the most important. The second part of the graph shows the quantitative effect of a factor that is responsible for the efficient or non-efficient use of water. This is not as important as the WLY. Experimental factor results including K can be presented in the classical FAS form as shown in Fig. 1, or graphically represented as a fractional yield (Figs. 2, 3, 4).

2.2 Potassium effects on WUE: case studies

2.2.1 Winter wheat

The applicability of the FAS concept has been validated for four groups of crops that were cultivated in temperate regions, including our own experiments in Poland where there is a high continental climate impact, resulting in an elevated frequency of spring and/or summer droughts (*Falloon* and *Betts*, 2010; *Olesen* et al. , 2011). Cereals dominate the agricultural production of this region (*Rabbinge* and *van Diepen*, 2000). Winter wheat yields depend significantly on both soil fertility and soil management. The level of grain yields in Poland is approximately 4 t ha^{-1}, which constitutes 66% of the attainable yield as defined by the water supply. As reported by *Grzebisz* and *Diatta* (2012), the main reason for low yields is not only the water supply but also the limited supply of nutrients, mainly potassium. This has been fully corroborated by data from field experiments. As shown in Fig. 1, winter wheat yields are irregularly scattered without any significant response to the quantities of supplied water. It is necessary to mention that the establishment of optimum growth conditions for winter wheat is difficult. This crop is sensitive both to water deficiency stress and excess during the whole growing season (*Passioura*,

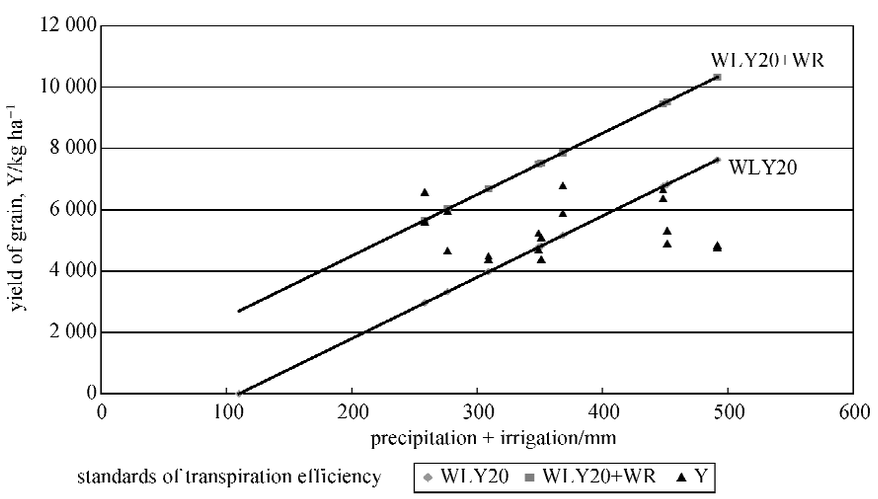

Figure 1 Graphical interpretation of winter wheat yield-response to available water and potassium against a background with two standards of transpiration efficiency (basic data adapted from *Musolf*, 2003).

2006). The water-limited yield in Central Europe is fixed for a majority of countries at 6.5 t ha^{-1} (*MARS*, 1995; *Rabbinge* and *van Diepen*, 2000). As implicitly indicated by the WLY20 and WLY20+WR threshold lines, grain yields for most treatments under study showed complicated response patterns to the water supply (Fig. 1). Under low-precipitation conditions, the yields depended on soil water resources to a great extent, i.e., the amount of water at the beginning of the growth season. These reserves are an important source of water for crops in the temperate regions, especially for those that are dominated by continental water supplies (*Debaeke* and *Aboudrare*, 2004; *Supit* et al., 2010). As indicated by some of the treatments, the wheat responded to irrigation and K-fertilizer application. In two of the three points on and above the WLY20+WR line, the optimal supply of K during the dry year of 1999 was the source of yield increase (Fig. 1). However, other previously unrecognized growth limitations have appeared under high-water conditions (current precipitation+irrigation), as indicated by the yield-points below the WLY20 line.

2.2.2 Spring triticale

In temperate regions with strong influence from a continental climate, spring cereals are much more vulnerable to water-deficiency stress than winter crops (*Hlavinka* et al., 2009; *Martyniuk*, 2008). As shown in Fig. 2, the assumed high dependence of WUE on other growth factors has been documented. Spring triticale was grown under a strongly diversified water supply *via* irrigation as well as an artificially imposed water deficit (*Wyrwa*, 1997) through the use of a shelter. The plant response to water deficiency stress was studied in two chronologically separated stages called BBCH 30－49 and BBCH 60－80. The principal goal of the first period was to evaluate the changes in total biomass and the number of ears that resulted from the induced water deficit. The main objective of the second period was to assess the impact of artificially imposed drought on the yield components. As expected, all targets were fully achieved. The effect of the second experimental factor, i.e., K application, was evaluated by using the graphical formula from the FAS. The difference that resulted from the growth factor application, i.e., between the actual harvested yield and the calculated WLY, was expressed as a yield gain (Y-G) or loss (Y-L).

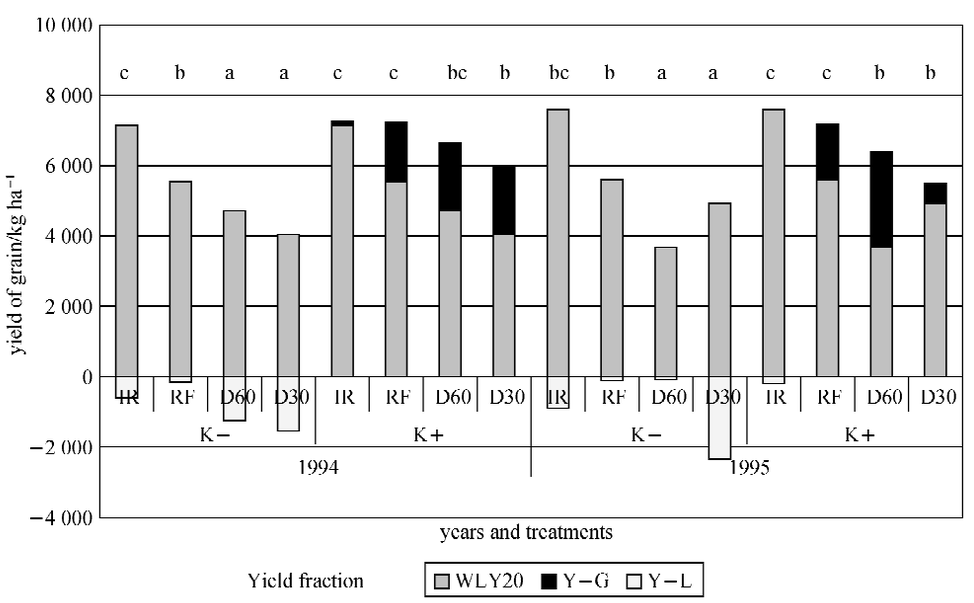

Figure 2 Structural components of grain yield from spring triticale as affected by water and K supply (base data adapted from *Wyrwa*, 1997). WLY=water-limited yield for TE=20 kg grain ha^{-1}, mm^{-1}; Y-G=yield gain, Y-L=yield loss—fractional yields; IR=irrigated at BBCH 30 and 60 for 3 weeks; D30, D60=drought imposed at BBCH 30 and 60, for 3 weeks, respectively, RE=rain-fed conditions. Statistical analysis concerns real yields; columns marked with the same letters are not significantly different.

The data reported in Fig. 2 implicitly underline the reliability of the graphical FAS concept. Firstly,

it was possible to calculate the maximum attainable yield resulting from the maximum unit water productivity. This conclusion is corroborated by the almost 100% equivalence for the real and calculated yields in irrigated treatments. It can therefore be concluded that under an ample water supply, the effect of K fertilizer was insignificant and indirectly indicative of high soil K fertility. Secondly, the FAS method enabled the elucidation of the yield-forming effect for the growth factor of interest, i. e. , K fertilizer. The stress-alleviation effect was best corroborated in the D30 and D60 treatments. Plants grown without a K supply (K-main plot) had yields that were below the calculated WLYs, which was quite a different response pattern to artificially imposed drought than in the plots with freshly applied potassium (K + main plot). For all cases with K-fertilizer applications, excluding the irrigated treatments, a significant yield response was observed. This finding implicitly illustrates the importance of K fertilizer as a measure to at least partially alleviate mildwater-deficiency stress.

A detailed explanation of this phenomenon cannot be conducted without insight into the formation of a given yield component. The harvest index, or HI, can be considered to be crucial at the canopy level as shown in equation[2]. It is simply defined as the relative mass of harvested grains per mass of the whole plant or for the biomass of the canopy. In addition, the index indirectly shows how growing conditions affect the number of grains and their individual weight. The first component reached its potential expression starting at the shooting period and going until the watery stage of grain development, with elevation at heading. The number of ears per unit area and grains per ear are used to indicate a cereal's physiological development (*Shearman* et al. 2005; *Zerche* and *Hecht*, 1999). The second component, which refers to the grain mass and in practice is counted as the thousand grain weight (TGW), depends on the factors that impact cereal growth during the grain-filling period (*Yang* and *Zhang*, 2006). As presented in Fig. 2, the yield gain in the D30 treatments, i. e. , with drought imposed during the shooting and booting of spring triticale, illustrates the importance of potassium management to plants during the primary stage of grain yield development and is responsible for the number of grains per unit area.

The chosen WUE calculation method affects the evaluation of applied factors to some extent in the case of potassium. To validate this conclusion, calculations were performed on the WUE indices for spring triticale based on both methods discussed above. The ET_a in 1994 was 4 710 m^3 ha^{-1} and 4 850 m^3 ha^{-1}in 1995, as calculated for the Brody Synoptic Station and based on the FAO methodology (*Brouwer* and *Heibloem*, 1986). Both methods allow the evaluation of applied potassium's effect on WUE (Table 1). As shown in Fig. 2, the grain yield of spring triticale decreased in concert with increasing water shortage. However, the degree of yield drop was much lower in treatments with K fertilizer. This effect can be explained fairly well by using both indices. On the basis of the ET_a, these indices underline a quantitative difference in evaluations of K yield effects. In the present case, the calculated WUE-ET_a indices were significantly higher for K-fertilized plants. The WUE-FAS indices allow for a view of the contrary course of K management and its impact on water productivity, which in turn indicates the alleviating effect of applying K fertilizer.

Table 1 WUE indices calculated for spring triticale using two different methods[1]. IR = irrigated at BBCH 30 and 60 for 3 weeks; D30, D60 = drought imposed at BBCH 30 and 60, for 3 weeks, respectively, RE = rain-fed conditions.

Potassium and water treatments		Available water* mm		WUE-ET_a kg ha^{-1} mm^{-1}		WUE-FAS kg ha^{-1} mm^{-1}	
		Mean	SD	Mean	SD	Mean	SD
Without potassium (K−)	IR	428.6	±16.2	13.9	0.07	20.2	0.65
	RE	338.7	±2.3	11.4	0.14	22.8	0.08
	D60	269.9	±36.8	7.4	0.01	21.4	5.18
	D30	284.1	±31.3	5.4	0.07	14.1	2.05

续 表

Potassium and water treatments		Available water* mm		WUE-ET_a kg ha^{-1} mm^{-1}		WUE-FAS kg ha^{-1} mm^{-1}	
		Mean	SD	Mean	SD	Mean	SD
With potassium (K+)	IR	428.6	±16.2	15.4	0.07	22.3	0.80
	RE	338.7	±2.3	15.0	0.64	30.3	0.44
	D60	269.9	±36.8	13.7	0.64	39.2	7.47
	D30	284.1	±31.3	11.8	0.71	31.7	7.04

* based on *Wyrwa* (1997)

2.2.3 Maize

Maize is a crop with extremely high potential yields, but it presents economic risk to growers because of its high sensitivity to external growth factors, which can induce year-to-year grain yield variability (*Tollenaar* and *Lee*, 2002). Maize yields in Poland are far below yield potentials for current cultivated varieties. The main reasons for these variations are low soil fertility levels and imbalanced fertilization (*Potarzycki*, 2010). The impact of soil fertility has been reported by *Szczepaniak* et al. (2010). As presented in Fig. 3, maize that was cultivated on light soil produced 3.2 and 9.4 t ha^{-1}, but 8.1 and 10.1 t ha^{-1} grain were produced on medium soil during 2006 and 2007, respectively. However, the general course of the ET_a over both growing seasons showed small variations. The calculated sum of evapotranspired water amounted to 6 220 and 5 720 m^3 ha^{-1} in 2006 and 2007, respectively. Two main reasons for the yield differences were noted. The primary reason relates to the distribution of precipitation, which was unfavorable for maize in 2006. The negative water balance, which occurred at the onset of an thesis, exceeded 150 mm. However, the decisive factor was not the quantity of supplied water, but its use by plants, which depended on both the soil fertility and the K management. On sandy loam, the yields of maize fertilized with K were higher than the calculated WLYs, regardless of the weather conditions. This finding implicitly indicates that K significantly increased water-use efficiency. Maize yields in loamy sand also exceeded the WLYs and responded to applied K. However, this pattern prevailed only during years without water stress. There was a long-lasting water shortage in 2006, and the calculated WLYs were much higher than the actual yields and indirectly indicated the dominant role of the water supply in maize that was grown on light soil, which is naturally poor in K internal resources (*Fotyma*, 2007).

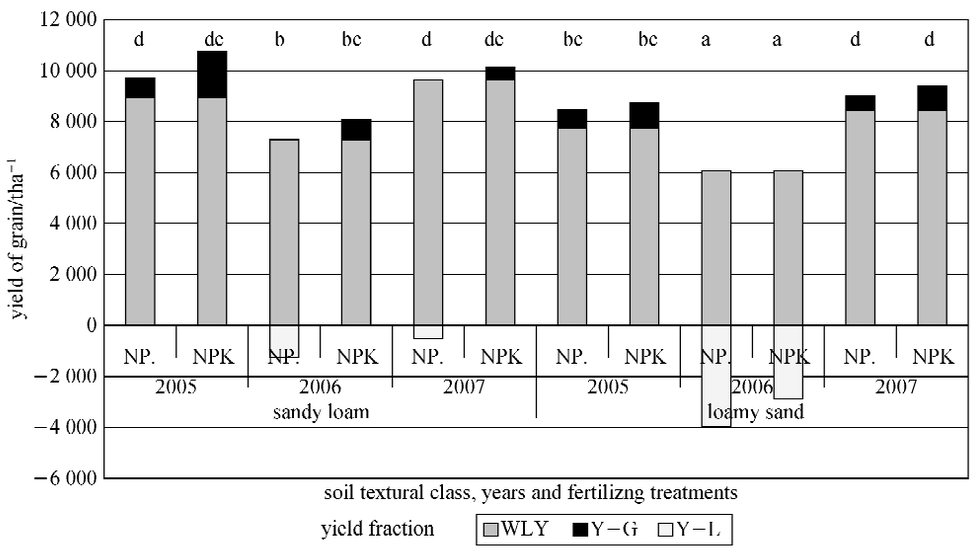

Figure 3 Structural components of maize grain yields as affected by weather for two soil textural classes and potassium treatments (base data adapted from *Szczepaniak* et al., 2010). WLY=water-limited yield for TE =20 kg grain ha^{-1}, mm^{-1}; Y-G=yield gain; Y-L=yield loss—fractional yields. Statistical analysis concerns real yields columns marked with the same letters are not significantly different.

2.2.4 Sugar beet

The third group of plants that are cultivated in temperate regions, especially in Europe, are potatoes and sugar beets (*Olesen* and *Bindi*, 2002). One key factor in the expected response of these two crops to potassium fertilization is the frequency and severity of droughts during the growth season. In the case of sugar beet, there is no fixed value for the maximum unit of water productivity (TE). However, it could be assumed that the highest productivity of this crop reaches 50 kg ha^{-1} mm^{-1} (*Jones*, 2010), on the basis of dry matter yield. On the basis of this value, the FAS critical standard was fixed at 150 kg of fresh beets ha^{-1} mm^{-1} of transpired water (storage roots+amount of leaves). On the basis of a simulation study with a limited K and water supply, it has been documented that K is a factor that significantly affects the WUE (*Musolf* et al., 2004a). As shown in studies throughout Europe, the response of both crops to K fertilization is generally not consistent, both in humid and semi-continental European environmental zones, as reported by *Allisson* et al. (2001) and *Milford* et al. (2000) in Great Britain and *Barłóg* and *Grzebisz* (2004) in Poland. Sugar beets are typically fertilized with K, often heavily so (*Milford* et al., 2000). An extended study that was conducted in the 1990s by *Wojciechowski* et al. (2002) in Poland showed that K application affects the WUE. However, the response depends on the course of weather during beet vegetation development. The applied graphical form of the FAS method allowed for the determination of WLYs with high accuracy with respect to attainable sugar beet yields (Fig. 4). During three annual series of experiments in two distinct localities on soils originating from loamy sand, the sugar beet yields reached their maximum productivity within two years (1996, 1997). Storage root yields were averaged over locations and treatments and amounted to 70.5 t ha^{-1}, whereas the WLY was fixed at 77.5 t ha^{-1}. The latter value is close to a potential sugar beet yield of 80.2 t ha^{-1} in Poland, as reported by *Supit* et al. (2010). Therefore, the fixed unit value of TE at 150 kg ha^{-1} mm^{-1} can be used to evaluate the effects of K on the sugar beet WUE. In the third year (1998) there was a mild drought in the summer months, and the WLY was calculated at a much lower level. The effect of applied K on the WUE was significant at both locations. In the first area its optimum rate amounted to 66 kg K ha^{-1}, whereas in the second 198 kg K ha^{-1} were sufficient to reach the maximum attainable yield of 80 t ha^{-1}.

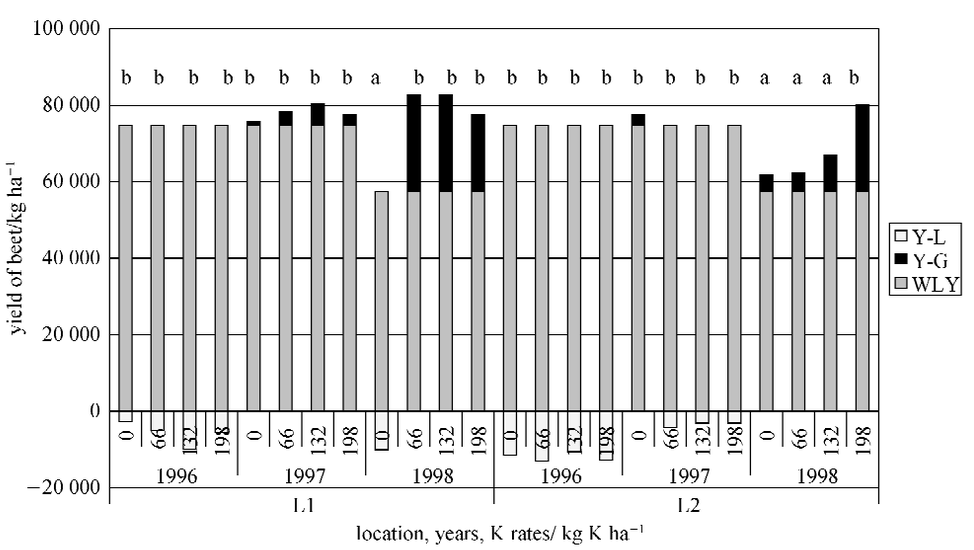

Figure 4 Structural components of sugar beet yields from storage roots as affected by potassium fertilizer rates (base data adapted from *Wojciechowski* et al., 2002). WLY = water-limited yield for TE = 150 kg beets ha^{-1}, mm^{-1}; Y-G = yield gain; Y-L = yield loss—fractional yields. Statistical analysis concerns real yields; columns marked with the same letters are not significantly different.

3 Potassium as a waterstress-alleviating agent

3.1 Determining the critical stage in crop plant sensitivity to K supply

The physiological roles of K in plants have been extensively described in recent reviews (*Maathuis*, 2009; *Marschner*, 2012). Potassium is the main osmotic solute in plantsand it affects water homeostasis both at the cellular and the whole-plant level. Therefore, its accumulation in the cell is a driving force for water uptake, which in turn impacts the water status of its reaction milieu, which is important for the rate of metabolic and growth processes, respectively (*Marschner*, 2012). Potassium is a cofactor for numerous key enzymes that control basic plant metabolic reactions. Therefore, K deficiency depresses the rate of photosynthesis, and in turn affects the amounts of assimilate production and partitioning to roots and shoots (*Amtmann* and *Armengaud*, 2009; *Cakmak*, 2005). K accumulation is the key force that governs the rate of cell expansion and consequently influences the rate of a particular plant part's growth, such as the leaves or roots (*Hawkesford* et al., 2012; *Walker* at al., 1998). Potassium is a very mobile ion in the plant body and a large portion of it cycles between the shoots and roots. As a result, pressure-driven solute transport in plant tissues is the key mechanism for controlling water status, such as the closing and opening of stomata. The co-transport of K^+ ions with nitrate ions (NO_3^-) in the xylem and its circulation with malate in the phloem are classical examples of K transportation functions during its root-shoot turnover. The transportation of assimilates in the phloem is also K concentration-dependent (*Engels* et al., 2012; *White*, 2012; *Szczerba* et al., 2009).

It can therefore be supposed that any disturbance in the plant's potassium supply during its life cycle depresses the development of plant biomass and the formation of structural yield components. This assumption explains the prioritization of K nutrition in the strategy of a particular crop plant's performance during the growth season. In response, some questions concerning the impact of potassium on both nitrogen and WUE or both are needed: does K uptake depend, to some extent, on water supply, which would in turn disturb nitrogen delivery to aerial plant parts? This question can be formulated in a way that stresses the agronomic point of view: is it possible to decrease the negative impact of water shortage on the development of structural yield components through an adequate supply of potassium?

The general pattern of K accumulation in a crop plant over the course of its vegetative development is different in comparison to the sigmoid-like curves of dry matter accumulation (*Yin* et al., 2003). A specific course of K accumulation has been found for wheat (*Barraclough*, 1986, *Cannell*, 1984), oil-seed rape (*Barłóg* et al., 2005; *Orlovius*, 2000), and sugar beet (*Grzebisz* et al., 1998). The main difference is related to a well-defined maximum, which is elevated during the whole season. One of the most important characteristics of K accumulation patterns during the growth season is its significant decrease following the maximum. This non-specific drop may be substantial, i.e., approaching ¼ and even ⅓ of the K maximum at harvest (*Barraclough*, 1986; *Beaton* and *Sekhon*, 1985; *Grzebisz* et al., 1998). Therefore, the K demand of high-yielding arable crops is often underestimated in agronomic practice, and critical growth stages are not always well defined.

Based on the course of K accumulation during the growth season, three main characteristics of K uptake by a particular crop can be determined. They are as follows: (a) maximum K accumulation, (b) the absolute rate of K accumulation, and (c) the relative rate of K accumulation. The second parameter, i.e., the absolute rate of K accumulation (AR_K) determines the most sensitive stage of a given crop's response to K supply. The basic criterion of its determination is the defined K accumulation rate. For example, assuming an AR_K at the level of 8 kg K ha^{-1} d^{-1}, the length of the K maximum uptake rate is approximately 14 d (Fig. 5). In this case, this period would extend from the 72nd to the 95th day of sugar beet vegetation development. The period of highest demand in the sugar beet canopy for K coincides with its main growth parameters. Firstly, the absolute rate of dry matter and nitrogen

accumulation in both the leaves and roots by a high-yielding sugar beet canopy takes place between 80 and 90 days for sugar beet vegetation (*Grzebisz* et al., 2012, *Szczepaniak* et al., 2012). The relative rate of K accumulation (RRA_K), is another crop characteristic, which is useful in determining the earliest stage of its sensitivity to a particular nutrient supply. In the present case, the RRA_K reached a maximum around the 7th week after plant emergence. At this period of sugar beet development, the rate of foliage expansion depends on the supply of nitrogen, which is a decisive factor in solar energy capture (*Malnou* et al., 2006). According to *Marschner* et al. (1996) the rate of nitrate ion uptake is significantly related to a concomitant K supply. Both parameters, i. e., the maxima for the absolute rate of K accumulation (AR_K) and the relative rate of K accumulation (RRA_K), define the critical period of a crop's response to K supply.

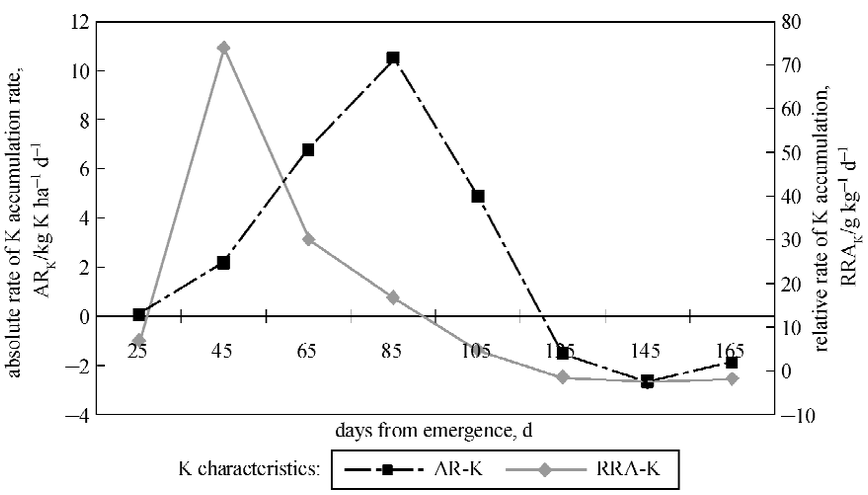

Figure 5 Characteristics of K accumulation dynamics in sugar beet during the growth season (adapted from *Grzebisz* et al., 1998).

Both K accumulation parameters are most likely inherently related to the rate of root system extension (length, R_L) during the growth season. The key characteristics of root system growth during the growing season are the transition point (TP_{RL}) and the rate of extension (R_{Lr}). Both parameters have been calculated for sugar beets (based on *Windt*, 1995) by using the first derivative of the polynomial function of the third degree (RL'):

$R_L = -0.012d^3 + 3.022d^2 - 76.26d - 379.3$ for $R^2 = 0.99$

$R'_L = -0.036d^2 + 6.044d + 76.26$

$TP_{RL} = 83.94d$ and $R_{Lr} = 330$ m ha^{-1} d^{-1}

The transition point (TP_{RL}) describes the time point (days after sowing) at which the root system reaches its highest rate of growth, as indicated by the maximum R_{Lr} value. The sugar plantation yielded 80 t ha^{-1} of beets, reaching its maximum rate of root system extension 84 dafter sowing, i. e., during the main period of K uptake (Fig. 5).

A comparison of critical stages of K accumulation by the sugar beet canopy and root system extension parameters indicates a significant coherence in both processes. However, there are no scientific data to implicitly corroborate this hypothesis. A question remains as to what extent the pattern of root growth in a particular crop, for example, the TP_{RL} occurrence, is affected by environmental and agronomic conditions. *Vincent* and *Gregory* (1989) concluded that the general pattern of root growth in wheat reflects changes in dry matter partitioning over the course of crop development on the basis of their own studies and others that were conducted in Great Britain during the 1970s and 1980s. The authors did not observe any significant effect of nitrogen treatment and season. The conservative behavior of wheat system dynamics over the growth season has also been corroborated by *Zhang* et al.

(2009). That study, which was conducted from 1990 to 2008, showed that the distribution of wheat roots along the soil profile at harvest was only slightly affected by a difference in water regimes, seasons, and variety selection. As documented by *Zhang* et al. (2009) in wheat and *Grzebisz* and *Kryszak* (1992) in winter rye, a mild shortage of water or nutrients increases the depth of crop rooting. These observations show that the K-uptake rate is driven by the aboveground demand for water and nutrients in equilibrium with the root system expansion (*King* et al., 2003; *Van Noordwijk* and *van deGeijn*, 1996). This conceptual analysis of the critical period of sugar beet response to K supply can be applied to other crops. On the basis of key crop characteristics, this procedure can indicate the stages that are potentially sensitive to a reduced K supply. It is worth mentioning that there are only a few studies on the dynamics of root systems and the simultaneous accumulation of nutrients (*Barraclough*, 1986).

3.2 Potassium as a waterstress-alleviating agent: Case studies

Wheat, maize and sugar beets have been selected to explain the role of externally applied Kin alleviating water-deficiency stress.

3.2.1 Wheat

The majority of arable lands worldwide are cropped with cereals (*FAOSTAT*, 2012). The sensitivity of this group of crops K is generally weakly recognized at the canopy level. The main reason for this knowledge gap is the high genetic adaptability of cereal species to varying soil fertility and water environments (*Calderini* and *Slafer*, 1999; *Zhang* et al., 2009). In Europe, wheat is among the most productive cereals, but it also requires the most fertile soils (*Rabbinge* and *Diepen*, 2000). The yield potential of this crop in Europe is high, ranging from 7.7 t ha^{-1} in Bulgaria to 12.4 t ha^{-1} for Ireland, in turn indicating a slight decrease following the increasing impact of the continental climate. However, actual yields show a much deeper contrast between European countries (*Olesen* and *Bindi*, 2002; *Supit* et al, 2010). The size of the yield gap depends upon both the growth conditions (soil and climate) and nutrient management, especially K (*Grzebisz* and *Fotyma*, 2007, *Grzebisz* and *Diatta*, 2012; Olesen and *Bindi*, 2002; *Rabbinge* and *van Diepen*, 2000).

A winter wheat yield of 10 t ha^{-1} exerts the highest demand for K during the period that extends from the beginning of shooting (BBCH 30) to the beginning of anthesis (BBCH 60; *Cannell*, 1984). This period lasts approximately 45 d, and the daily rate of Kuptake amounted to 4.4 kg K ha^{-1}. In this case, the maximum rate of K accumulation occurred at heading, and then slightly decreased towards anthesis. At this particular stage of growth, wheat reached maximum K accumulation of 320 kg K ha^{-1}. In addition, its K uptake always preceded the amount of simultaneously accumulated nitrogen. Therefore, the pattern of K accumulation in wheat during a given season can be considered to be a prerequisite of high grain yield. This conclusion is supported by a wheat study from Great Britain. As reported by *Barraclough* (1986), the daily rate of nitrogen and K uptake of 2 and 3 kg ha^{-1} during the critical period (180 - 260 d after sowing) is required to cover requirements for the production of 9.5 t ha^{-1} of wheat grain. As reported by *King* et al. (2003), the shoot dry mass increase is ca. seven-fold during this period, which indirectly underlines a high sensitivity to the shortage of both nutrients. However, the impact of water shortage on wheat performance in the British Islands is much lower than in Central Europe or in semi-arid regions (*Dodd* et al., 2011; *Rabbinge* and *Diepen*, 2000; *Turner*, 2004). The main reason for this yield gap is the frequency and severity of drought during wheat development (*Passioura*, 2006).

Figure 6 shows the results of simultaneously imposed water and K stress, which significantly affected the K accumulation rate (AR_K) of wheat during the growth season. For most treatments, the highest AR_K was achieved by wheat at the booting stage (BBCH 40-49). With an ample water supply, the recorded growth rate of wheat plants at this stage did not depend on the soil content of available K. Therefore, it can be concluded that an adequate water supply during the most critical stages of wheat

growth (from shooting to anthesis) can, to some extent, be alleviated by additional water. In many parts of the world, irrigation is the key to ameliorating water-deficiency stress, and it significantly increases wheat yields, i. e., WUE (*Liu* et al., 2007). As shown in Fig. 6, plants experiencing a water shortage developed different K accumulation strategies. Those grown on K-rich soil could maintain a sufficiently high rate of K accumulation during most of the season. However, plants experiencing both water and K stresses had a decreasing trend in their K accumulation rates from the booting stage onwards.

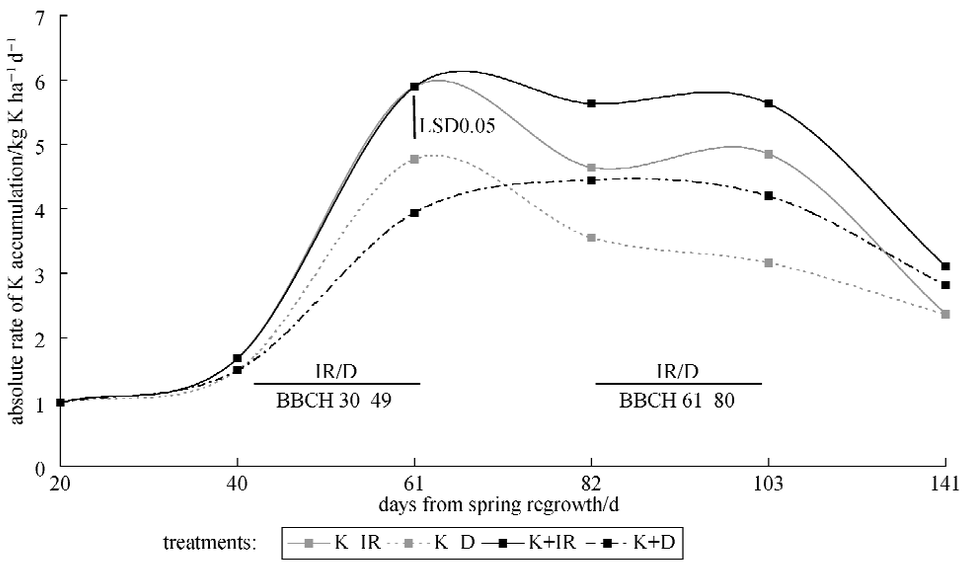

Figure 6 Potassium accumulation rate in wheat under different water and potassium fertilizer treatments (basic data adapted from *Musolf*, 2003). K−IR, K+IR=irrigated treatments without and with K application; K−D, K+D=treatments with double drought imposed for 3 weeks during stem elongation and anthesis, without and with K application.

In light of the known K accumulation patterns for wheat, a question arises about the response of yield structure components to the shortage of water. Cereals are sensitive to water deficits for a period extending from shooting to ear formation and are under strong stress until maturity (*Day*, 1981; *Grzebisz* et al., 2009; *Krumm* et al., 1990). As reported by *Baque* et al. (2006), potted wheat plants living under drought during the vegetative part of their development first reduced the number of effective tillers, i. e., ears. This yield-forming element was decisive for the final grain yield. This phenomenon is also observed under field conditions, but may be attributed to wheat and/or other cereals that were cultivated on soil with an extremely low K supply during the pre-anthesis period of growth. However, the alleviating effect of added K, even at high rates, was not significant in the *Baque* et al. (2006) study. In other cases, as in Fig. 6, the wheat canopy shows a high adaptive plasticity to water and K stress.

As reported by *Grzebisz* et al., (2009), wheat plants that were adequately supplied with K during vegetative growth, but especially during early stages of grain development (milk stage), are able to reduce the stress severity and in turn increase grain yield. At this particular stage, the most decisive nutritional factor in determining the grain yield was the K concentration of the flag and third leaves. It is well documented that the flag leaf is important for covering grain development requirements by assimilate production (*Akmal* et al., 2000; *Grzebisz*, 1988, *Inoue* et al., 2004; *Xu* and *Yu*, 2006). The reported importance of the third leaf in yield determination emerged only under stress conditions as noted by *Grzebisz* et al., (2009). The year-to-year variability of K concentration in both wheat leaves explained 75% and 51% variability in the grain yield:

1) flag leaf: $Y_a=2.349K+4.0$ for $R^2=0.75$, $n=9$ and $p<0.1\%$

2) third leaf: $Y_a = 2.877K + 4.71$ for $R^2 = 0.51$, $n = 9$ and $p < 5\%$

where: Y_a, grain yield (t ha^{-1});

K, K accumulation (kg K ha^{-1}).

A K fertilizer effect on grain-yield performance is possible, provided that the soil K pool, which is a primary source of plant K, is sufficiently large. According to *Cakmak* (2005), high K accumulation in the leaves enables a plant to extend its capability to produce and transport assimilates from the leaves to the grain. This hypothesis is supported by a higher thousand grain weight (TGW), which was achieved in trials with artificially imposed drought when fertilized with K (*Baque* et al., 2006; *Grzebisz* at al., 2009; *Yang* and *Zhang*, 2006).

3.2.2 Maize

The seasonal course of maize-canopy growth is different from wheat, which results from the number of plants established after sowing. Therefore, the cob is the plant part with the highest potential sensitivity to water-deficiency stress, as corroborated by a high year-to-year variability in the kernel number per plant (*Otequi* and *Bonhomme*, 1998). The main characteristics of K accumulation in maize are highly similar to other cereals (*Novák* and *Vidovi*, 2003). In general, a shortage of water negatively affects the rate of K accumulation during early stages of maize development (Fig. 7). The highest disturbance in plant growth, which occurred during the vegetative period, resulted in decreasing amounts of accumulated K and nitrogen. At the end of this period, the daily rate of K accumulation was $^1/_3$ lower under sub-optimal growth conditions, as imposed by a water shortage (*Heckman* and *Kamprath*, 1992). Plants experienced a mild drought during the vegetative period of growth, which could compensate for the K uptake rate during the grain-filling period. In spite of this "K compensation effect," the grain yield of maize was 25% lower.

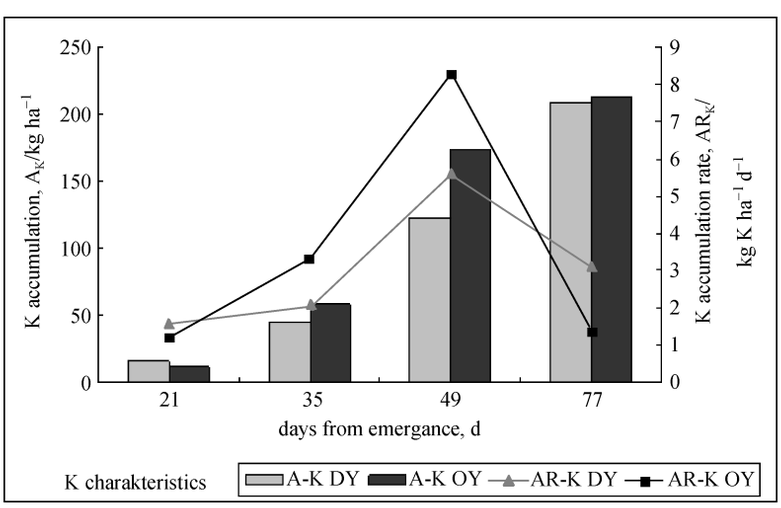

Figure 7 Characteristics of potassium accumulation dynamics in maize during two contrasting seasons (basic data adapted from *Heckman* and *Kamprath*, 1992). DY, OY = drought and optimum water conditions during vegetation.

The first classical symptom of water deficiency in maize is leaf rolling (*Kadioglu* et al., 2012). During the course of the day, rolling appears in mid-day, increasing towards noon and recovering in the evening. This plant behavior results from decreased leaf turgor, which is a consequence of temporary water deficit. As reported by *Premachandra* et al. (1993), the K supply can significantly decrease both the degree of leaf rolling and its length. Water shortage during the vegetative period of the maize life cycle results in a significant reduction in plant growth, revealing a stunted canopy at the beginning of anthesis (*Barłóg* and *Frckowiak*, 2008).

The key period of yield formation in maize, which is called the *critical window*, extends from

tasselling (BBCH 51) to the watery stage of kernel development (BBCH 71; *D'Andrea* et al., 2008). During this period, maize is sensitive to water, K and nitrogen supply. All these factors affect the kernel number per plant (KNP), (*D'Andrea* et al., 2008; *Otequi* and *Bonhomme*, 1998; *Subedi* and *Ma*, 2005). It is therefore necessary to assume that lower K uptake negatively affects the degree of yield component development. This hypothesis has been corroborated by *Barłóg* and *Frckowiak* (2008), who showed that the kernel number per plant significantly responded to K application. However, the effect of applied K fertilizer was year-specific, revealing a positive trend during dry year 2006 (+0.5 t ha^{-1}) and semi-dry year 2007 (+0.5 t ha^{-1}), but not during 2005, an optimum for maize growth. The same conclusion can be drawn from the work of *Damm* et al., (2013), who found a 1.0 t ha^{-1} yield increase ofan already high-yielding crop in response to K application during the semi-droughty 2009 season. A study conducted by *Subedi* and *Ma* (2009) in Canada showed that the K shortage reduced maize grain yields by 13%.

3.2.3 Sugar beet

Sugar beet is an example of a crop with a high dependence on K supply during the growth season. As reported by *Barłóg* et al., (2002), the variability in beet yield can be 96%, which may be explained by the variability in K accumulation at harvest. In this study, the yield response to K fertilization was observed in years with drought and semi-drought during the summer months. Beet yields were high even in years with drought. The highest yield, which was approximately 90 t ha^{-1}, was achieved in 1998; however, the yields did not show any response to increasing K rates. Analogous conclusions have been drawn by *Milford* et al., (2000) under British conditions. The same trend of seasonal beet response to applied K was reported by *Damm* et al. (2013).

The study on dry matter accumulation by sugar beets in response to K management showed a high dependence on the weather pattern. As presented in Fig. 8, the absolute rate of beet growth was affected both by the weather within a given year and K fertilization. In 2001, the water supply during the summer months amounted to 235 mm, while it was only 105 mm in 2003. The absolute rate of dry matter for beet growth was higher in the NPK treatment, regardless of the weather. The degree of difference between non-K and K-fertilized treatments was much higher in 2001, when the water supply was ample. However, during the dry conditions of 2003, the maximum rate of beet and absolute growth was significantly delayed. This finding is most likely the key reason for yield depression in relation to the summer water deficit.

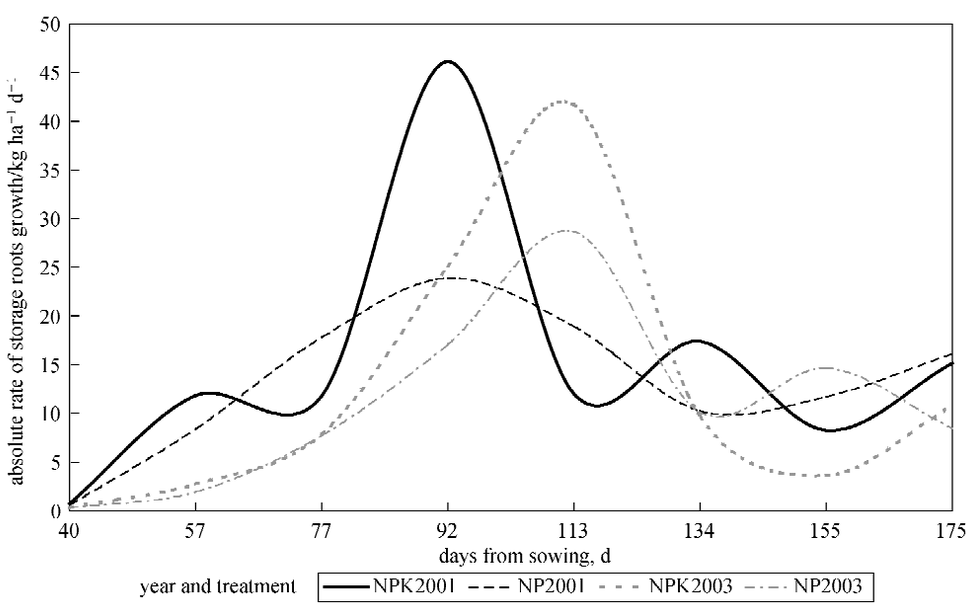

Figure 8 Effect of natural drought and limiting potassium supply on absolute rate of storage root growth in sugar beet (adapted from *Grzebisz* et al., 2012).

A study on the response of sugar beets to induced water and K stress during the summer months showed a significant dependence on the K supply. As reported by *Musolf* et al. (2004b), plants grown under conditions without K application had much lower concentration of K and nitrogen, both in the leaves and young roots, at the 6th leaf stage. It is worth mentioning that an insufficient supply of nitrogen in beets results in a slower rate of canopy growth. As a consequence, plants are not capable of efficiently absorbing solarenergy, which is critical to their final yield (*Malnou* et al., 2006; *Milford* et al., 1985). Early K stress impacts the performance of the sugar beet canopy, which is the primary reason for its high sensitivity to water stress. As presented in Tab. 2, the artificially imposed water stress affected K accumulation in plants in July. However, a significant response was noted only in the treatment that was fertilized with K. The same conclusion was found for nitrogen. The harvested yield of sugar beets had a significant response to both experimental factors, but in this particular case, K was the dominant factor and water was minor. The regression analysis, which was based on K accumulation at harvest and was averaged over years, had much higher yield predictability (Y_{SR}) when using the amount of accumulated K (A_K) in the beets in comparison to leaves, as in the independent value:

1) leaves: $Y_{SR}=0.078A_K+31.88$ for $R^2=0.44$, $n=8$ and $p\leqslant 0.05$;

2) roots: $Y_{SR}=0.282A_K+32.21$ for $R^2=0.63$, $n=8$ and $p\leqslant 0.01$.

The above equations corroborate a hypothesis of higher beet sensitivity relative to the leaves with a K shortage during the critical yield-performance stage. These results are in agreement with the opinion of *Kenter* et al. (2006), who stressed the important but not dominant effect of water shortage during July and August on the performance and yield of the sugar beet canopy.

Table 2 Accumulation of K by sugar beet around the transition point (TP) of canopy growth as imposed by different water and potassium regimes in kg ha^{-1}.

Water treatments	Leaves		Storage roots		Total	
	K+	K−	K+	K−	K+	K−
Rain-fed	216.9^{ab}	88.9^{c}	61.7^{a}	20.1^{d}	278.7^{ab}	109.1^{c}
Irrigation	237.0^{a}	78.4^{c}	55.0^{b}	16.5^{d}	292.1^{a}	94.9^{c}
Drought	172.5^{b}	88.0^{c}	43.5^{c}	18.9^{d}	219.1^{b}	106.9^{c}

[1] Based on *Musolf* (2003); numbers marked with the same letters are not significantly different. Irrigation and drought were imposed in July and August.

4 Potassium as a root-growth induction factor

In general, the pattern of root-system development during the growth season for particular crop species is consistent and under genetic control (*Taylor* and *Klepper*, 1978). However, this pattern undergoes changes throughout consecutive vegetative stages that depend on the soil physical properties, water and mineral nutrient content throughout the soil profile (*Smucker* and *Aiken*, 1992). Soil profile moisture plays a dual role and is considered to be a plant-growth resource and the source of life for growing roots. The rate of nutrient uptake by crop plants is governed by the rate of growth, so the demand is stage-dependent. In general, it is assumed that roots grow intensively in the top soil at the beginning of the growth period. As a rule, this soil layer contains sufficient amounts of nutrients to cover the requirements of the developing seedlings (*King* et al., 2003). In contrast, the amounts of water and available nutrients in the upper soil layer continuously decreases during crop development, which forces plants to extend their roots towards moist and nutrient-rich zones of the soil profile (*Forde* and *Lorenzo*, 2001). Therefore, the plant-oriented pattern of root-system growth undergoes a change to become more soil-oriented throughout the life cycle, i.e., it becomes more and more dependent on the water and particular nutrient distribution throughout the rooted soil profile (*King* et al., 2003; *Van*

Noordwijk and *van de Geijn*, 1996). Under the limited supply of resources required by the growing plant, roots tend to grow faster in soil layers, which creates more favorable conditions with an ample water and nutrient supply (*Taylor* and *Klepper*, 1978). As a consequence of the lack of soil property uniformity throughout the growing process and over the course of the season, roots are not homogenously distributed in the soil profile (*Smucker* and *Aiken*, 1992). However, the general pattern of wheat-root distribution along the soil profile was highly conserved, in spite of the different varieties that were cultivated over an 18-year period, as presented recently by *Zhang* et al. (2009). This study corroborates an opinion on the domination of plant-oriented patterns in root-system growth, which were only slightly modified by the impact of external growth factors.

The chemical characteristics of soil K in response to its external supply are well described in many papers, but they are not the subject of this conceptual review. However, the effect of K application on physical soil properties is little recognized in the scientific literature. The main reason for this data scarcity is the low number of experimental fields with differentiated levels of K and related studies on this subject. It is necessary to note that a reliable estimation of an impact of a particular nutrient on soil properties is possible, provided that it occurs for a long time period. As reported by *Damm* et al. (2013), a 14-year period with constant rates of K application significantly improved the structure of a topsoil. The most important remark from this work refers to the content of soil water, which increased across the whole range of the water retention functions up until the permanent wilting point. The long-term application of K, which is dependent on the fertilizer rate, significantly changed its available content in the soil. As shown in Fig. 9, the content of water that is available to barley plants showed a significant, linear response to increasing K contents in the topsoil. In the case of winter wheat, the amount of available water in this layer increased the most, up to 6 mm, when compared to the K non-fertilized treatment. The positive effect of K application on soil structure as a soil-aggregating agent has been reported by *Hamza* and *Anderson* (2003) and *Holthusen* et al. (2010). *Soulié* et al., (2007) explained the stabilizing effect of K on soil structure, pointing out its glue-like effect on soil elementary particles.

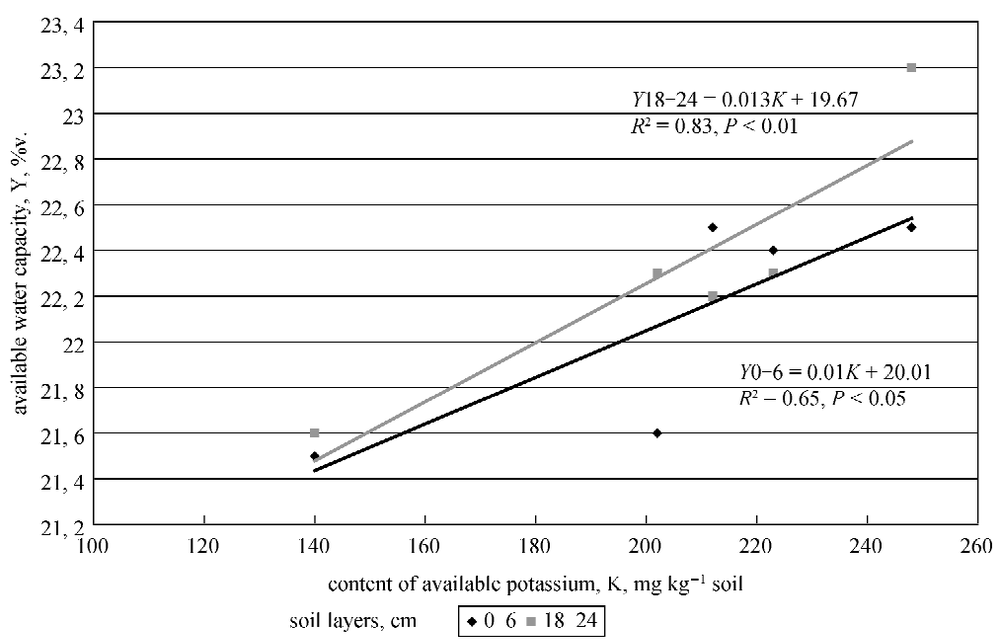

Figure 9 Available water capacity as a function of soil available potassium content (basic data adapted from *Damm* et al., 2013).

The second aspect of K management refers to its availability to crop plants under various soil water regimes. The uptake of nutrients from the soil solution is governed by two main processes: (a) the

transport of ions from the soil solution to the root surface, and (b) root growth into soil patches that are rich in nutrients. The rate of K-ion diffusion towards the root depends on the K concentration gradient between the root surface and the soil solution. As a consequence of the low mobility of K-ions in soil solution, K concentration near the roots decreases very quickly. However, the degree of the decrease depends on its content in the bulk soil and soil moisture. Therefore, any process that decreases the K concentration in the soil solution lowers the supply of K to the above-ground parts of the plant (*Jungk* and *Classen*, 1997; *Gäth* et al., 1989). On the other hand, a decrease in soil-water content may result in increasing K concentrations in the soil solution. At the same time, a decreased K-ion transporte-rate to the root has been observed when the soil moisture drops (*Clarkson*, 1981, *Barber*, 1985; *Gäth* et al., 1989).

Plants have evolved numerous regulatory mechanisms to water-deficiency stress to control water loss from the leaves. The primary one is abscisic acid (ABA), the key signal molecule that is produced in the dehydrating root (*Shao* et al., 2009). It is transported in the xylem water stream to the leaves, and in turn induces stomatal closure (*Luan*, 2002; *Shao* et al., 2009). In light of recent scientific advances, the increasing concentration of endogenous ABA is now known to differentially affect the shoots and roots (*Taiz* and *Zeiger*, 2006). The rate of shoot growth is significantly limited, but roots show an opposite response, which increases the rate of extension. In addition, potassium deficiency increases ABA synthesis in root cells as documented by *Schraut* et al. (2005) for maize and *Vysotskaya* et al. (2008) for durum wheat. On the other hand, root cells that are exposed to temporary shortage of K at the root surface induce high-affinity K transporters (*Ashley* et al., 2006; *Shao* et al., 2007). It can therefore be concluded that the negative impact of endogenous ABA production in dehydrating roots on shoot growth is partly controlled by soil K supply. Therefore, the uptake of the required amount of K by a water-deficient plant depends on both the rate of root-system growth and an adequate K supply (*Kuchenbuch* et al., 1986; *Shao* et al., 2009). This hypothesis is in agreement with the Cushman mechanistic model of K uptake by plants. According to this model, the extension of root length, followed by the initial K concentration in the soil solution, is the dominant factor of K uptake by the growing crop (*Barber*, 1985).

Crops that are cultivated under rain-fed conditions are subject to frequent wetting-drying cycles during the vegetative period. Under these conditions, nutrient and water supply to roots on one side and their growth rate on the other side are significantly disturbed. The main issue of interest is the impact of a particular nutrient on root extension. Most published scientific papers on this subject focus on nitrogen and phosphorus (*King* et al., 2003; *Van Noordwijk* and *Geijn*, 1996). There are limited data on K, especially regarding its impact on the root system when the plant is subjected to a water deficit. In addition, reports dealing with the K supply to a crop plant and the resulting root system responses are contradictory. The most frequently cited work by *Tennant* (1976) implicitly indicated that a lack of K in the growth medium of wheat significantly decreased the number of seminal roots and their length, and at the same time entirely halted the development of nodal roots. In addition, the root growth, especially in nodal roots, were considerably reduced in response to a half rate or a doubled rate of the required amount of K. These conclusions are contradictory to results presented by *Drew* (1975), who showed prolific growth of barley roots in response to increasing rates of applied K.

These earlier findings by *Drew* (1975) have been recently corroborated by *Perna* and *Menzies* (2010). Their work showed that the morphology of the maize root system underwent proliferation in the presence of banded or fractional K fertilization (when a small part of soil is mixed with K fertilizer). A study conducted by *Valadabadi* and *Farahani* (2010) on the effect of water deficit impact on C_4-crop root-system lengths showed a crop-specific response to applied K. Maize extended its root system in the presence of K when given optimum water conditions. The growth of a millet root system was mainly controlled by water deficits, and only sorghum showed a high response to increasing rates of K.

Andersen et al. (1991) found higher root densities in the subsoil in response to increasing K rates (1991) when working with barley grown in the field, but under controlled water conditions. However, this extra root growth appeared only during one year of the study and did not show any significant impact on the grain yield.

A long-term field study by *Damm* et al. (2013) with winter barley, spring barley, maize and sugar beet showed a significant but crop-specific response of the root system to K management. The most important conclusion in this paper refers to the increasing rate of root extension in early stages of each crop's growth in response to high amounts of available soil K. It is necessary to stress that higher rates of root-system growth were revealed during the year with prevailing semi-drought conditions. As shown in this paper, all crops cultivated in plots with highs content of both available and recently applied K grew faster than the control K treatments, i. e. , with medium attainable K content and without freshly applied K. As shown in Fig. 10, the fractional distribution of sugar beet true roots at the full rosette stage showed a significant response to differences in soil K status. Plants grown on soil that was rich in available K could increase the fraction of actual roots in the deeper soil layers as a consequence of the faster growth rate. This phenomenon is a classic example of a drought-avoidance strategy that was used by sugar beet plants in response to a mildwater stress deficiency (*Farooq* et al. , 2009; *Monneveux* and *Belhassen*, 1996; *Shao* et al. , 2009).

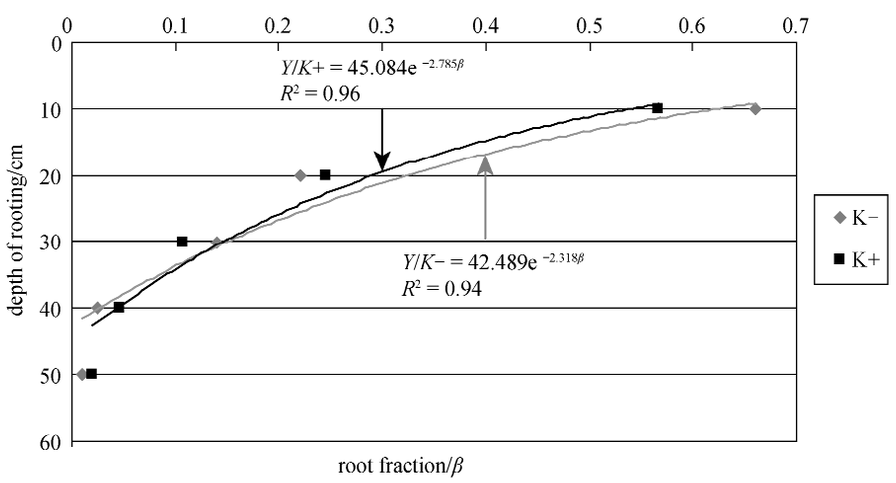

Figure 10 Effect of potassium long-term fertilization on asymptotic root distribution in sugar beet with depth (*β* values calculated by means of Gale and Grical function (*Li* et al. , 2006; basic data adapted from *Damm* et al. , 2013).

The acclimation mechanism of crop plants to a decreasing supply of water and nutrients showed a significant dependence on the K supply. Sugar beets that were grown on soil rich in K developed a much deeper root system at the full rosette stage (BBCH 41). As a consequence, plants growing with high available soil K had yieldsthat were 12% higher when compared to the K non-amended crop. These findings are in agreement with the study on sugar beet responses to induced potassium and water stresses (*Musolf*, 2003; *Musolf* et al. , 2004b). Young beet plants were grown on soil with a moderate K content in comparison to those with an ample supply of K and were not able to take up a sufficient amount of both K and nitrogen (Fig. 11). As a result, the plant biomass of both the leaves and storage roots was much lower, which negatively affected the beet yield.

5 Concluding remarks

Water-deficiency stress is irregular in temperate regions, which has unforeseeable results throughout crop plant development of varying duration and severity (*Ludlow* and *Muchow*, 1990;

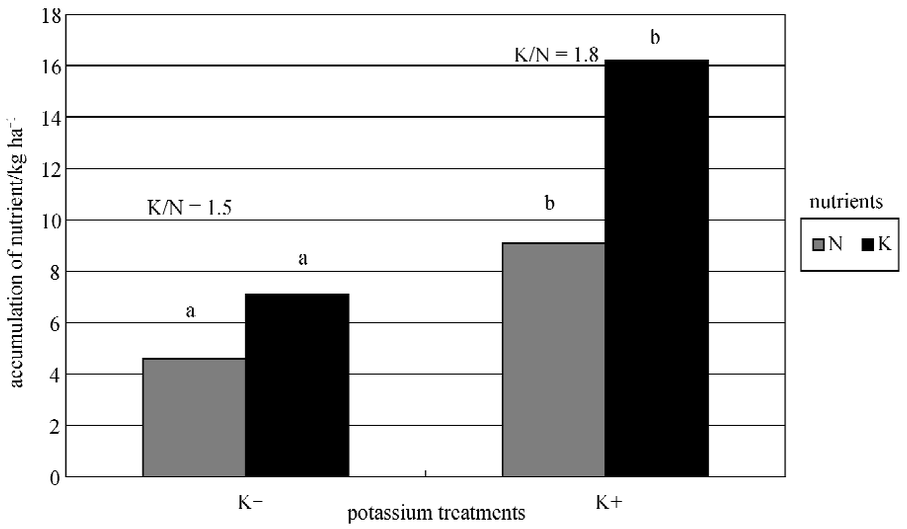

Figure 11 Effect of long-term potassium fertilization on nitrogen and potassium accumulation in sugar beet at BBCH16 (basic data adapted from *Musolf*, 2004b). Analysis of variance conducted for each nutrient separately; respective columns marked with distinct letters are significantly different.

Monneveux and *Belhassen*, 1996). Therefore, the efficient water management of any farming system should be oriented towards increasing the resistance of crops to potential water stress. However, the degree of a crop plant's response to water deficit is stage-dependent (*Martyniuk*, 2005). Yield losses occur when water stress negatively impacts the dry matter accumulation rate, in turn inducing a change in its partitioning among the plant organs during development progress (*Bingham*, 2001; *Farooq* et al., 2009). As a consequence of water deficits, the development of key yield components is disturbed, so it has been believed that any growth factor that increases the uptake of water and/or its internal efficiency use can decrease the extent of water stress effects on the plant growth rate (*Debaeke* and *Aboudrare*, 2004; *Ritche* and *Basso*, 2008). Potassium is a plant growth factor that should be carefully considered on the basis of its physiological function in the plant, and as one of the most important amendments that can be applied by farmers to cope with water stress deficiency (*Cakmak*, 2005).

This review has evaluated the alleviating effects of K application on the basis of yield increases. The positive response of selected crops to K fertilizer is mostly revealed under conditions of mildwater deficit. The drought resistance increase is a result of adequate K supply to a crop during its life cycle. The water stress-alleviating action of K is summarized as follows:

(1) The higher the rate of root-system growth at early stages of crop performance, the higher the growth rate of above-ground plant parts.

(2) The greater the canopy biomass of a crop at its early stages of growth, the lower the losses of unproductive evaporated water.

(3) The denser the root system in a larger volume of occupied soil, the higher the amount of resources available for the plant crop.

(4) The better the K supply to a crop at the critical stages of yield formation, the higher the probability of yield potential realization.

The acclimation mechanisms of a particular crop plant to temporary water shortage can be strengthened by K application. Its anti-stress action may be manifested through the increasing rate of root-system growth into humid parts of the soil profile in response to a decreasing water supply (*Damm* et al., 2013; *Perna* and *Menzies*, 2010).

The yield gain that results from K application, which is considered to be the fractional part of the harvested yield, is most likely soil-specific, as documented in this paper with examples from cereals, maize, and sugar beet. The alleviating effects of an adequate external K supply under mildwater

deficiency has also been documented for sorghum (*Asgharipour* and *Heidari*, 2011), and sorghum and millet (*Valadabadi* and *Farahani*, 2010).

It could be hypothesized that the K-induced growth of roots towards humid zones of the soil profile in response to a decreasing soil water supply primarily depends on the nitrogen status of the plant. As documented in many papers, nitrate is transported to the root surface *via* mass flow (*Clarkson*, 1981). However, under conditions of decreasing soil water content, diffusion becomes a more and more important route for nitrate to flow to the root surface (*Gonzalez-Dugo* et al., 2010). It is possible to state, when taking into account the values of diffusion coefficients for NO_3^- and K-ions, (2.7×10^{-6}, 2.8×10^{-8} cm^2 s^{-1} respectively), that nitrate develops a depletion zone around the root several times faster than K (*Clarkson*, 1981; *Raynaud* and *Leadley*, 2004). Recent progress in the study of plant response mechanisms to N deficiency explains its complexity. The uptake of nitrate is controlled by two signaling pathways. The first local uptake is induced by decreasing the concentration of nitrate in the soil solution. It has been recently shown that decreasing the supply of nitrate to the root encodes the activity of high-affinity transporters. The initial sites of early nitrate shortage-sensing have been found in the lateral root cap, the root stele and the pericycle. The second main route of N deficiency signaling is located in the shoot and is driven by the internal status of nitrogen or nitrate (*Alvarez* et al., 2012; *Ho* and *Tsay*, 2010). Therefore, a hypothesis can be formulated to explain the crawling-like pattern of nitrate *mining* that is followed by a plant root in drying soil, which most likely acts as the primary signal of its deficiency. Next, the signal is directly transferred to the aerial parts of a plant, resulting in a change of N metabolism (*Bingham*, 2001; *Forde* and *Lorenzo*, 2001).

A decreased soil water content interferes with relationships between cations in the soil solution, which in turn modifies the intracellular concentration of Ca^{2+} ions in the root apoplast (*Shao* et al., 2007). Calcium acts as a sensor of environmental signals, including the soil-water gradient, which affects the processes that are responsible for plant water management (*Bray*, 1997; *Luan*, 2002). Potassium deficiency in the growth medium also affects the Ca^{2+} sensors, which in turn activate the high-affinity K^+ transporters in cells within the root cortex (*Maathuis*, 2009; *Szczerba* et al., 2009). Recent investigations have also revealed that nitrate and K deficiency can be recognized in the growth medium by the same molecule, protein kinase (CIPK23). Its activation by calcium-binding proteins is a required step to induce the high-affinity K transporters (*Ho* and *Tsay*, 2010).

The nitrogen and especially the nitrate status of a plant is the key factor in regulating a series of processes that are responsible for the synthesis, signalling and control of hormone flows in the shoot-root continuum. The response of young parts of the plant to an insufficient supply of nitrogen results in a decreased downward transportation of auxin (*Krouk* et al., 2011). The movement of this signal molecule within the roots has been addressed by K carrier TRH1 (*Vicente-Agullo* et al., 2004). As a consequence, this molecule affects the rate of growth and the shape of the root system in the soil profile (*Ashley* et al., 2006; *Casson* et al., 2003; *Eapen* et al., 2005).

The modified root system of a crop plant is a consequence of a consecutive series of metabolic and physiological processes, which result from the action of hormones in the root-shoot continuum. Therefore, these secondary processes, which are primarily induced by nutrient deficiency in the plant medium, have recently been termed as *trophomorphogenic* plant response (*Forde* and *Lorenzo*, 2001). There is most likelysome cross-talk between water and nutritional deficiency signaling. The water supply to a plant is considered to be the main factor in nutrient mass flow, and can induce plant nutrient deficiency signaling, which in turn is a driving force for root growth into the soil layers toreach both water and nutrients.

The proposed hypothesis of water-stress deficiency-control relies on a simple agronomic trait, i. e., the improvement of soil K management. It is well recognized that a decrease in soil water content is accompanied by a subsequent decrease in transpiration rate, resulting in less mass flow of K to the root

surface, which in turn reduces K uptake in the K non-amended soil. Increasing K in the soil solution through fertilizer application compensates for this effect by providing an adequate K supply and maintaining root growth. Maintaining root growth allows access to other mineral elements (including nitrogen) and water. Thus, yields are greater under mild drought when K fertilizer is added. High available K content in the soil is therefore the primary reason for the K-induced prolific growth of the root system in response to an increasing water deficit in upper layers of the soil profile.

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施钾对作物水分利用效率的影响

摘　要:作物在生长关键时期的水、N 供应是决定其产量的主要因素。在依赖雨水灌溉的农业中,作物在其生命周期中会经历无规律的缺水。因此,一种有效的抗逆措施必须注重增加单位水分的生产力。这篇概念性综述的主要目的是表明钾素充足可以减少水分缺乏对作物生长、产量组成因子及产量的负面影响。本文将 French 和 Schultz 方法中的水分限制产量(WLY)以图来展示,以此区分依靠水分蒸发形成的产量与 K 肥导致的产量。用这种方法可以说明数种作物(冬小麦,春黑麦,玉米,甜菜)对 K 供应的响应程度。施 K 带来的增产通常发生在轻度水分缺乏的情况下。对甜菜来说,找到它对 K 敏感的关键时期是理解水分利用效率中的决定性步骤。已经证实,在谷类(小麦、春黑麦)、玉米和甜菜产量形成关键期 K 供应不足会导致产量下降。施 K 是一种可用于增加作物对短期缺水耐受力的简单农业措施。可能是轻度缺水胁迫下作物吸 K 能力的提高可以增加根细胞对水分的吸收,这反过来又增加了其渗透势从而能够进一步生长,继而促进了对其他矿质养分(包括氮素)及水分的吸收,有利于作物的生长和产量形成。

关键词:干旱胁迫;水分限制产量;关键时期;根系

Potassium and stress alleviation: Physiological functions and management of cotton§

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Abstract: Potassium (K) plays a major role in the basic functions of plant growth and development. In addition, K is also involved in numerous physiological functions related to plant health and resistance to biotic and abiotic stress. However, K deficiency occurs widely resulting in poor growth, lost yield and reduced fiber quality. This review describes the physiological functions of K and its role in stress relief and also provides some agronomic aspects of K requirements, diagnosis of soil and plant K status, and amelioration. The physiological processes described include enzymes and the regulation of organic compound synthesis, water relations and stomates, photosynthesis, transport, cell signaling, and plant response to drought stress, cold stress, salt stress, as well as biotic stresses. The agronomic aspects of K fertilization include the K requirements of cotton, K uptake and soil characteristics, genotypic variation in K uptake and use, and characteristics of K deficiency in cotton. In addition, diagnosis and amelioration of K soil and plant status is discussed.

Key words: Fertilizer application / *Gossypiumhirsutum* / plant analysis / soil analysis / stress resistance

1 Introduction

Potassium (K) plays a major role in plant metabolism, growth, development, and yield. Deficiencies of K result in perturbations of numerous physiological functions, including water relations, enzyme activation, and charge balance, poor growth and reduced yield, as well as decreased resistance to stress. Furthermore, K is also involved in numerous physiological functions related to plant health and resistance to biotic and abiotic stress. For optimal growth and productivity, modern crop production requires a large amount of K, particularly during reproductive development. Potassium is the mineral element, next to nitrogen, required in the largest amount by plants. The K requirement for optimal plant growth is 2%-5% of the plant dry weight (*Marschner*, 1995). However, this requirement is often not met due to adverse soil and plant factors, and deficiencies occur resulting in yield reductions. Furthermore, the concentration of plant-available K is often influenced by the availability/abundance of other essential elements.

Farmers in the USA and elsewhere are using substantially more commercial fertilizer than 20 years ago and major improvements have been made in how these fertilizers are managed. However, despite soil analyses and subsequent soil applications of fertilizer prior to planting, K deficiencies have occurred sporadically and somewhat unpredictably. This has prompted a renewed focus on K management in cotton with some emphasis on understanding K fertilizer requirements and use by the cotton plant. An efficient fertilizer regime requires an accurate knowledge of the nutrient status of the soil, as well as a reliable tissue analysis during the season to fine-tune the fertility status and avoid any unforeseen deficiencies. Fundamental to this is an understanding of the role of the nutrient in plant metabolism, yield formation and in amelioration of stress. This review describes the general agronomic characteristics of K, the physiological functions and mitigation of stress by K, and common methods of deficiency diagnosis and amelioration using cotton as a model crop.

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2 Agronomic aspects of potassium

2.1 Importance of potassium in cotton

From an agronomic standpoint, K deficiencies and excesses are financially and environmentally inefficient and have negative yield-impacting consequences. General characteristics of excessive K in cotton (*Gossypiumhirsutum*, L.) include increased boll rot (*Bennett* et al., 1965), increased plant height (*Bennett* et al., 1965; *Pettigrew* and *Meredith*, 1997), and delayed maturity (*Bennett* et al., 1965; *Gwathmey* and *Howard*, 1998; *Clement-Bailey* and *Gwathmey*, 2007; *Gwathmey* et al., 2009). Deficiencies of K enhance water-deficit stress (*Coker* et al., 2000), reduce lint percentage (*Pettigrew* et al., 1996), dry matter production (*Gerardeaux* et al., 2010; Rosolem et al., 2003; *Zhao* et al., 2001), plant height (*Zhao* et al., 2001), leaf area (*Zhao* et al., 2001; *Gerardeaux* et al., 2010), internode length (*Gerardeaux* et al., 2010), seed mass (*Pettigrew* et al., 1996), boll mass (*Pettigrew* et al., 1996), N use efficiency (*Pettigrew* and *Meredith*, 1997), and lint yield (*Stromberg*, 1960; *Pettigrew* et al., 1996; *Gormus*, 2002; *Read* et al., 2006). Deficiencies of K also effect crop maturity by stopping reproductive growth prematurely and increasing early season flowering rate (*Pettigrew*, 2003).

2.2 Potassium requirements of cotton

Normal cotton growth and fiber development requires K in quantities second only to N. An average mature cotton crop is estimated to contain between 110 - 250 kg K ha^{-1} (*Hodges*, 1992) or about 2 - 5 kg K ha^{-1} day^{-1} (*Halevy*, 1976; *Bassett* et al., 1970; *Mullins* and *Burmester*, 11990), i. e., about 130 g K kg^{-1} lint(*Mullins* and *Burmester*, 2009), with 50% of the K in the boll (*Rimon*, 1989) and 24% in the seed and lint (*Mullins* and *Burmester*, 2009). At maturity, the capsule wall of the boll accounts for over 60%, the seed about 27% and the fiber about 10% of all the K accumulated by the boll (*Leffler*, 1986). Large quantities of K in non-harvested tissues result in only about 20 kg of K required to produce one 218 kg bale of cotton fiber, with about 2.5 - 6 kg being removed mainly by the seeds (*Rimon*, 1989; *Hodges*, 1992).

2.3 Characteristics of potassium deficiencies in cotton

Cotton is more sensitive to low K availability than most other major field crops, and often shows signs of K deficiency on soils not considered K-deficient (*Cassman* et al., 1989). Visual symptoms of K deficiencies in cotton have traditionally been noted in the lower, more mature leaves and progress from the bottom of the canopy to the top (*Dong* et al., 2004) due to the nutrient's very mobile nature in the plant. The traditional symptoms often begin with inverveinalchlorosis of leaves and necrosis of the leaf margins. Leaves become brittle and become bronze in color as the deficiency progresses, and because of these characteristics K deficiencies have been referred to as, "cotton rust" (*Maples* et al., 1988).

Although traditional deficiency symptoms are still occasionally noted, more recent characterization of K deficiencies describe symptoms later in the growing season during boll development in younger leaves, and include interveinal leaf chlorosis which turns to a gold-like color as deficiency worsens with necrosis of leaf margins. The occurrence of these K deficiency symptoms was first recognized in California during the early 1960's (*Brown* et al., 1973; *Ashworth* et al., 1982). Visual deficiency symptoms on younger tissues are similar to the traditional margins leaf-edge curl, necrosis and early defoliation. In contrast to traditional symptoms, however, the deficiencies progress from the top of the canopy to the bottom (*Stromberg*, 1960; *Maples* et al., 1988). These "modern" deficiencies have manifested themselves during the latter half of the season in a range of soils and cotton cultivars.

It is commonly suggested that three major contributing factors to these shifts in K deficiency characteristics are (1) an inefficiency of cotton roots to utilize K in the top soil exacerbated by genetic shifts to earlier-maturing cultivars which fail to develop as expansive of a root system, (2) the decrease in root growth after mid-season when the boll load sink increases (*Cappy*, 1979), and (3) higher

yielding, earlier maturing cultivars which require much more K and other nutrients than lower-yielding traditional cultivars (*Oosterhuis*, 1976). Understanding the nature and reasons for late-season cotton K deficiencies should result in reduced frequencies and severities of in-field K deficiencies (*Bednarz* and *Oosterhuis*, 1998).

2.4 Potassium acquisition and oil characteristics

The main mechanisms of soil K transport to the root surface are mass-flow and diffusion (*Barber*, 1962). Under normal conditions, the vast majority of K transport occurs through diffusion, as mass-flow may only represent 1%-3% of total K transport (*Marschner*, 1995; *Rosolem* et al., 2003). Still, the importance of these two mechanisms varies with soil and plant parameters such as root characteristics, plant K requirements, and water flux rates (*Baligar*, 1985). Cotton uptake of K during the season follows a pattern similar to dry weight accumulation until peak flower, at which time maximum K uptake is reached and begins to decline (*Bassett* et al., 1970; *Halevy* et al., 1987; *Schwab* et al., 2000). This is also the period in which K demand rises dramatically due to the developing boll load as the bolls are the major sinks for this element (*Halevy*, 1976; *Leffler* and *Tubertini*, 1976).

Plants can, in the most basic sense, be considered as nutrient (and more specifically K) wicks. Cotton removes K from the soil solution and the exchangeable sites on soil colloids and organic matter at various soil depths and concentrates the nutrient in above-ground tissues (*Brouder* and *Cassman*, 1990). In contrast to crops harvested for their biomass, cotton returns much of the K back to the soil in leaves, stems, and capsule wall (burs). These tissues are either incorporated in the top soil or in no-till and conservation tillage systems allowed to decompose on the soil's surface. Due to the negative charge of medium to heavy-textured soils and the characteristics of K as a cation, it is not common for K to leach out of these upper soil layers. Many examples of this can be found in the San Joaquin Valley (SJV). Although this region generally possesses high-fertility soils with respect to K (*Brown* et al., 1973) this region was one of the first to characterize modern cotton K deficiencies (*Stromberg*, 1960) due to stratification of K through the profile in the SJV with more K located in the vermiculitic topsoil than subsoil. Depletions of subsoil K have also been noted in the mid-southern and south-eastern regions (*Maples* et al., 1988).

Mimicking the K stratified characteristics of the SJV, *Gulick* et al. (1989) examined the response of cotton and barley (*Hordeumvulgare* L.) to soil K in layered profiles. Results suggested cotton rooting pattern was very similar to barley in all layers except the topsoil, in which barley had 2.7 times greater root length density than cotton. As a result, cotton K uptake from the topsoil was much lower than barley. Long-term fertility trials conducted in the south-eastern United States comparing nutrient uptake of cotton to soybeans (*Glycine max* L.) and corn (*Zea mays* L.) found cotton to be much more sensitive to K deficiencies than the other two crops studied (*Cope*, 1981). Research by *Brouder* and *Cassman* (1990) in this region examined root growth of a K deficiency-sensitive and a K deficiency-resistant cultivar. The resistant cultivar was characterized by a larger mean root diameter and increased root extension after peak bloom, at which point most K deficiencies become visually apparent. Furthermore, results from examination of root zone densities suggested neither cultivar utilized nutrients in the topsoil.

2.5 Genotypic variation in K uptake and use

It has been suggested that the increasing reports of K deficiencies in modern cultivars may be due to their earlier maturity or increased yields as compared to traditional cultivars (*Oosterhuis*, 1995). In theory, earlier maturing cultivars will require more K earlier in the growth season than their late-season isolines. Although it seems logical that an earlier maturing cultivar would not have the time to grow as expansive of a root system or store as much K as a later maturing cultivar, experiments testing these theories have shown mixed results.

Scientists began examining differences in K uptake due to maturity (earliness) as early as the mid

70s. *Halevy* (1976) found an earlier maturing cultivar to be more sensitive to K deficiencies due to greater K demands by reproductive parts earlier in the growth season and its relatively smaller root system as compared to the later-maturing cultivar. The afore-mentioned characteristics of the earlier cultivar resulted in earlier translocation of K from the leaves to the fruit than in the later-maturing cultivar. As a result, the earlier maturing cultivar displayed visual deficiency symptoms earlier than the later-maturing cultivar. *Clement-Bailey* and *Gwathmey* (2007) reported similar findings. The authors only noted significant increases in yields from additional K for the earlier maturing cultivar, whereas no yield response to additional K was noted in the later-maturing cultivar. Results are also in agreement with findings of *Tupper* et al. (1996), who concluded earlier cultivars required higher levels of soil test K as applications of fertilizer K increased earlier maturing cultivars' yields but failed to greatly impact the yields of later-maturing cultivars. *Cassman* et al. (1989a) observed differences in K uptake between two cultivars and suggested K uptake from soil was the main factor determining efficiency as partitioning was not different between the two. Furthermore, the author only noticed differences in K efficiency at low K levels; at high K levels differences were not noted. Similar results were noted under controlled growth conditions by *López* et al. (2008). Further uptake research was conducted by *Keino* et al. (1996), who examined the response of K uptake from two cultivars of differing maturities after foliar K was applied. The authors found foliar K doubled the root uptake of K from both the early and late-maturing cultivars, although increases in number of squares and shoot tissue and decreases of root length tended to be elevated in the later-maturing cultivar.

Still, other research examining cultivars of varying maturity has not shown significant differences in response to K fertility. *Pettigrew* (1999) and *Pettigrew* et al. (1996) examined the responses of early, mid and late-maturing cotton cultivars to varying K fertilizer rates and found genotype effects to be insignificant. Concern that the previously examined cultivars included genetic differences beyond maturity led the investigator to conduct further research examining the response in two okra and normal leaf-type isogenic pairs (*Pettigrew*, 2003). This approach was chosen due to the earlier maturity of okra leaf-type cultivars as compared to normal leaf-type cultivars while maintaining similar genotypic traits than cultivars examined in earlier experiments. Significant responses to K deficiencies were noted, but earlier maturing cultivars did not significantly increase this response. *Gwathmey* et al. (2009) also found no significant differences in K utilization or uptake ratios among cultivars of differing maturity, but suggested differences may be significant at low K status. Although inconsistent, earlier maturing cultivars did have greater K uptake in 1 of 3 years and greater K accumulation in the fruit in 2 of 3 years of the study. Evidence to date clearly shows that genotypic differences exist in K uptake and response to K fertilizer, mainly with regard to crop maturity and in low K-fertility situations. This should be taken into consideration in formulating K fertilizer practices in cotton production.

3 Physiology of potassium and relief of stress

3.1 Physiology of potassium nutrition

From a physiological standpoint, K is an essential macroelement for plant growth and development that affects many fundamental physiological processes (*Clarkson* and *Hanson*, 1980, *White* and *Karley*, 2010). Potassium is the most abundant cationic inorganic nutrient, usually constituting 2%-10% of plant dry weight with cotton's critical leaf concentrations occurring at 0.9%-1.2% plant dry weight (*Marschner*, 1995; *Bednarz* and *Oosterhuis*, 1996). Potassium can be stored either in the cytoplasm and/or the vacuole (*Marschner*, 1995). In plant cells, K concentrations are usually higher in the cytosol (ranging between 130-150 mM) with lower concentrations (20-100 mM) occurring in the vacuoles and determining K supply (*Fernando* et al., 1992, *Marschner*, 1995). Potassium is taken up against its concentration gradient through K^+ transporters and channels located in the plasma membrane of root

cells (*Ashley* et al., 2006) while two independent transport mechanisms are employed: (1) a selective, high-affinity pathway that allows active K^+ uptake at low concentrations (<1 mM) andinvolves plasma membrane proton pumping ATPase complexes, and (2) a passive, low-affinity, channel-mediated pathway that mainly functions at high external concentrations (>1 mM) (*Epstein* et al., 1963; *Britto* and *Kronzucker*, 2008, *Aleman* et al., 2011). A highly mobile nutrient, not only within short-distance transport, such as between individual cells and neighboring tissues, but also within long-distance transport, such as through xylem and phloem, Kis transported throughout the plant with the help of three channel families, Shaker, tandem-pore (TPK), and inwardly rectifying (Kir), and three transporter families, KUP/HAK/KT (K^+/H^+ symporters), HKT (K^+/H^+ or K^+/Na^+ transporters), and CPA (cation $/H^+$ antiporters) (*Cherel*, 2004; *Amtmann* and *Armengaud*, 2009; *Wang* and *Wu*, 2010). K^+ transporter and channel families have been extensively investigated in arabidopsis (*Arabidopsis thaliana* L.) with less information existing on crops such as barley (*Hordeumvulgare* L.), wheat (*Triricumaestivum* L.), beans (*Vicia faba* L.), rice (*Oryza sativa* L), maize (*Zea mays* L.), tomato (*Lycopersiconesculentum* L.; *Ashley* et al., 2006; *Szczerba* et al., 2009) while to our knowledge essentially zero information exists on cotton. In addition to the above qualities, Kis also involved ina multitude of fundamental physiological processes such as enzyme activation, osmoregulation and photosynthesis, phloem transport and charge balancing (*Clarkson* and *Hanson*, 1980, *Marschner*, 1995, *Maathuis*, 2009). This section of this review will summarize the role of K in various physiological functions.

3.2 Enzyme activation

Binding of K to a specific site of the protein has been shown to induce conformational changes of inactive enzyme structures that result in enzyme activationand increased substrate affinity (*Evans* and *Wildes*, 1971). More than 60 enzymes, involved in a variety of plant metabolic and physiological functions (*Suelter*, 1970; *Marschner*, 1995) have been reported to be dependent on high K concentrations for their activation. Carbohydrate accumulation is one of the most common symptoms observed to occur under lower than optimum K concentrations in the plant and has been attributed in decreased efficiency of enzymes such as starch synthase (*Hawker* et al., 1974; 1979), sucrose phosphate synthase (*Huber* et al., 1985), β-amylase and sucrose phosphate synthase (*Berg* et al., 2009), invertase (*Ward* et al., 1960), phophofructokinase (*Läuchli* and *Pflüger*, 1978) and pyruvate kinase (*Matoh* et al., 1989). In cotton, K deficiency has been reported to result in increased hexose concentrations in the leaves (*Bednarz* and *Oosterhuis*, 1999; *Pettigrew*, 1999) which was consequently attributed to decreased pyruvate kinase activity and/or increased invertase activity. Furthermore, cotton leaf starch concentrations were significantly decreased under lower K supply (*Pettigrew*, 1999) and it was speculated to be due to starch synthase inhibition. On the contrary, *Bednarz* and *Oosterhuis* (1999) reported increases in leaf starch levels and *Zhao* et al. (2001) reported similar results in hexose, sucrose and starch concentrations of K-deficient cotton leaves, although enzyme activities were not explored further. Research with other crops has also shown that protein metabolism as well as photosynthesis is affected by K supply due to nitrate reductase (*Wakhloo* and *Staudt*, 1988) and ribulosebisphosphate carboxylase (*Mengel* and *Kirkby*, 2001) efficiency-dependence on K. Further investigation is needed in cotton in order to elucidate the effect of K supply on the activity of enzymes of carbohydrate, protein and photosynthesis metabolism.

3.3 Osmoregulation

Potassium is an important solute and its vacuolar concentrations regulate cell osmoregulation (*Beringer* et al., 1986; *Morgan*, 1992; *Ashraf* et al. 2002, *Barragan* et al., 2012). Water potential has been reported to be greatly affected by K concentrations in the cell vacuole (*Hsiao* and *Läuchli*, 1986) with K salts (KNO_3, KCl, and K malate) largely controlling cell osmotic potential and maintenance of adequate turgor pressure for optimum cell function. Osmotic adjustment, the process of

increasing solute concentrations in the cell in order to maintain optimum water potential values under adverse environmental conditions, is also dependent on K accumulation (*Hsiao* et al. 1976; *Morgan*, 1984). In cotton, *Pervez* et al. (2004) reported that both water and osmotic potential were decreased under increasing K concentrations in the soil while pressure potential increased. Similar results were reported by *Bar-Tsur* and *Rudich* (1987) while *Pettigrew* (1999) reported that water potential and osmotic potential remained unaffected under various K fertilization rates. However, pressure potential was again increased under increased K supply (*Pettigrew*, 1999) and it was concluded that K supply enhances osmotic adjustment in cotton.

The K concentrations of guard cells of leaf stomata control turgor pressure of guard cells and consequently regulate stomatal function (*Marschner*, 1995). Lower-than-optimum K levels have been reported to result in decreased stomatal conductance in cotton (*Longstreth* and *Nobel*, 1980; *Bednarz* et al., 1998; *Zhao* et al., 2001; *Pervez* et al., 2004). In addition, *Bednarz* et al. (1998) observed that K deficiency decreased leaf internal CO_2 concentrations indicating that mesophyll conductance is also affected by K supply. In addition to its important role in maintenance of cell turgor, K has a fundamental role in plant growth, as osmoregulation is a pivotal step in cellular expansion, pollen tube growth, as well as root and fruit enlargement (*Rayle* and *Cleland*, 1992; *Maathuis* and *Sanders*, 1996; *Elumalai* et al., 2002).

Cotton fiber growth is greatly affected by K supply (*Dhindsa* et al., 1975). However, contrasting observations have been recorded for fiber elongation by *Cassman* et al. (1990), Pettigrew et al. (1996) and *Pettigrew* (2003) who noticed significant decreases with lower than optimum K concentrations, while no differences were reported by *Benett* et al. (1965) and *Minton* and *Ebelhar* (1991). Similarly contrasting observations were reported on fiber strength with insufficient levels of K resulting in weaker fibers (*Cassman* et al., 1990; *Minton* and *Ebelhar* (1991) while no difference was observed by *Bennett* et al. (1965), *Pettigrew* et al. (1996) and *Pettigrew* (2003). Subsequent research is needed in order to understand the role of K in osmoregulation and control of elongation and strength of the cotton fiber.

3.4 Photosynthesis

Potassium is indispensable for optimum function of the photosynthetic apparatus of the plant (*Hartt*, 1969). Apart from its regulatory role in stomatal function by maintaining turgor pressure, K additionally controls ribuloseb is phosphate carboxylase activation (*Peoples* and *Koch*, 1979; *Mengel* and *Kirkby*, 2001), which is responsible for regulating CO_2 fixation rates as well as chlorophyll concentration (*Pier* and *Berkowitz*, 1987). Furthermore, K levels control chloroplasts' inner membrane ATPases that maintain optimum pH values for efficient conversion of light energy into chemical energy (*Berkowitz* and *Peters*, 1993), while adequate concentrations of K are needed for optimum function of ATPase (*Shingles* and *McCarty*, 1994). Significant reductions in rates of photosynthesis due to lowK availability have been reported in cotton (*Longstreth* and *Nobel*., 1980; *Bednarz* and *Oosterhuis*, 1999, *Zhao* et al., 2001; *Pervez* et al., 2004) and they were attributed mainly to stomatal limitations. *Bednarz* et al. (1998) argued that stomatal limitations are the primary reason for reductions in photosynthesis under mild K deficiencies, while biochemical factors become more prominent under severe deficiency stress. In support of their observation, *Zhao* et al. (2001) reported that chlorophyll concentration of severely K-deficient leaves was greatly reduced while significant compromises in chlorophyll ultrastructure were concomitantly observed leading them to suggest that reductions in photosynthetic rates were also due to reductions in the photosynthesis system. Mesophyll conductance was also reported to contribute to lower photosynthetic rates in cotton (*Bednarz* et al., 1998) while ATP concentration of K-deficient leaves was significantly higher compared to the adequate K control (*Bednarz* and *Oosterhuis*, 1996). Research in other crops has indicated that feedback inhibition of photosynthesis might occur due to accumulation of photo-assimilates and decreased sink activity (*Pflüger* and *Cassier*, 1977; *Pier* and *Berkowitz*, 1987; *Kanai* et al., 2007). Carbohydrate

accumulation under low K supply has also been reported for cotton (*Pettigrew*, 1999; *Zhao* et al., 2001) in conjunction with low translocation rates (*Ashley* and *Goodson*, 1972). As discussed, cotton photosynthetic capacity is dramatically affected by K supply. However, further information is needed in order to attain a better understanding on the effect of K concentrations on the photosynthetic processes.

3.5 Translocation

Transpiration may influence translocation of carbon and nitrogen compounds from production sites to sinks. Potassium has been reported to control transpiration rates through its effect on stomatal function (*Blatt*, 1988) and consequently the root-shoot transport of mineral salts, nitrate and aminoacids (*Ben-Zioni* et al., 1971; *Marschner*, 1995; *Schobert* et al., 1998). *Koch and Mengel* (1974) reported that adequate supply of K was needed for optimum translocation of aminoacids and nitrate as well as incorporation of nitrogen into proteins in tobacco (*Nicotianatabacum* L.). In addition, K influences the rate of phloem loading not only by promoting the efflux of assimilates into the apoplast prior to phloem loading (*Mengel* and *Haeder*, 1977; *Doman* and *Geiger*, 1979), but also by regulating activation and function of invertase in the sink organs (*Oparka*, 1990). Furthermore, K not only is essential for maintenance of osmotic and pH gradients between the phloem and the parenchyma cells within the sieve tubes that are required for phloem loading and transport of assimilates (*Marschner*, 1995), but also provides the energy needed for the transmembrane phloem re-loading processes (*Gajdanowicz* et al., 2011). Carbohydrate translocation, therefore, is largely dependent on plant K levels with many researchers reporting that lower than optimum K levels result in accumulation of carbohydrates in several plant species (*Haeder* et al., 1973; *Mengel* and *Viro*, 1974; *Geiger* and *Conti*, 1983; *Cakmak* et al., 1994a, b, *Amtmann* et al., 2008; *Amtmann* and *Armengaud*, 2009), including cotton (*Bednarz* and *Oosterhuis*, 1999; *Pettigrew*, 1999; *Zhao* et al., 2001).

In addition to the increased carbohydrate concentrations in the leaves of K-deficient cotton plants, *Zhao* et al. (2001) noticed that stem sucrose concentrations of K-deficient plants were significantly lower compared to the control, suggesting either an inhibition of sucrose entry in the transport pool or a compromise in the phloem-loading mechanism. In support of those observations, *Ashley* and *Goodson* (1972) observed that insufficient K severely reduced the translocation^{14}C-labeled photosynthate. Translocation rates are also dependent on transpiration rates. However, *Bednarz* et al. (1998) reported that K starvation increased transpiration rates while the opposite was observed by *Zhao* et al. (2001) and *Pervez* et al. (2004). More research needs to be focused on the effect of K supply on photosynthate translocation and phloem loading in cotton. Furthermore, studies need to be extended to include nitrogen compound translocation since similar inhibitions and accumulations have been reported for amino acids and other nitrogen compounds to occur under K deficiency in tobacco (*Koch* and *Mengel*, 1974), as well as in rice, soybean and sunflower (*Helianthus annuus*, L.; *Yamada* et al., 2002).

3.6 Drought stress

As mentioned above, K levels significantly affect the efficiency of plant photosynthetic machinery with lower-than-optimum levels resulting in significant decreases in CO_2 fixation due to its involvement in ribulosebisphosphate carboxylase/oxygenase activation and stomatal function through turgor regulation. Water-deficit stress significantly reduces photosynthetic rates due to stomatal limitations, decreases in leaf stomatal conductance that result in decreased CO_2 fixation rates (*Lawlor* and *Cornic*, 2002), as well as due to non-stomatal or metabolic impairment where activities of photosynthetic enzymes such as ribulosebisphosphate carboxylase/oxygenase and ribulosebisphosphate are disturbed (*Gimenez* et al., 1992; *Medrano* et al., 1997; *Tezara* et al., 1999). Efficiency and function of adenosine triphosphate synthase has also been reported to be reduced under conditions of water stress (*Younis* et al., 1979; *Tezara* et al., 1999) resulting in disturbances of stromal pH values (*Berkowitz and Gibbs*, 1983) and concomitant reductions in energy production. Most importantly, however, due to the decreased efficiency of the photosynthetic mechanism to utilize the incoming light energy, production

of reactive oxygen species (ROS) is increased (*Lawlor* and *Cornic*, 2002).

Water-stressed chloroplasts have been observed to suffer increased leakage of K resulting in further suppression of photosynthesis (*Sen Gupta* and *Berkowitz*, 1987) while high K levels have been associated with maintenance of optimum pH values in the chloroplast's stroma and optimal function of photosynthetic mechanism (*Pier* and *Berkowitz*, 1987). Research with spinach (*Spinaciaoleracea* L.) and wheat (*Triticumaestivum* L.) indicated that water-stressed plants containing higher-than-optimum quantities of K were able to maintain efficient photosynthetic activity (*Berkowitz* and *Whalen*, 1985; *Pier* and *Berkowitz*, 1987) due to the alleviating effects of K on chloroplast stromal pH balance and dehydration. Further investigation on wheat also reported that detrimental effects of water-stress on photosynthetic activity were minimized when K supply was sufficient (*Sen Gupta* et al., 1989) and similar results were also obtained from mung beans (*Vignaradiate* L.) and cowpea (*Vignaunguiculata* L.; *Sangakkara* et al., 2000) leading researchers to suggest that modification K plant concentrations can maintain CO_2 assimilation rates by regulating stomatal function and balancing cell water relations (*Cakmak* and *Engels*, 1999; *Mengel* and *Kirkby*, 2001). Research with cotton has indicated the importance of K supply on the photosynthetic functions. However, limited attention has been given to the combination of K and water stress. *Bar-Tsur* and *Rudich* (1987) observed that K-deprived cotton plants were able to survive successive water stress, nevertheless with significant growth inhibition. However, the biochemical explanations of the results were not pursued further. Clearly, more research on the combined effects of K and water supply on cotton physiological and metabolic functions is needed.

3.7 Cold stress

Lower-than-optimum or freezing temperatures result in photooxidative damage to plant chloroplasts and reduce their CO_2 fixation capacity since their membrane structure is significantly damaged (*Marschner*, 1995; *Thomashow*, 1999). Increased ROS production has also been related to cold or freezing temperatures (*Prasad* et al., 1994; *Huner* et al., 1998; *Foyer* et al., 2002; *Devi* et al., 2012) due to the impaired photosynthetic electron transport chain. In addition, leaf stomatal conductance rates were significantly decreased (*Ort*, 2002) and similar reductions have also been observed for ribulosebisphosphate carboxylase activity, while membrane fluidity was greatly affected (*Makino* et al., 1994; *Allen* and *Ort*, 2001). As early as 1980, *Beringer* and *Trolldenier* (1978) indicated that a high cell K-concentration has the ability to enhance cold tolerance by decreasing the cell's osmotic potential. Further research revealeda positive correlation between K availability and cold stress tolerance, with lower-than-optimum K concentrations escalating the negative effects of cold stress (*Kafkafi* et al., 1990; *Yermiyahu* and *Kafkafi*, 1990). In contrast, increased K levels enhanced plant defenses against cold stress by acting as an osmolyte, lowering the freezing point of sap and preventing cell dehydration (*Kafkafi*, 1990; *Kant* and *Kafkafi*, 2002). In addition, significant yield losses and extensive leaf damage due to cold temperatures were reported to occur under low K fertilization, while the effects were alleviated once K supply was increased in a number of vegetable crops such as potato (*Solanumtuberosum* L.) and tomato(*Lycopersiconesculentum* L.; *Hakerlerler*, 1997). In experiments with maize, *Farooq* et al. (2008) observed that seed treatment with KCl was able to enhance frost tolerance by increasing production of antioxidant enzymes such as catalase, ascorbate peroxidase and superoxide dismutase and similar results were reported by *Devi* et al. (2012) in ginseng (*Panax ginseng* L.). Unfortunately, similarly to water stress and K supply, no research on the effects of the combination of low temperatures and K supply has been devoted to cotton.

3.8 Salt stress

Increased salt levels inhibit plant growth by inducing both osmotic and ionic stresses (*Shabala* and *Cuin*, 2007) while also damaging the photosynthetic machinery(*Sudhir* and *Murthy*, 2004; *Chaves* et al., 2009). High Na levels in the soil solution significantly reduce K uptake by the plant, while in the cytoplasm water is driven out of the cell vacuole resulting in decreased cell turgor (*Yeo* et al., 1991; *Zhu*

et al., 1997). High concentrations of Na cations compete in the soil with K cations substantially reducing their uptake by the plants (*Zhu*, 2003). As a consequence, higher concentrations of Na in the cytoplasm compete with K for uptake sites at the plasma membrane, including both low-affinity and high-affinity transporters (*Shabala* et al., 2006) and more Na crosses the plasma membrane resulting in a significant membrane depolarization (*Shabala* et al., 2005). Under such circumstances passive K uptake is impossible and an increased K leakage from the cell is observed (*Shabala* and *Cuin*, 2007). Furthermore, in order for the cell to retain metabolic functions through osmotic adjustment, significant quantities of ATP are used for *de novo* synthesis of compatible osmolytes synthesis, making active K acquisition even more problematic.

Regarding CO_2 fixation, photosynthetic capacity and quantum yield of oxygen evolution have been reported to significantly decrease under conditions of high Na concentrations (*Sudhir* and *Murthy*, 2004; *Chaves* et al., 2009) resulting in detrimental increases of ROS production and further chlorophyll and membrane damage (*Kaya* et al., 2001; *Cakmak*, 2005). Higher K levels as well as increased capacity of plants to accumulate K have been associated with increased salt resistance initially in arabidopsis (*Liu* and *Zhu*, 1997; *Zhu* et al., 1998) and later in wheat (*Rascio* et al., 2001; *Santa-Maria* and *Epstein*, 2001), cucumber (*Cucumissativus L.*) and pepper (*Piper nigrum* L.; *Kaya* et al., 2001) due to potassium's ability to enhance the plants' antioxidative mechanism. In cotton, a relatively salt tolerant crop with a threshold level of 7.7 dS/m (Maas, 1986), research has been mainly focused on the effects of partial replacement of K^+ with Na^+ (*Cooper* et al., 1953; *Joham* and *Amin*, 1964) and their effect on cotton yield. Later research indicated that substituting K supply with appropriate amounts of Na could be beneficial for cotton yield (*Chen*, 1992; *Zhang* et al., 2006) while *Bednarz* and *Oosterhuis* (1999) observed that a similar treatment could delay K deficiency development. Nevertheless, the physiological and biochemical explanations for those results in cotton have not been explored further. Future research should try elucidate the physiological and metabolic pathways involved in the interaction between K and Na levels in cotton plants.

3.9 Potassium and biotic stress

Potassium plays a significant role in plant protection against biotic stresses since high concentrations of K have been reported to alleviate detrimental effects of disease and pest infestations (*Perrenoud*, 1990; *Bergmann*, 1992; *Prabhu* et al., 2007). This has been attributed to the regulation by K of primary metabolic plant functions. In more detail, high levels of K in the plant promote the synthesis of high-molecular weight compounds, such as proteins, starch and cellulose while simultaneously suppressing the formation of soluble sugars, organic acids and amides, compounds indispensable for feeding pathogens and insects (*Marschner*, 1995; *Amtmann* et al., 2008). Additionally, canopy discoloration due to K deficiency has been observed to be more prone to attack by parasites, while cracks and lesions on leaf surfaces that develop under low K supply provide additional access (*Krauss*, 2001). *Haerdter* (1997) reported increased K supply in rice resulted in increased resistance to brown leaf spot disease (*Helminthosporiumoryzae*) and bacterial leaf blight (*Xanthomonasoryzae*). In tomato, Kirali (1976) observed that higher K supply successfully suppressed disease incidence, and similar results were reported in soybean (*Mondal* et al., 2001) and wheat (Sweeney et al., 2000). In cotton, K application significantly reduced wilt and root rot caused by *Fusariumoxysporum*sp. (*Prabhu* et al., 2007), while reductions from nematode (*Meloidogyne incognita*, *Rotylenchulus reniformis*) damage due to high K supply were also reported by *Oteifa* and *Elgindi*, 1976). However, the exact mechanisms by which K supply controls disease incidence in cotton are still unclear and further research is needed in order to incorporate K nutrition in biotic alleviation management.

3.10 Potassium and stress signaling

Apart from its major role in plant protection from a variety of abiotic and biotic stresses, K has been suggested to be significantly involved in plant stress responses (*Ashley* et al., 2006; *Wang* and *Wu*,

2010). Potassium deficiency not only to induced K transporter up-regulation (*Gierth* et al., 2005; *Lee* et al., 2007), but additionally controlled stress-signaling mechanisms such as ROS synthesis (*Shchatman* and *Shin*, 2007) as well as hormone synthesis (*Ashley* et al., 2006). Reactive oxygen species production, and especially production of hydrogen peroxide (H_2O_2), increased under conditions of limited K supply (*Shin* and *Schactman*, 2004), with H_2O_2 further activating K uptake mechanisms in order to increase K plant status. In addition, genes regulating jasmonic acid and auxin synthesis were up-regulated at low plant K-concentrations (*Armengaud* et al., 2004) while ethylene productions rates were increased two-fold in K-starved Arabidopsis plants compared to control plants (*Shin* and *Scachtman*, 2004). In cotton, research indicated that K deficiency resulted in increased absiscic acid concentrations in the roots and the xylem sap while cytokinins (zeatinriboside and isopentenyl adenosine) levels were decreased in the xylem sap and leaves (*Wang* et al., 2012) indicating that K affects the hormonal balance in cotton. Future studies should also focus on auxin, ethylene and jasmonic acid metabolism in cotton and the effect of K supply on them since reports in other crops have indicated that they are greatly affected by K levels.

4 Diagnosis and amelioration of plant potassium status

The nutrient demands of currently planted, high-yielding varieties are not entirely met by natural soil fertility. The application of fertilizer is therefore required, yet spatial and temporal variability of abiotic and biotic factors results in varying nutrient demands of different fields across seasons. For K, two methods are currently used to determine optimum fertilizer applications.

4.1 Soil sampling and analysis

Soil sampling is the traditional method to determine necessary fertilizer applications (*Baker* et al., 1992). Recommendations for sampling are created by the cooperative Extension Services in each cotton-growing State in the US (in cooperation with the United States Department of Agriculture). Generally, soil sampling should be conducted at the depth of tillage (typically 15 cm) in a zig-zag pattern through uniform areas of each field every 3 – 4 years. Mixed samples are dried and analyzed for mg K kg^{-1} soil. Soil testing laboratories typically calibrate their recommendations based upon the type of analysis utilized, type of soil, and crop to be grown and estimated yields. Still, deficiencies have been noted under laboratory-determined "sufficient" levels (*Oosterhuis* and *Weir*, 2010). These unanticipated deficiencies may be due to sampling shallow soil depths which cotton may fail to fully exploit (*Brouder* and *Cassman*, 1990) or seasonal factors which require a mid-season measurement to accurately determine nutrient demands.

4.2 Tissue sampling and analysis

Although the most practical method to detect K deficient areas is through pre-plant soil testing, in-season plant tissue analysis has the potential to also be a valuable tool (*Baker* et al., 1992). Unfortunately, the characteristics of plant K have complicated the establishment of critical values.

Potassium is generally concentrated in the leaves and stems early in the growth season and transferred to the reproductive structures, which become the dominant K sinks, later in the growth season (*Bassett* et al., 1970; *Halevy*, 1976; *Cassman* et al., 1989a). These shifts result in a moving target depending upon growth stage. Inability to accurately characterize the sampled plant growth stage and/or failure to accurately describe tissue concentrations at differing locations on the target cotton development curve are major difficulties in tissue sampling programs. Many other genetic and environmental conditions and stresses can also influence K tissue concentrations through shifts in uptake and translocation. Furthermore, cotton takes up K in luxury amounts (*Kafkafi*, 1990) and this could possibly confuse tissue diagnostic recommendations (*Oosterhuis*, 1995). All of these properties of K have led to inconsistent and often conflicting reports of critical leaf K values (*Reddy* and *Zhao*, 2005).

Contrasting reports on the sensitivities of specific tissues have also been reported. *Rosolem* and *Mikkelsen*(1991) *suggested tissue sensitivity to* K *stress to increase in the following order*: *leaves*<*bolls* <roots<stems. These results suggest that only a severe deficiency would result in decreased leaf K concentrations. In contrast, *Bednarz* and *Oosterhuis* (1995) noted the following degrees of sensitivity: bolls<stems<leaves<roots. Still, many reports have suggested petiole sampling is more useful due to its more sensitive nature, noting declines in petiole K concentrations as early as 7 d after treatment establishment (*Coker* et al., 2003).

4.3 Amelioration with fertilizer

Although research in the San Joaquin Valley (SJV) stratified soils seemed to suggest deep-placed K fertilizer would increase K uptake and yields, research from the south-eastern and mid-southern regions of the United States often found no consistent yield responses. *Mullins* et al. (1994) examined the response of cotton yield to subsoil and surface applications of K and found no significant difference associated with application method. Further research by *Mullins* and *Burmester* (1997) in Alabama examining subsoil, banded, and broadcast applications of K fertilizer also noted no significant differences between methods of applications. *Adeli* and *Varco*(2002) examined broadcast and banded applications of K in Mississippi and found similar results. The authors only noted consistent yield increases from banded K applications in dry growth seasons. There has been some interest in deep placement of K (*Tupper* et al., 1988) although yield responses from this method of K placement have been inconsistent (*Reeves* and *Mullins*, 1995).

Failure of these banded and subsoil applications to affect yield regardless of soil depth may be best explained by research conducted by *Brouder* and *Cassman* (1994). These authors examined the response of cotton roots and shoots to localized supplies of N, P, and K. Results suggested that although root proliferation and compensatory growth were typically observed after N and P enrichment, neither were observed after K enrichment. Therefore, the quantity and distribution of N through the profile can greatly influence K uptake by influencing root proliferation. This may be one reason that increasing the amount of N fertilizer increases the amount of K uptake (*Halevy* et al., 1987), but that increasing the amount of K fertilizer does not increase N uptake (*Pettigrew* and *Meredith*, 1997).

When soil analysis calls for K, the cotton crop is usually fertilized with a single preplant broadcast application of K fertilizer. Potassium chloride, commonly referred to as muriate of potash, is the most common source of fertilizer K due to its cost and high K composition (IPNI, 2011a). The contained chloride (Cl^-) typically leaches with the application of water and is not considered to negatively affect cotton growth in most humid regions. Still, in arid regions where application of Cl is of concern or where sulfur is needed, potassium sulfate, commonly referred to as sulfate of potash, is another acceptable K source (IPNI, 2011b). Under these conditions research has shown significant cotton yield penalties associated with muriate of potash as compared to sulfate of potash (Pervez et al., 2005). Other sources of potassium include potassium magnesium sulfate, commonly referred to as Langbeinite, and potassium nitrate, but use of these fertilizers is typically restricted to high value crops and not commonly used in cotton production (IPNI 2011c; 2011d).

Mid-season applications are infrequently applied, and foliar applications are only used occasionally to correct K deficiencies during fruiting. Foliar applications of K offer the opportunity of correcting mid-season deficiencies quickly and efficiently, especially late in the season when soil application of K may not be effective. The practice of foliar fertilization has only caught on in cotton production in the last two decades, but there is still considerable speculation about the benefits and correct implementation of this practice. While there are many reports on research involving soil applied K (e.g. *Kerby* and *Adams*, 1985), there are no definitive studies available on the usefulness of foliar-applied K. Earlier research (*Oosterhuis*, 1976; *Oosterhuis* and *Weir*, 1999) indicated that foliar-applications of K significantly increased seed yield of cotton. There have also been reports of foliar-applications of K improving both

lint quality and yield (*Oosterhuis* et al., 1990; *Pettigrew* et al., 1996). With the current emphasis on lint quality (*Sasser*, 1991) and the introduction of high-volume instrumentation classification, the positive effect of K on lint quality may be of paramount importance.

5 Conclusions

This review has described the major role that K plays in plant physiological processes fundamental to normal growth and yield development of cotton. Potassium deficiency was described and related to functions in the plant. It was shown that K is also involved in numerous physiological functions related to plant health and resistance to biotic and abiotic stress. In addition, the role of K in stress relief was highlighted. Lastly, the agronomic aspects of K requirements, diagnosis of soil and plant K status, and amelioration of K soil and plant status were discussed. However, as it was pointed in the assorted sections, research has mainly focused on model crops such as arabidopsis or rice and maize with very little or even no information existing on the physiology, biochemistry and most importantly molecular biology of K nutrition in the cotton plant. Identification of the metabolical pathways that may be controlled by K in the cotton plant will improve our understanding on plant's adaptation to deficiency aiding farmers to generate more efficient fertilization strategies on marginal soils and additionally provide us with valuable information on targets for future genetic improvement efforts.

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钾缓解棉花逆境胁迫的生理功能及养分管理措施

摘　要:钾在维持植物基本生长发育中有着重要作用,同时还与维持植物健康、抵御生物和非生物胁迫等的很多生理功能有关。广泛缺钾导致植物长势不佳、减产、纤维品质下降。本文综述了钾的植物生理功能,及在缓解植物逆境胁迫上的作用,并在钾素需求、土壤和植物钾素诊断及改良等农学方面提出了一些建议。钾的植物生理功能方面涉及酶活性、有机物合成和调节、气孔与水的活动、光合作用、矿物质运输、细胞信号以及植物对于干旱、严寒、盐害及生物胁迫的反应等。农学方面包括了棉花对钾的需求、吸收,不同基因型对钾的吸收和利用、棉花缺钾特征及相应土壤钾的变化等。此外,还对土壤与植物钾素状况诊断及改善方面也进行了一些讨论。

关键词:施肥;棉花;植物分析;土壤分析;抗逆

UV-B 辐射增强下施钾对大麦光合及蒸腾生理日变化的影响[①②]

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摘　要：通过大田实验，研究在 UV-B 辐射增强条件下，不同施钾量对大麦抽穗期叶片净光合速率、气孔导度、蒸腾速率、胞间二氧化碳浓度和水分利用率等生理指标日变化的影响。UV-B 辐射设 2 个水平，即对照（CK，自然光，辐射强度 1.5 kJ/(m^2 · h)）和增强 120%（1.8 kJ/(m^2 · h)）；施钾（K_2O）量设 2 个水平，即低钾（K1，73 kg/hm^2）和高钾（K2，150 kg/hm^2）。结果表明，UV-B 辐射增强会降低大麦的叶绿素含量、净光合速率、气孔导度、蒸腾速率和水分利用率。增施钾肥可提高叶片中叶绿素的含量、净光合速率、气孔导度和蒸腾效率，但对大麦胞间 CO_2 浓度和水分利用效率的影响不明显。增施钾肥可减缓 UV-B 辐射增强对大麦净光合速率的抑制作用，但不能减缓 UV-B 辐射对大麦气孔导度和蒸腾速率的抑制作用。

关键词：大麦；UV-B 辐射；施钾；日变化

由于氟氯烷烃（CFCs）和氮氧化物的大量排放，平流层臭氧层正不断变薄。地球臭氧层的破坏已成为最受关注的环境问题之一。臭氧浓度每减少 1%，到达地面的紫外线辐射就增加 2%[1-2]。从生物学角度分析，对地球生物造成直接影响的主要是 UV-B 辐射[3]。研究表明，UV-B 辐射增强显著影响农作物生长，表现为：作物生长受阻，分蘖数减少，叶面积和叶绿素含量下降[4-7]，降低了 Hill 反应活力[8]、蒸腾速率和光合速率[9]，导致作物生物量和产量下降[10]。此外，有关 UV-B 辐射增强与其他因子的复合作用对植物生理、生化及生态系统影响的研究也越来越多。如矿质元素缺乏、干旱[11]、高光强[12]、高温[13]能降低甚至掩盖 UV-B 辐射增强对植物的效应，盐胁迫[14]、酸雨[15]、臭氧浓度增加[16]及重金属污染[17]以协同或叠加方式与 UV-B 辐射共同抑制植物生长。

大麦是重要的禾谷类作物，具有啤酒酿造、饲料加工及食用等多种用途。有关 UV-B 辐射增强对大麦生长发育、形态结构、产量构成、品种遗传差异等方面的相关研究已有不少。钾是植物生长发育必需的营养元素，对农作物的生长过程起着重要的作用。钾能促进植株体内酶的活化，能促进植物的光合作用和光能利用，能增强植株体内物质合成和运输，能增强植物的抗逆性[18]。但是，增施钾肥能否缓解 UV-B 辐射增强对大麦的抑制作用，迄今未见相关报道。通过大田模拟试验，研究了 UV-B 辐射增强下增施钾肥对大麦抽穗期植株光合和蒸腾生理指标的影响，旨在探讨通过施用钾肥能否减缓 UV-B 辐射增强对大麦生产的影响，为进一步开展相关研究提供试验依据。

1　材料与方法

1.1　试验设计

大田试验于 2011 年 11 月—2012 年 5 月在南京信息工程大学农业气象试验站（32°03′N，118°51′E）进行。采用可升降灯架，将 UV-B 灯管（光谱为 280～320 nm）置于大麦冠层上方，用于模拟 UV-B 辐射增强。用国产紫外辐照计测 297 nm 处辐射强度（以植株上部计）。UV-B 辐射强度设 2 个水平，即 CK（自然光）和增强 UV-B（1.8 kJ/m^2），相当于南京地区4—5月 UV-B 辐射量的 120%。施钾（K_2O）量设 2 个水平，即低钾（K1，73 kg/hm^2）和高钾（K2，150 kg/hm^2）。采用完全区组设计，随机排列，重复 3 次。小区面积＝3 m×3 m＝9 m^2。

大麦种子（品种为“益引 2 号”）经消毒处理后于 2011 年 11 月 10 日进行播种，每小区播种大麦 100 g。

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三叶期间苗，以保持适宜的种植密度，同时开始 UV-B 辐射处理。处理期间，光源与植株顶部始终保持 0.8 m 左右的距离不变，每日辐照时间为 8：00—16：00，共 8 h，阴雨天停止照射。田间管理按当地生产习惯进行。在连续无雨的情况下进行人工灌溉，以保证植株不受到干旱的影响，直到其成熟。

1.2 生理指标的测定

观测大麦生长进程，在抽穗期选择晴朗无风的天气，于 8：00—16：00，采用英国 PPS 国际有限公司生产的 CIRAS-1 型便携式光合作用测定系统，测定大麦叶片净光合速率、蒸腾速率、气孔导度、光和有效辐射和胞间 CO_2 浓度等光合和蒸腾生理参数的日变化。每 2 h 测定一次，每个处理每次取 3 个重复，每个重复取 3 片叶，并重复读取 3 次数值，以平均值作为该时次的测量结果。

1.3 统计分析

数据处理采用 SPSS 统计分析软件进行统计分析。$p < 0.05$ 表示差异性显著，用 * 表示；$p < 0.01$ 表示差异极显著，用 ** 表示；没有标明的表示未达 0.05 的显著性水平。

2 结果与分析

2.1 施钾对 UV-B 辐射增强下大麦叶绿素含量的影响

从图 1 可看出，与对照相比，UV-B 辐射条件下，大麦叶片中的叶绿素含量明显下降，降幅在 3.8%～11.9%之间，高钾处理比低钾处理的叶绿素含量要偏高些，且低钾处理在各个观测点的差异基本显著，而高钾处理的差异显著性没那么明显。说明钾肥可以增加大麦叶片的抵抗能力，提高大麦叶片中的叶绿素含量，且在一定程度上减缓了 UV-B 辐射增强对大麦叶绿素含量降低的抑制作用。

UV-B 辐射会使植物叶绿体受到伤害，使叶绿素的合成受阻，叶绿素和类胡萝卜素被诱导非酶化光氧化，希尔反应活性降低，叶片气孔阻力增大或气孔关闭，从而抑制植物的光合作用[19]。其原因可能在于 UV-B 辐射增强破坏了叶绿素膜，使得叶绿素含量降低。相关研究表明，UV-B 辐射增强下，叶绿体膜上镁-三磷酸腺苷酶活性下降，导致叶绿体基质 pH 降低；叶绿体膜组分改变，不饱和脂肪酸下降，饱和脂肪酸含量上升，造成膜流动性降低[20]。李元等[21]研究，在大田条件下，随 UV-B 辐射增强，春小麦叶片叶绿素 a、叶绿素 b 和叶绿素(a+b)含量显著降低。UV-B 辐射能破坏敏感植物的叶绿体结构和它们的前体，或使叶绿素的合成受到阻碍，从而降低叶绿素含量，这在大豆、水稻、小麦、玉米等多种植物中已经得到观察[26]。UV-B 辐射可能是能够加剧植物膜脂的过氧化作用，破坏叶绿体膜相，从而导致光合色素分解。

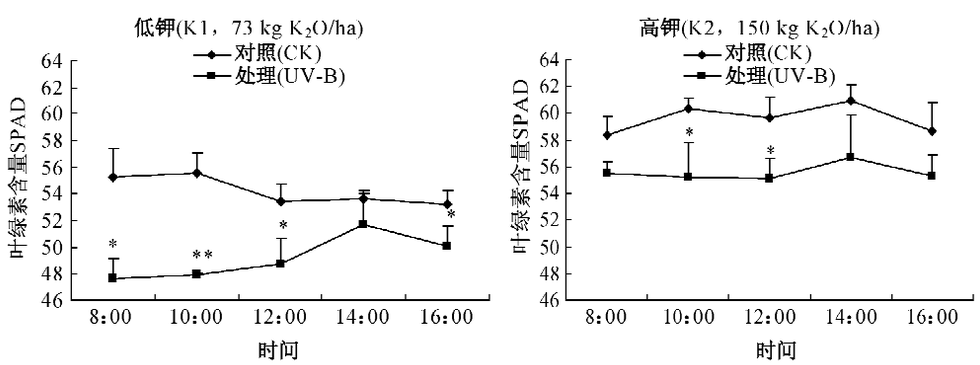

图 1 不同处理大麦叶片中叶绿素含量的影响

Fig. 1 The diurnal change of chlorophyll content in leaves of barley as affected by enhanced ultraviolet-B radiation and K supply

2.2 施钾对 UV-B 辐射增强下大麦净光合速率的影响

从图 2 可以看出，与对照相比，UV-B 辐射增强明显降低了大麦叶片的净光合速率，在各个观测点的差异均达到显著水平（$p < 0.05$），甚至达极显著水平（$p < 0.01$）。说明 UV-B 辐射增强对大麦净光合速率有明显的抑制作用。

在同等 UV-B 辐射条件下，高钾处理叶片的净光合速率要比低钾处理略高，说明钾肥可提高大麦叶片的净光合速率，且在一定程度上减缓了 UV-B 辐射增强对大麦净光合速率的抑制作用。其原因在

于增施钾肥可增加叶片光合作用，抵御 UV-B 辐射增强对叶片造成的伤害，从而达到减缓抑制的作用。

在各种处理当中，叶片净光合速率的日变化都呈现双峰趋势，峰值出现在 10:00 和 14:00。在 12:00 出现明显的“午休”现象，净光合速率明显较之前的 10:00 和之后的 14:00 低。据研究[22]，植物不仅能被动地接受环境条件的变化，而且能够通过改变生长策略和生理过程来适应这种变化，其中植物“午休”现象正是叶片抵御外界强光的一种适应能力。

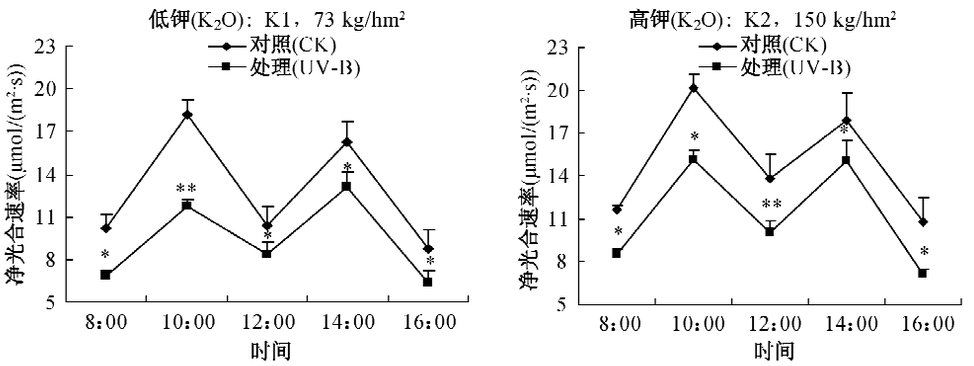

图 2　不同处理大麦抽穗期叶片净光合速率日变化

Fig. 2　The diurnal change of net photosynthetic rate in leaves of barley as affected by enhanced ultraviolet-B radiation and K supply

2.3　施钾对 UV-B 辐射增强下大麦气孔导度的影响

气孔是植物与外界交换的“大门”，气孔导度大小直接影响着作物光合、蒸腾等重要生理过程，同时又和呼吸作用共同决定了胞间二氧化碳浓度的高低。气孔导度减小必将对叶片的光合作用产生不利的影响。据研究，UV-B 辐射增强能够明显影响气孔的开启和关闭速率，减少叶片蒸腾速率[23]，进而会影响到光合作用[24]。

从图 3 可以看出，叶片气孔导度在观测时间内，8:00 时为最大值，之后呈现逐渐下降趋势。与对照相比，UV-B 辐射增强使大麦叶片气孔导度的日平均值在低钾处理下和高钾处理下分别降低了 38.5% 和 29.9%。在各个观测点的差异普遍达显著水平（$p<0.05$），甚至极显著水平（$p<0.01$），说明 UV-B 辐射增强可以抑制大麦的气孔导度。而在同一辐射水平下，低钾处理和高钾处理后大麦同一时刻的气孔导度基本一致，说明增施钾肥对大麦气孔导度的影响并不明显。

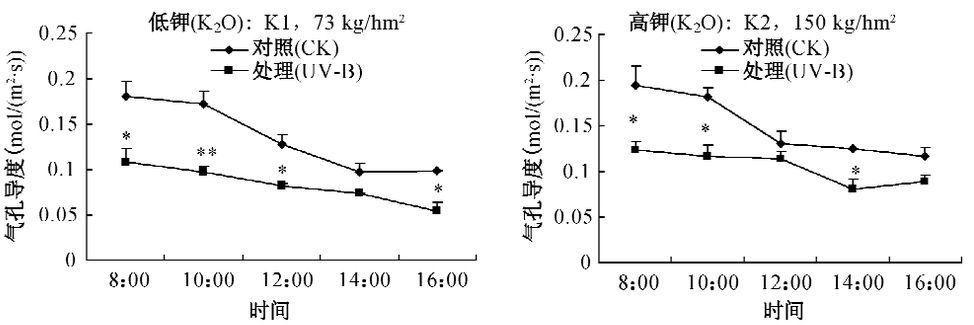

图 3　不同处理大麦叶片气孔导度的日变化

Fig. 3　The diurnal change of stomatal conductivity in leaves of barley as affected by enhanced ultraviolet-B radiation and K supply

2.4　施钾对 UV-B 辐射增强下大麦胞间 CO_2 浓度的影响

从图 4 可以看出，低钾处理时，UV-B 辐射增强可明显提高叶片胞间二氧化碳浓度，差异性在各个观测点基本达到显著水平（$p<0.05$），其中 12:00 为极显著（$p<0.01$）。高钾处理时与低钾处理时相似，差异性在除 8:00 和 10:00 的各个观测点均达到显著水平（$p<0.05$）。不同处理下的胞间 CO_2 浓度日变化均呈现双谷趋势，其中 8:00—10:00 快速下降，10:00—12:00 有较明显的上升，之后又下降，14:00 以后

快速升高。从日变化趋势看，其与施钾对 UV-B 辐射增强下大麦气孔导度的趋势并没有明确的对应关系，而与施钾对 UV-B 辐射增强下大麦净光合速率的趋势相反。说明胞间 CO_2 浓度的日变化与净光合速率的日变化直接相关，UV-B 辐射对大麦净光合速率的影响并不是通过影响气孔导度而阻碍二氧化碳的供应来起作用的，而可能是通过影响光合作用本身的反应过程而产生效果的。

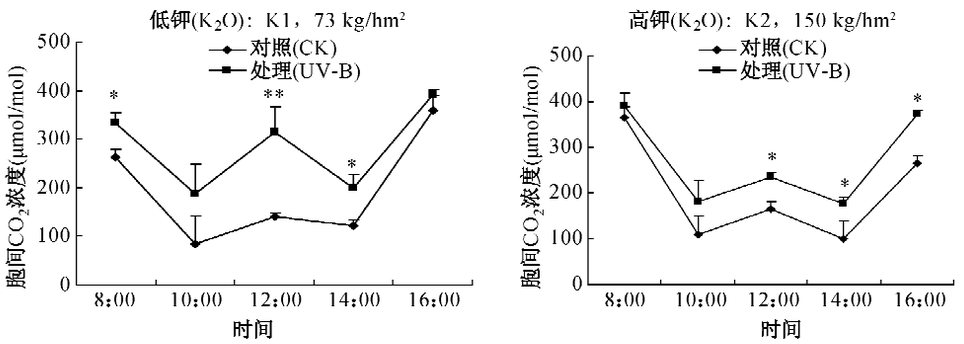

图 4　不同处理大麦抽穗期叶片胞间 CO_2 浓度的日变化

Fig. 4　The diurnal change of intercellular CO_2 concentration in leaves of barley as affected by enhanced ultraviolet-B radiation and K supply

2.5　施钾对 UV-B 辐射增强下大麦蒸腾速率的影响

从图 5 可以看出，叶片蒸腾速率的日变化趋势呈现单峰曲线，均在 14:00 时达到最高，然后迅速下降。在同一施钾水平下，与对照相比，UV-B 辐射增强下大麦叶片的蒸腾速率都有所降低，但显著性不明显，只在个别观测点达到显著水平。说明 UV-B 辐射增强对大麦叶片蒸腾速率有一定的抑制作用，可提高水分利用效率，以进一步抵抗 UV-B 辐射对其自身的伤害。许多研究表明，UV-B 辐射会诱导叶表面气孔开度减小和气孔阻力增大，根系活力降低，从而降低蒸腾速率，这也在黄瓜、萝卜和大豆中观察到[25]。与对照相比，UV-B 辐射增强使大麦叶片蒸腾速率的日平均值，在低钾处理下和高钾处理下分别降低了 28.7%和 23.2%。在同一 UV-B 辐射水平下，低钾处理和高钾处理后大麦同一时刻的蒸腾速率差异不明显，说明增施钾肥对大麦蒸腾速率的影响不明显，不能有效减缓 UV-B 辐射增强对大麦叶片蒸腾速率的抑制作用。

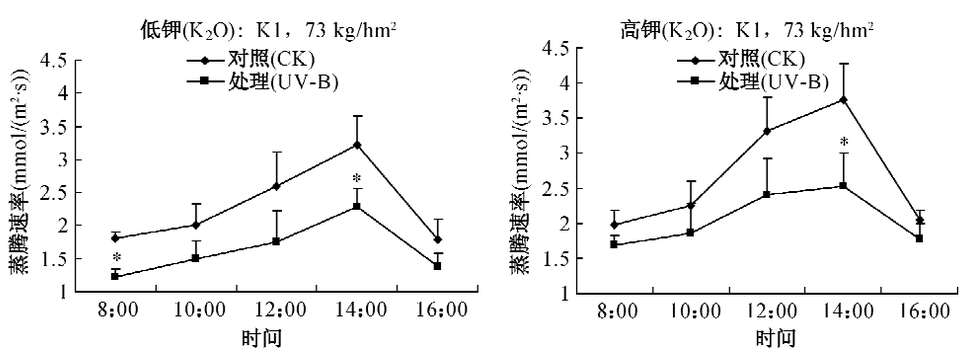

图 5　不同处理大麦叶片蒸腾速率的日变化

Fig. 5　The diurnal change of transpiration rate in leaves of barley as affected by enhanced ultraviolet-B radiation and K supply

2.6　施钾对 UV-B 辐射增强下水分利用率的影响

水分利用效率是指植物蒸腾消耗单位重量的水分所同化的二氧化碳的量，常用净光合速率与蒸腾速率的比值表示[26]。即 $W = Pn/Tr$，其中 W 为水分利用效率；Pn、Tr 分别为光合速率与蒸腾速率。从图 6 可看出，UV-B 辐射增强对水分利用率有一定的抑制作用，但显著性不明显。在整个观测时间内总体呈下降趋势，中间有一定的起伏。但在同一辐射水平下，相同观测点经低钾处理和高钾处理的水分利用率相差很小，说明钾肥对大麦叶片水分利用效率的日变化没有明显影响。

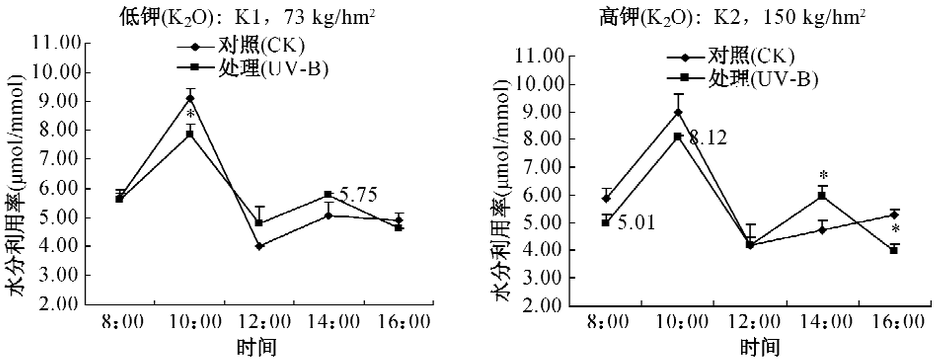

图 6　不同处理大麦叶片水分利用率的日变化

Fig. 6　The diurnal change of water use efficiency in leaves of barley as affected by enhanced ultraviolet-B radiation and K supply

3　讨论和结论

本研究表明，在 UV-B 辐射增强下，大麦叶片气孔导度减小，但胞间二氧化碳浓度升高，说明光合作用所需二氧化碳的供应量并没有减少，也就是说气孔导度减小并不是净光合速率降低的主要原因，而很可能是 UV-B 辐射对光合作用本身的反应过程有影响。大麦叶片通过减小蒸腾速率和气孔导度的方式来提高水分利用率，以抵抗 UV-B 辐射增强对其自身的伤害，这也与颜景义等的研究结果基本相同[27]。

在一定 UV-B 辐射强度下，大麦叶片中的叶绿素含量明显下降，降幅在 3.8%～11.9%之间。高钾处理比低钾处理的叶绿素含量要偏高，且在 UV-B 辐射增强下的降幅也较小，说明增施钾肥增加了大麦叶片的抵抗力。高钾处理的叶片净光合速率要比低钾处理的高，说明增施钾肥可提高大麦叶片的净光合速率，在一定程度上可以有效缓解 UV-B 辐射增强对大麦净光合速率的抑制作用。大麦胞间 CO_2 浓度的日变化与净光合速率的日变化直接相关。UV-B 辐射增强可以抑制大麦的气孔导度。而在同一辐射水平下，低钾处理和高钾处理后大麦同一时刻的气孔导度基本一致，说明增施钾肥对大麦气孔导度的影响并不明显。在同一 UV-B 辐射水平下，低钾处理和高钾处理后大麦同一时刻的蒸腾速率差异不明显，说明增施钾肥对大麦蒸腾速率的影响并不明显，也不能有效减缓 UV-B 辐射增强对大麦叶片蒸腾速率的抑制作用。因此，增施钾肥后大麦叶片净光合速率的提高，不是通过影响蒸腾速率、气孔导度间接完成的，也不是通过影响气孔导度而阻碍二氧化碳的供应起作用的，而是通过影响光合作用本身的一些反应过程实现的[28]。

在未来农业生产实践中，可通过增施钾肥等能够增强作物抵抗力的肥料或是筛选或培育抗 UV-B 辐射或对 UV-B 辐射不敏感的作物品种，来缓解 UV-B 辐射增强对作物生产不良影响的有效措施。在全球变暖、紫外辐射增强的背景下，通过合理的施肥方式，筛选或培育作物品种，增强作物对外界环境的适应和抵抗能力，是农业生产和社会经济持续稳定发展的重要措施。本研究仅针对大麦抽穗期某一天晴朗无风天气下的日变化数据，并不能代表大麦全部生育期生理特性的日变化趋势，在不同天气情况下各个参量的日变化趋势应该有所差异，这有待进一步的研究。

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Effect of potassium supply on diurnal variations of photosynthesis and transpiration at barley heading stage under enhanced UV-B radiation

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Abstract: Field experiment was conducted to investigate the effects of K supply on diurnal variations of net

photosynthetic rate, transpiration rate, stomatal conductivity, intercellular CO_2 concentration and water use efficiency in barley leaves at heading stage under enhanced UV-B radiation at the Station of Agricultural Meteorology, Nanjing University of Information Science and Technology, Nanjing, China. The experiment was designed with two UV-B radiation levels, i.e. ambient (CK, 1.5 kJ/(m^2 · h)) and enhanced by 120% (1.8 kJ/(m^2 · h)); and two K supply levels, i.e. 73 kg K_2O/hm^2 (low) and 150 kg K_2O/ hm^2 (high). The results showed that enhanced UV-B radiation declined chlorophyll content, net photosynthetic rate, transpiration rate and stomatal conductivity in barley leaves, but had no obvious effect on intercellular CO_2 concentration and water use efficiency. Increasing K supply could alleviate the damage of enhanced UV-B radiation to net photosynthetic rate from enhanced UV-B radiation, but not to transpiration rate and stomatal conductivity.

Key words: Barley, UV-B radiation, Potassium fertilization, Diurnal variations

Simulating the effect of potassium fertilization on carbon sequestration in soil §

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Abstract: The impact of horticultural management on carbon sequestration in soils has been limited so far to tillage and nitrogen fertilization. Our objective was to evaluate by mathematical modeling the effect of potassium fertilization on CO_2 binding in cropland soils. The developed model integrates three subunits: (1) A published simulator of crop dry-matter (DM) production in response to N, P, K fertilization, but not DM partitioning; (2) a published soil-crop-atmosphere model predicting crop yield and DM partitioning as a function of N but not K fertilization; (3) an original model computing the organic-inorganic carbon transformations, inorganic-carbon reactions and transport in soil, CO_2 diffusion, and soil carbon sequestration. The model described the K-fertilization effect on C binding in soil as a function of the soil pH, the Ca^{2+} concentration in the soil solution, hydraulic properties, air temperature, and crop DM production, and partitioning characteristics. In scenarios of corn (*Zea mays* L.) growth in clayey soil and wheat (*Triticum aestivum* L.) in loam soil, the computed K-induced CO_2 sequestration amounted to ≈14.5 and 24 kg CO_2 (kg K)$^{-1}$, respectively (0 *vs*. 100 kg ha^{-1} K application). The soil CO_2 sequestration declined by 8% when corn grew in sandy instead of clayey soil and by 20% when the temperature was 10℃ higher than the temperature prevailing in mild semiarid zones. All predicted CO_2-sequestration results were approximately 30-fold higher than the 0.6 kg CO_2 emitted per kg of K manufactured in industry.

Key words: CO_2 diffusion/carbonates/corn/mineralization/organic carbon/wheat

1 Introduction

Tillage and nitrogen-fertilization effects on soil carbon sequestration (SCS) have been investigated during the last two decades (*Walcott* et al., 2009). The results proved that reduced tillage practices increase C sequestration in cropland soils in comparison with conventional tillage practices (*Lal*, 2004b), but the effect of N fertilization remained unclear. *Schlesinger* (1999) claimed that nitrogen application does not increase soil C sequestration, while *Izaurralde* et al. (2000) and *Allmaras* et al. (2004) reported that N application enhances SCS in corn fields. The impact of nutrients other than N on SCS has been meagerly discussed so far in the literature (*International Potassium Institute*, 2009). The uncertainty regarding the role of fertilizers in SCS is not surprising considering the complexity of the biotic and abiotic processes involved. Biotic processes include crop dry-mass (DM) response to fertilization, DM partitioning and allocation to roots, root turnover, respiration and excretion into soil, and soil microbial activity (*Coleman* et al., 2004). Respirationinduced CO_2 release affects soil pH, Ca^{2+} activity in soil solution (*Lindsay*, 1979), and carbonate reactions and transport in soil. Abiotic factors include rainfall and irrigation, which determine leaching (and in the case of flooding runoff), plant growth, microbial activity, and CO_2 diffusion in soil (*Vossbrinck* et al., 1979; *Pumpanen* et al., 2003; *Turcu* et al., 2005). The CO_2 efflux from soil to atmosphere depends on cultivation methods and mulching (*Ben Asher* et al., 1994; *Pumpanen* et al., 2003).

Models predicting SCS may be divided into three groups: (1) models emphasizing inorganic-C (C_i) reactions and transport in soil but neglecting plants (*e. g.*, *Simunek* and *Suarez*, 1993); (2) models concentrating on organic-C (C_o) transformations in the soil but disregarding C_i chemistry and plants (*e.*

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§ J. Plant Nutr. Soil Sci. 2013, 176, 375-386

g., *Allmaras* et al., 2004); and (3) models combining organic-N and C transformations in soil but oversimplifying C_i reactions (*Molina* et al., 1983; *Parton* et al., 1988).

The objective of this work is to develop a model predicting Kfertilizer effects on carbon sequestration in soil by taking into account crop growth, soil chemical and physical properties, climatic conditions, and irrigation and tillage practices. Such a model is timely because empirical results of fertilizer effects on SCS are scarce, and theoretical evaluation of this effect might elucidate the role of nutrients in enhancing organic-car-bon content in soil. Potassium was chosen as a test fertilizer because it has a negligible effect on soil pH and microbial activity; its impact on C sequestration stems from its effect on plant growth only; and it tends to increase the plant root-toshoot ratio (*Ericsson*, 1995; *Jordan-Meille* and *Pellerin*, 2008) due to its role in sugar transport from leaves to roots (*Marschner*, 1986). Wheat and corn were selected as test crops due to their importance as feed crops, and because they have been intensively investigated and modeled in the literature.

2 Model description

The developed model integrates three submodels:

(1) QPAIS (*Greenwood* and *Karpinets*, 1997a; *Zhang* and *Greenwood*, 1997), which calculates temporal aboveground DM ($AGDM_q$) production, and N, P, K, and water uptake as functions of the fertilizer-application rate, soil properties, weather conditions, and water regime, but not DM partitioning in plants. The model was validated by *Greenwood* and *Karpinets* (1997b) in terms of K-fertilization effects on temporal K concentration in soil, yield of spring wheat, summer cabbage, and turnips grown in England, and %K in tops. Good agreement between experimental and simulated results was also reported for plant weight and %K at harvest in another ten crops. Additional validation in temperate climates was published by *Zhang* et al. (2007). Because QPAIS does not compute the temporal root DM weight in soil, this parameter was estimated from $AGDM_q$ by multiplying $AGDM_q$ by the temporal ([root DM weight]/[aboveground DM weight]) ratio ($=RF(t)$) calculated by DSSAT (see later) for nonlimiting soilfertility conditions. Under limiting K supply, $RF(t)$ is multiplied by a crop-specific factor F_K($\leqslant 1$) that decreases as the %K in the plants (predicted by QPAIS) declines. As a first approximation, F_K is independent of the plant age and its minimum value is set to 0.8 (severe K deficiency).

(2) DSSAT (Decision Support System for Agro-Technology Transfer; *Hoogenboom* et al., 2003; *Jones* et al., 2003) simulates the impact of weather conditions, soil properties, crop characteristics and management on temporal DM production; root-to-aboveground DM ratio, yield, and N and water uptake, but not K impact on growth and yield. The root net DM weight is obtained by subtracting respiration C and senescence C from the total DM allocated to roots. The simulation of water and N transport follows the one-dimensional "tipping bucket" soil water-balance approach, employing several soil layers and root growth as a function of depth, soil water content (θ), and DM allocation to roots. The model was evaluated simulating the number of days required to attain major physiological stages in peanuts (*Anothai* et al., 2008), simulating the yield as a function of N fertilization in wheat (*Inglesias*, 2006) and corn (*Ma* et al., 2006), and simulating the temporal leafarea index in corn (*Soler* et al., 2007) and wheat (*Wagger*, 1983). Over 90% of these comparisons had $R^2>0.70$ and RMSE$<$1.2, indicating good performance of the model. Notably, the QPAIS and DSSAT models have not yet been sufficiently validated under semiarid conditions.

(3) A new soil C sequestration model (SCSM) that simulates C_o and C_i transformations, reactions, and transport in soil as a function of soil carbon content and composition, tilling, and environmental conditions. This model uses the QPAISDSSAT crop output data as input and runs in Excel. The governing equations in the model's five subroutines are given in Tab. 1, abbreviations are explained in

Tab. 2. The model calculates root-respiration CO_2 from the input root-DM function with a known root maintenance factor (Eq. 6) and dynamic root-excretion and senescence factors, which multiply the input root-DM function (F_{Ri}, Eq. 7). Another crop-specific factor is soil root volume (default value 40 cm), which is assumed homogenous with respect to all soil properties. Carbon that moves below the soil root layer is defined as sequestered. The model was tested and found to be satisfactory (see later).

Table 1 Subroutines and governing equations in the SCSM model. Units and parameter values that are not presented here are given in Tab. 2.

#	Subroutine	Governing equations	Comments
1	speciation of C_i forms	six equations (not presented) describing the equilibrium relationships among $CO_{2(g)}$, H_2CO_3, HCO_3^-, CO_3^{2-}, $CaHCO_3^-$, $CaCO_3$, and $NaHCO_3$	all species expressed in terms of H_2CO_3 and given pH, C_{Ca}, and C_{Na}; reaction constants derived from *Lindsay* (1979)
2	sorption and precipitation/ dissolution	HCO_3^- adsorption:[1] $A_{HCO_3}=Kl\ Bl\ C_{HCO_3}$ for $C_{HCO_3} \leqslant C_{HCO_3\,Lim}$ $A_{HCO_3}=Bl$ for $C_{HCO_3} > C_{HCO_3\,Lim}$ $CaCO_3$ precipitation: $K_{sp}=(Ca^{2+})\ (CO_3^{2-})$ $K_{sp}=10^{-5.30}$[2] $d(CaCO_{3(s)})/dt=K_{CaCO_3}(C_{CO_3}-C_{equil})$[3]	derived from the Langmuir equation: $A=Kl\ Bl\ C_{HCO_3}/(1+Kl\ C_{HCO_3})$ (K_{sp} from *Lindsay*, 1979) $C_{equil}=K_{sp}/(Ca^{2+})$
3	CO_2 diffusion	$F_{CO_2}=-D_{CO_2\,soilair}\times(C_{CO_2\,soilair}-C_{air})/(\text{soil depth})$[4] $D_{CO_2\,soilair}=D_{CO_2\,air}\times(\theta_{air})^h$[5]	C in mol C $(L\ air)^{-1}$, soil depth in m, F in mol $m^{-2}\ s^{-1}$ (*Pumpanen* et al., 2003) h is dimensionless
4	roots	$\Delta CO_{2Release}=\Delta Rt\times(\text{C fraction in Rt DM})\times(\text{root maintenance fraction})/12$[6] $\Delta(\text{Excretion}+\text{Senescence})\ C_{oRelease}=\Delta Rt\times(F_{Rexcr}+F_{Rsenes})$[7]	$\Delta C_{Release}$ in mol $m^{-2}\ d^{-1}$; ΔRt = Δroot DM wt between successive days; 12 is C molecular weight; F_{Rexcr}, F_{Rsenes} are crop factors (F_{Ri})
5	microbial	mineralization of soil C_o pools: $(S_{oCi})_t=(S_{oCi})_o[1-EXP(-(K_{soc})_i\times t)]$[8] $(S_{oCi})_o=$total C_o conc × mineralizable fraction × $\theta/\theta_{saturation}$ ΔS_{oC} is divided between microbial mass and respiration CO_2 at given ratio $K_{soc}=A\ e^{-(E/R)/T}$ (Arrhenius equation)[9]	i stands for 6 soil C_o pools and corresponding rate constants (K_{soc}): microbial (MOC), natural soil (SOC), sloughed roots and excretions (ROC), canopy debris (CDOC), manure (MNOC), and sludge (SLOC) T=temperature, E=activation energy, R=gas constant
6	solution	the inorganic c (C_i) mass-balance equation: $\Delta Q_{iC}/\Delta t=-\Delta F_{iC}/dX-R_{CaCO_3}+S_{CO_2}$[10] $Q_{iC}=\theta_{water}(H_2CO_3+CO_3^{2-}+CaHCO_3^-+CaCO_3+NaHCO_3)+(\theta_{water}+B_{HCO_3})\times HCO_3^-+\theta_{air}\times C_{CO_2\,air}$[11] $\Delta F_{iC}=$irrigation volume × C_{iCirr} − leachate volume × $C_{iCleach}$[12] leachate=irrigation−ET−$\Delta\theta\times X$[13]	$Q_{iC}=C_i$ in soil (mol C/L_{soil}), F = flux, R = precipitation rate, S = rate of root and microbial CO_2 respiration, X = soil depth B_{HCO_3} = slope of adsorption isotherm (eq. [1]) $\theta_{air}=[2\times\theta_{fc}-\theta]$ $C_{iCirr}=C_i$ conc in irr water $C_{iCleach}$=calculated C_i conc in leachate (neglecting C_i uptake) ET=evapotranspiration

Table 2 Abbreviations, parameters, and default parametric values (where applicable).

Term	Definition	Unit and default value
A	system constant in the Arrhenius equation	s^{-1}
ACS	actual carbon sequestration in soil	kg ha^{-1}
AGDM	aboveground DM	kg ha^{-1}
$AGDM_q$ $AGDM_{DSSAT}$	aboveground DM predicted by QPAIS or DSSAT	kg ha^{-1}

续 表

Term	Definition	Unit and default value
Bl	maximum adsorption of HCO_3^- by soil (Langmuir eq.)	mol (kg soil)$^{-1}$, 0.02
CDOC	canopy debris organic carbon pool in soil	% soil weight
$D_{CO_2\,air}$, $D_{CO_2\,soilair}$	diffusion coefficient of CO_2 in air and in soil, respectively	cm^2 s^{-1}, 0.15, 0.027
DAP	number of days after planting	
DM_K, DM_{nlK}	dry matter under limiting and non-limiting K supply, respectively	kg ha^{-1}
DSSAT	soil crop model predicting DM production and partitioning in response to N (*Jones* et al., 2003)	
E	activation energy in the Arrhenius equation	kcal
F_K	a%K-dependent factor (<1) multiplying the DSSAT simulated root DM-to-aboveground DM weight ratio	dimensionless, 0.8
F_{Ri}	coefficients for calculating root C respiration, excretion, and senescence (i =1, 2, 3) from root DM weight	dimensionless, 0.30, 0.05, 0.45
GPCS	gross potential C sequestration (=total DM × 0.46)	kg C ha^{-1}
h	coefficient in $D_{CO_2\,soilair}$	dimensionless, 1.4
C_i, C_o	inorganic C, organic C	mol L^{-1}
ICSM	integrated carbon-sequestration model	
K_{appl}	applied K	kg ha^{-1}
K_{sloc}, K_{mnoc}, K_{cdoc}, K_{roc}, K_{moc}, K_{soc}	rate constants of the first order organic carbon mineralization in the six organic c pools in soil	d^{-1}, 0.05, 0.15, 0.01, 0.1, 0.006, 0.005
Kl	affinity constant of HCO_3^- by soil (Langmuir equation)	L mol^{-1}, 500
K_{appl}, K_{max} LDM, SDM, FDM, RDM	K applied as fertilizer, and maximum (nonlimiting) rate leaf (L), stem (S), fruit (F), and root (R) DM weight	kg K ha^{-1} kg ha^{-1}
MNOC	manure organic carbon pool in soil	% soil weight
MOC	microbial mass organic carbon pool in soil	% soil weight
OM	organic matter	% soil weight
PCS	total C added to soil by plant	kg ha^{-1}
QPAIS	soil crop model predicting crop response to N, P, K (*Zhang* and *Greenwood*, 1997)	
ROC	root organic carbon pool in soil	% soil weight
SCS	soil carbon sequestration	kg ha^{-1}
SCSM	soil carbon-sequestration model (this work)	
SLOC	sludge organic carbon pool in soil	% soil weight
SOC	soil indigenous organic carbon pool	% soil weight
TDM	total plant DM (leaves + stems + fruits + roots)	kg ha^{-1}
Y_K, Y_{nlK}	crop yield under limiting and nonlimiting K supply, respectively	t ha^{-1}
θ, θ_{fc}	volumetric soil water content, and at field capacity	v/v, 0.25

When running a problem, the integrated model (ICSM) requires an acceptable agreement between the DSSAT and QPAIS calculated crop-DM(t) functions when K is not a limiting factor. If deviations exceed a certain tolerance ε, an iteration adjusting the parameters in QPAIS and DSSAT is enacted until ε is reached.

The SCSM model simulates three levels of CO_2 sequestration (mol C m^{-2}): (1) gross potential CO_2 sequestration (GPCS), which equals the total DM production of the crop; (2) potential CO_2 sequestration (PCS), which equals (end-of-season root DM) + (cumulative CO_2 released to soil *via* root and microbe respiration) + (cumulative root excretions); and (3) actual CO_2 sequestration (ACS), which equals PCS - (CO_2 outflow from soil surface). The K-induced ACS is defined as ACS_K=([(CS under fertilization level K_1] — [ACS under nil K fertilization])/K_1. The simulation sequence of the

integrated model (ICSM) is as follows:

(1) For $K_{app}=K_{max}$ (nonlimiting K) use QPAIS to calculate $AGDM_q(t$; planting to harvest).

(2) Use DSSAT to calculate leaves, stem, fruit, and root (L, S, F, R) DM weight as function of time ($AGDM_s=L+S+F$).

(3) Compare between $AGDM_q(t)$ and $AGDM_s(t)$; if deviations $>\varepsilon$ adjust appropriate models parameters and re-run until required agreement is reached.

(4) Define from DSSAT, $RF(t)=R(t)/AGDM_s(t)$ and $FF(t)=F(t)/AGDM_s(t)$, then calculate root and fruit weights based on the QPAIS output as $Rm(t)=F_K\times RF(t)\times AGDM_q$ and $Fm(t)=FF(t)\times AGDM_q$ (F_K defined above).

(5) Transfer $Rm(t)$ to SCSM; update root weight in the soil root volume and calculate CO_2 outflow from soil, C_i reactions and transport, and hence soil SCS.

(6) Repeat step 1 for $K_{app}=K_{max}$ 0.75 (as example) and calculate new $AGDM_q(t)$. Use $RF(t)$ obtained in the case of $K_{app}=K_{max}$ to calculate $Rm(t)=F_K\times RF(t)\times AGDM_q$ and repeat 5.

(7) Estimate the contribution of K fertilization to SCS as explained above.

3 Material and methods

3.1 Model-evaluating experiments

Results from historic experiments were used for the evaluation. The experimental conditions are described in Tab. 3.

Table 3 Details of field experiments used in testing the model.

	Historic field experiments (IL Israel; IN India)			
	sweet corn cv. Jubilee	corn cv. Neve Yaar	wheat wheat cv. Lachish cv. PBW343	
Site, country	ARO, IL	Bet Dagan, IL	Pantnagar, IN	Dorot, IL
Latitude	31.2	31.3	28.7	31.2
Longitude	34.6	34.6	79.3	34.5
climate	semiarid	semiarid	semiarid, rabi	semiarid
Weather				
Monthly mean temperature range/℃	15-25	11.6-23.9	21.9-31.6	14.5-22.6
Radiation/MJ m^{-2} d^{-1}	23	20.8	20.4	14.5
Rain/mm	65	88	675	450
Irrigation/mm	365	332	—	—
Soil properties				
Clay/%	15	50	25	20
pH	7.3	7.8	7.8	7.3
Soil org C/%	0.4	0.7	1.2	0.5
Crop details				
Seeding/harvest	Mar 5/May 20	Mar 1/May 15 (silage)	Oct 15/May 15	Oct 28/May 12
Nutrients	N, P, K nonlimiting	N, P, K nonlimiting	N, P nonlimiting; 0, 30, 60 kg K ha^{-1}	N, P, K nonlimiting
Acquired data	5 plant top CO_2 efflux and conc. in soil air	7 plant (top and grain DM weight)	grain yield and DM at harvest	4 plant samplings and grain yield
Reference	*Bar-Tal* et al. (2008)	*Bar-Yosef* (1971)	IPI Report; *International Potash Institute* (2006)	*Yogev* et al. (1977)

3.2 Statistical analysis

Statistical analysis of the agreement between experimental and simulated results was based on correlation coefficients (r^2) of their linear regressions and the *F*-test (by analysis of variance) evaluating the significance of the regression slopes. The agreement between the predicted and experimental time functions was evaluated according to the root mean square error (RMSE) of deviations over time.

4 Results and discussion

4.1 Testing DSSAT and QPAIS under semiarid conditions

4.1.1 Growth under nonlimiting nutrient supplies

When nutrients were nonlimiting growth factors, DSSAT satisfactorily simulated corn aboveground DM in a semiarid climate as a function of time (data not presented). QPAIS predictions were not as good but still acceptable (data not presented). The predicted root DM-to-aboveground DM weight ratio varied between 0.15 on day 30 and 0.06 at harvest, compatible with available data in the literature on corn DM partitioning (*Westgate* and *Boyer*, 1985; *Davenport* and *Thomas*, 1988). According to *Rovira* and *Davey* (1974), 20%-30% of plant aboveground C was allocated to roots. This estimate is about twofold greater than the above-mentioned ratio of 0.15, indicating that, if we accept both results, then ≈50% of the allocated carbon was released to soil as C_o and CO_2. This estimate is supported by *Davenport* and *Thomas* (1988) who reported that the fraction of corn-plant C found in roots and released *via* roots to soil are practically even. A similar root-C-release percentage was used as a default value in the SCSM model.

DSSAT and QPAIS predicted wheat growth satisfactorily in a semiarid climate (Israel) under nonlimiting nutrition (data not presented). The predicted root DM-to-aboveground DM weight ratio was higher than in corn, compatible with the observation by *Davenport* and *Thomas* (1988), and it agreed with data by *Kuzyakov* and *Domanski* (2000) showing that the ratio in wheat varies between ≈0.30 (28-43 d after planting) and 0.12 (64 d after planting). The above results indicate that the fraction of total carbon production which contributes to potential soil C sequestration is greater in wheat than in corn.

The agreement between the DM predictions by DSSAT and QPAIS declined as temperature increased (not presented). At high temperature (representing an arid zone), QPAIS predicted a constant growth rate between 27 and 95 days after planting, whereas DSSAT predicted a maximum growth rate between 18 and 50 days after planting and a twofold decline thereafter, which decreased the gap in the DM weight between the two models at harvest.

4.1.2 Response to potassium fertilization

The predicted effect of K fertilization on corn and wheat DM production, kernel yield, and root mass was meaningful only when increasing the K-application rate from 0 to 100 kg K ha^{-1}; further increase to 200 kg ha^{-1} had a negligible effect (Fig. 1), which increased as temperature was elevated by 10℃ (Fig. 1C). The soil-K availability under zero K application was assigned a value representing a similar uncultivated soil. The effect of K level on the shape of the DM *vs.* time function was small (not presented). The predicted top: grain: root DM weight ratio in corn and wheat (all treatments average) were compatible with literature data for corn (*Anderson*, 1988) and for wheat (*Siddique* et al., 1990). According to predicted root weights, the corn root mass exceeded that of wheat, even though the computed fraction of C allocated to the roots was greater in wheat. The K-dose effect on wheat DM production and partitioning at elevated temperature (+10℃) and low rainfall (≈30% less in India than in Israel during January-May) was small (Fig. 1C) and properly predicted by the model. The harsh growth conditions reduced the predicted grain-to-top DM weight ratio in comparison with reference semiarid conditions, decreased the computed kernel DM yield, and increased root and canopy (the top minus grain) weight. The higher canopy weight in India in comparison with Israel stemmed from

stronger rainfall during the vegetative growth stage. The predicted final top DM weight as a function of the K dose agreed with experimental results in India, but grain yield was considerably underestimated (Fig. 1). The fact that kernels contained ≈14% moisture cannot explain this discrepancy, and it is explained in terms of underestimated C allocation to grains in the model at high temperature. The root DM was not determined in the India field experiment.

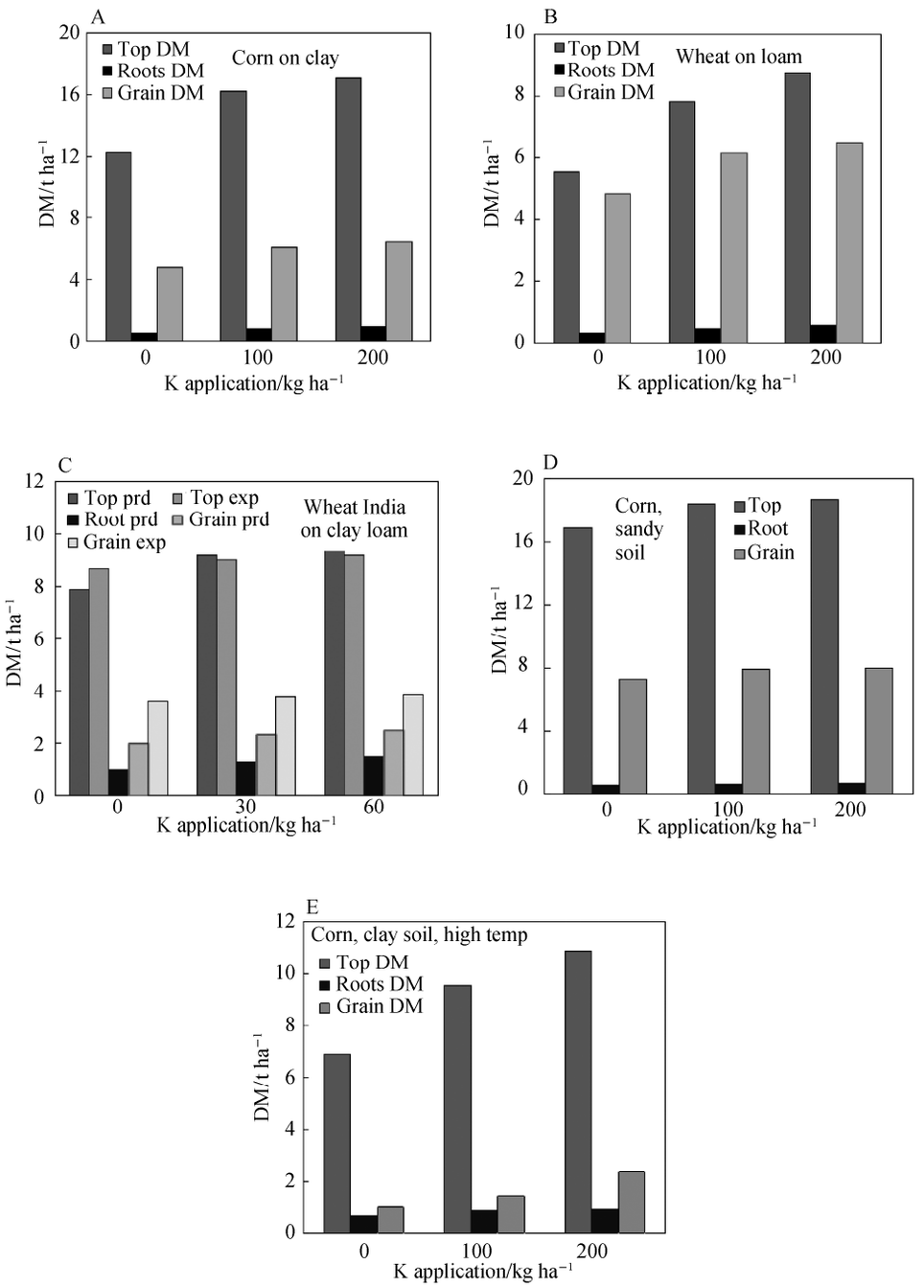

Figure 1 Simulated corn and wheat aboveground (top), root, and grain dry-matter (DM) weights at harvest by the combined DSSATQPAIS model. (A) corn on clayey soil; (B) wheat on loam soil (A and B in semiarid climate, Israel); (C) wheat on clay loam in Pantnagar, India, where temperatures were ≈10℃ higher and rainfall during grain filling was ≈30% lower than in case B (including experimental results); prd=production, exp=experimental; (D) corn on sandy soil, Israel; (E) same as case A, except that the air temperature was 10℃ higher.

A summarizing statistical analysis of the suitability of DSSAT and QPAIS to predict corn and wheat top DM weight is presented in Fig. 2. This analysis includes all of the aforementioned experimental and

DSSAT- and QPAIS-simulated results. The slopes of the regression lines (0.94±0.05 and 1.08±0.06) and their insignificant intercepts indicate very good predictions. Despite the fact that some points were outside of the 95% line of confidence limit (primarily from the India wheat experiment), the overall conclusion is that both DSSAT and QPAIS can satisfactorily simulate growth and development of wheat and corn not only in temperate climates, which was proven before, but also in semiarid and arid growth zones.

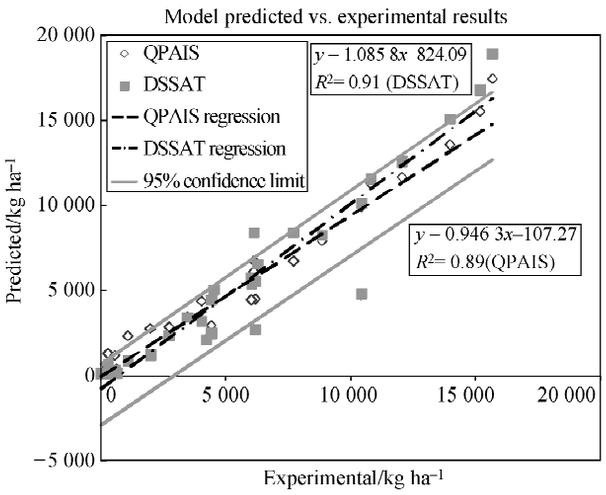

Figure 2 Simulated *vs.* experimental results of corn and wheat aboveground DM weight. Simulation by DSSAT and QPAIS; empirical results are temporal corn and wheat DM weights in Israel, and wheat DM weight at harvest in Pantnagar, India. Details and references on experimental results are given in Tab. 3. The outer lines are the 95% confidence limit, common to both models. The linear regression statistics are shown.

Model	Regression parameters						
	slope	intercept	r^2	SE (s/i)[a]	t (s/i)	p (s/i)	ttv[b]
DSSAT	1.08	−824	0.92	0.06/414	18.3/−1.5	>0.000 1/0.13	2.46
QPAIS	0.94	−107	0.93	0.05/380	17.7/0.05	>0.000 1/0.96	2.46

[a]SE=standard error, (s/i)=slope/intercept. [b]ttv=t-table threshold value

4.2 Testing SCSM

4.2.1 Sensitivity to soil factors

The effects of soil pH and solution Ca^{2+} concentration (C_{Ca}) on CO_2 efflux from soil to the atmosphere and C_i leaching and precipitation were simulated in a loamy-sand soil with sweet corn as a test crop. The model predicted that the maximum cumulative CO_2 efflux from soil occurred at pH 7.6 - 7.8, with a steep decline as the pH rose from 8 to 8.5. The effect of C_{Ca} (in the range of 5 - 50 mM) on CO_2 efflux was small at pH ≤7.9, but at pH 8.5, the efflux decreased linearly with increasing C_{Ca} (Fig. 3A). These results are compatible with simulated effects of soil pH and C_{Ca} on C_i leaching and precipitation (Fig. 3B, C). Leaching increased exponentially with elevating the pH from 7 to 8.5 due to the formation of $CaHCO_3^+$, $NaHCO_3$, and $CaCO_3$. This chemistry explains why the effect of pH on leaching increased with C_{Ca}, and why the effect of C_{Ca} increased with pH. Note that in the model, C_{Ca} and pH are input variables that do not vary with time, due to strong soil buffering capacity. The all-season cumulative C_i precipitation was insensitive to pH between 7 and 8 but steeply increased with an additional increase in pH. An increase in C_{Ca} in the range of 5 - 20 mM significantly enhanced C_i precipitation, but elevation to 30-50 mM had a small effect. At a C_{Ca} of 5 mM, $CaCO_3$ was predicted to dissolve at any pH between 7.3 and 8.5. Comparing C sequestration in soil at pH 8.4 and C_{Ca} 20 mM

stemming from deep-leaching or C_i precipitation reveals that deep-leaching contributed 3 mol C m^{-2} per season in comparison with ≈0. 1 mol C m^{-2} resulting from precipitation. At pH＜8. 3, carbonate dissolution increased CO_2 efflux from the soil thereby causing negative soil C sequestration (Fig. 3C).

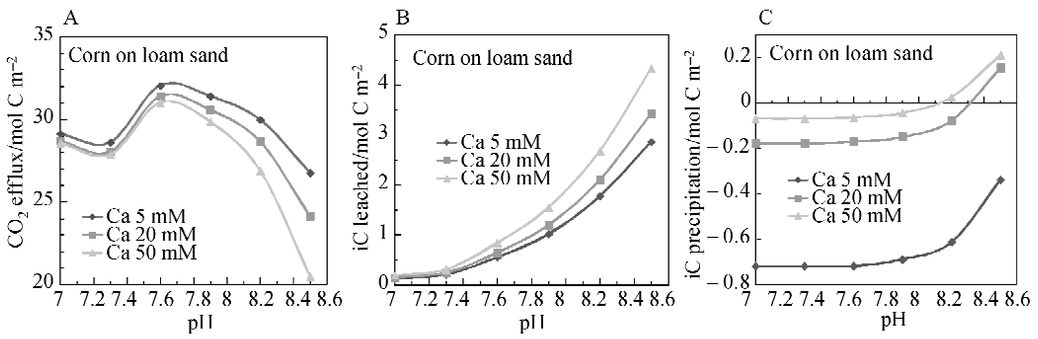

Figure 3 SCSM-simulated effects of pH and soil-solution Ca^{2+} concentration on (A) CO_2 efflux from soil to atmosphere; (B) inorganic C (C_i) leaching below 40 cm; and (C) carbonate precipitation in the 0－40 cm soil layer (negative precipitation=dissolution).

4. 2. 2 Validation

Direct validation of SCSM is tedious, as experimental data of C sequestration in soil subject to different growth conditions is scant. Therefore, the validation focused on comparing simulated and experimental CO_2 concentrations in soil air, and CO_2 outflow from soil to atmosphere under different soil organic amendments (*Bar-Tal* et al., 2008; Fig. 4). The model predicted quite closely both the CO_2 efflux and concentration in soil in a sweet corn field as a function of time and the differences in efflux and concentration between control, poultry manure-amended soil, and soil treated with corn-canopy residue. Discrepancies between empirical and simulated results (Fig. 4) are partly attributed to the fact that the experimental root-C was not determined but rather estimated from the aboveground DM as a function of time (*Bar-Tal* et al., 2008) multiplied by the time-dependent root DM-to-aboveground DM weight ratio of corn, discussed earlier.

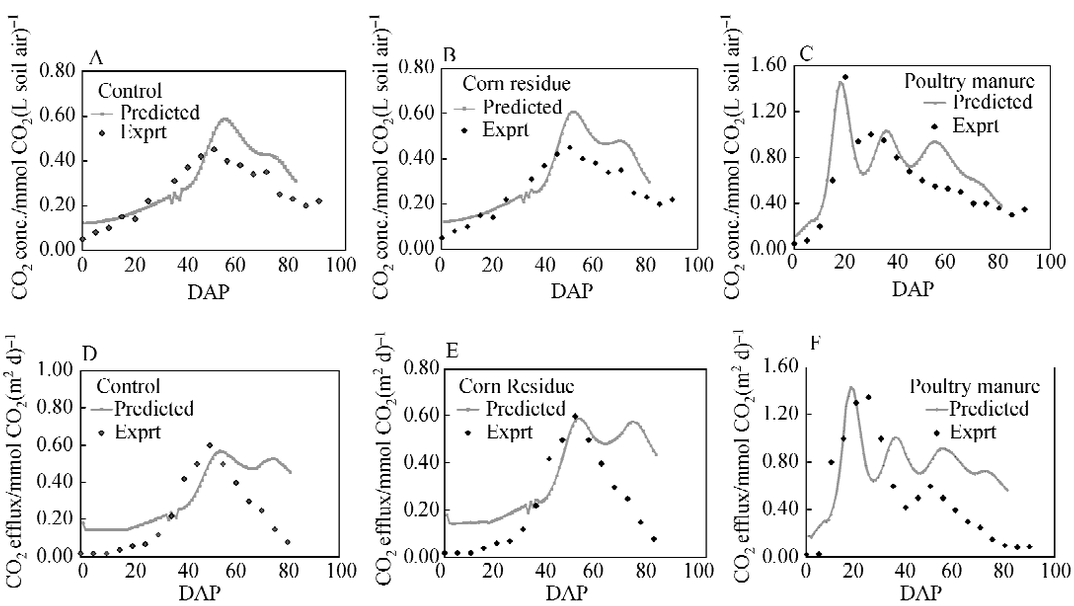

Figure 4 Experimental and simulated CO_2 concentration in soil air (A, B, C) and CO_2 efflux from soil surface (D, E, F) as a function of time after sweet corn planting and bio-solid application (A, D—control; B, E—chopped corn canopy, and C, F—pasteurized poultry manure). The experimental results (mean of 10 and 50 cm) were derived from *Bar-Tal* et al. (2008), later published by *Heller* et al. (2010).

Noting that an efflux of 1 mol CO_2 m^{-2} d^{-1} equals 500 mg CO_2-C m^{-2} h^{-1}, or 11. 6 μmol CO_2 m^{-2} s^{-1}, our highest prediction (0. 6－1. 4 mol m^{-2} d^{-1}, Fig. 4F) is compatible with the reported 300－400

mg CO_2-C m^{-2} h^{-1} peaks (*Boone* et al., 1998) or the 6－7 μmol CO_2 m^{-2} s^{-1} reported by *Khomik* et al. (2006). The overall temperature effect could not be validated due to a lack of experimental data, but the effect on organic matter-mineralization rates (*via* the Arrhenius equation [Eq. 9]) is compatible with the temperature effect on these reactions, as reported by *Evrendilek* et al. (2005), *Boone* (1998), and *Khomik* et al. (2006).

4.3 Testing the integrated model (ICSM) and its applicability

4.3.1 Scenario analysis

To warrant a proper K-fertilization range, the K-induced CO_2 sequestration was simulated alongside crop yield (Y), and only K doses resulting in yields that exceeded a given threshold yield were considered. Four scenarios analyzing K, crop, soil, and temperature effects were investigated by comparing them with a reference system consisting of corn grown in a semiarid climate (Israel) and a clayey soil (growth conditions are described in Tab. 4). Under the reference conditions, the computed Y and the gross potential C sequestration (GPCS) were ≈25% lower in the control than in the 100 kg K ha^{-1} treatment, while the potential C sequestration (PCS) was ≈50% lower. The stronger effect of K on PCS compared to GPCS resulted from the fact that potassium enhances not only the total DM production but also the C allocation to roots. The simulated actual C sequestration (ACS) was negative in both treatments (but more negative when no K was applied) because CO_2-C efflux from soil exceeded the C influx (roots + excretions + respiration) into the soil (Tab. 4). The larger efflux stemmed from microbial respiration while mineralizing the large indigenous soil organic C pool (*Lal*, 2004a). The enhanced PCS increased C_i concentrations, transport, and leaching in the soil, thus making ACS less negative with elevated K fertilization. When subtracting the control ACS from the 100 kg K ha^{-1} ACS, a positive value was obtained, and when dividing the difference by the K dose, the K-induced ACS was obtained. Under the reference growth conditions, the incremental increases in yield and ACS considerably declined as fertilization elevated from 100 to 200 kg K ha^{-1} (Tab. 2), rendering the 200 kg ha^{-1} K dose impractical. The predicted K-induced (0－100 kg K ha^{-1}) ACS significantly exceeded the CO_2 emission in industrial potash production (14.4 *vs.* the industry-reported 0.2－0.6 kg CO_2 [kg K]$^{-1}$, depending on production method and energy source; *Jenssen* and *Kongshaug*, 2003).

Table 4 Corn and wheat simulated grain yield, gross potential C sequestration (GPCS), potential C sequestration (PCS), and actual C sequestration (ACS) at three levels of K fertilization. Four case studies are presented: corn on clay soil, semiarid climate (Israel); wheat on loam (Israel); corn on sandy soil (Israel); and corn on clay soil, high temperature (India). Nutrients other than K were nonlimiting growth factors.

Variable	units K-application rate/kg ha^{-1}	Corn, clay soil Israel			Wheat, loam soil, Israel			Corn sandy soil, Israel			Corn clay soil, high temperature		
		0	100	200	0	100	200	0	100	200	0	100	200
Grain yield	t ha^{-1}	4.87	6.16	6.47	2.75	3.87	4.32	7.19	7.96	7.97	1.04	1.45	2.37
GPCS[1]	t C ha^{-1}	5.63	7.15	7.51	2.41	3.40	3.77	7.66	8.47	8.48	3.47	4.80	5.43
	t CO_2 ha^{-1}	20.64	26.22	27.54	8.84	12.48	13.82	28.08	31.07	31.10	12.71	17.60	19.93
PCS[2]	t C ha^{-1}	1.03	1.53	1.83	1.09	1.89	2.31	1.24	1.62	1.83	0.93	1.47	1.66
	t CO_2 ha^{-1}	3.78	5.61	6.71	4.00	6.95	8.47	4.54	5.95	6.70	3.40	5.38	6.08
ACS[3]	t C ha^{-1}	−0.64	−0.25	0	−1.92	−1.26	−0.88	−0.52	−0.15	−0.03	−2.69	−2.38	−2.16
	t CO_2 ha^{-1}	−0.23	−0.90	0	−7.04	−4.62	−3.24	−1.89	−0.56	−0.10	−9.86	−8.71	−7.92
K-induced ACS[4]	kg CO_2 kg^{-1} K	—	14.4	9.0	—	24.1	13.9	—	13.3	4.7	—	11.5	7.9

[1] GPCS (=gross potential C sequestration)=(total DM) × 0.46

[2] PCS (=total C added to soil by plants)=roots on last day of growth + sloughed roots + CO_2 released by roots and associated microbial respiration + root C excretions

[3] ACS (=actual C sequestration)=PCS + bio-solid added to soil − CO_2 efflux

[4] K-induced ACS per unit K (kg CO_2[kg K]$^{-1}$)=[(kg CO_2 sequestered at given K level) − (kg CO_2 sequestered at K=0)]/kg K; CO_2=C × 44/12

The second scenario, regarding crop-type effects on CO_2 sequestration, is evaluated by comparing the above reference system with wheat grown in the same climate zone (Tab. 4). The simulated GPCS and ACS were lower than in corn, but the PCS and K-induced ACS were higher. The latter result (24.1 in wheat *vs.* 14.4 kg CO_2[kg K]$^{-1}$ in corn) reflects a stronger K effect on net carbon production and allocation to roots in wheat compared with corn and the larger leaching of the C_i species under corn (not presented). The fact that wheat was simulated in loam soil (*vs.* clay soil for corn) had a secondary effect, as shown below.

The third scenario, regarding soil-type effects on DM production and CO_2 sequestration, was evaluated by comparing corn grown in sandy and in clayey soil, assuming all other factors to be identical. The shape of the simulated aboveground DM *vs.* time functions was similar in the two soils (not presented), but the final DM weight and kernel yield in all of the studied K treatments were higher in the sandy soil (Fig. 1A *vs.* 1D). The reason for these findings was that the DM-production rate in the clayey soil decreased during the last month of growth (not shown) due to a mild K stress resulting from reduced K availability in the clayey soil in comparison to the sandy soil. The lower availability also explains the fact that increasing the K dose from 100 to 200 kg K ha^{-1} caused a ≈6% increase in DM production in the clayey soil, but considerably less in the sandy soil (Fig. 1A *vs.* 1D). The K-induced ACS was higher in the clayey than the sandy soil (14.4 *vs.* 13.3 kg CO_2[kg K]$^{-1}$, respectively, when elevating K from 0 to 100 kg K ha^{-1}, and 9.0 *vs.* 4.7, respectively, when increasing K from 100 to 200 kg ha^{-1}; Tab. 4). The difference was due to stronger binding of K by clayey than sandy soil, which leads to greater responsiveness to applied K in the clayey soil and greater CO_2 efflux from the sandy soil (not presented).

The fourth scenario, regarding temperature effects on DM and CO_2 sequestration, makes a comparison between the reference weather in Israel and the hotter weather (by ≈10℃) that is characteristic of Pantnagar, India. The higher temperature caused a 35% decline in simulated corn top DM (Fig. 1A *vs.* Fig. 1E) and reduced the number of days from planting to harvest by ≈7 (not presented). The fraction of DM in roots increased with T, but the absolute root mass was nearly the same (compare Figs. 2D and 2A at K=200 kg ha^{-1}). The relative response in the root DM weight to K was unaffected by temperature. Increasing temperature resulted in more negative ACS and a 12%-20% decline in K-induced ACS, depending on the K-fertilization level (Tab. 4). Interpretation of the temperature effects is complex as temperature affects not only crop growth, water consumption, and soil water content but also microbial activity and CO_2 release by respiration.

4.3.2 Effects of uncertain parameters and assumptions

Two uncertain parameters that participate in the terms that define the role of K in DM allocation to roots (F_K) and the fraction of root carbon that is released to soil as CO_2, sugars and sloughed root C (F_{Ri}) are particularly important. The parameter F_K may increase the K-fertilizer effect on ACS by up to 20% relative to ignoring it and attributing the effect of K to DM production only. The role of K in sugar translocation is qualitatively well understood, but despite that it has not yet been used in crop modeling, and the value assigned to F_K (appendix 2) has not yet been ascertained experimentally. The F_{Ri} parameters may impose a carbon release by roots amounting to 40%-80% of root mass. Unlike F_K, these parameters could be estimated from the literature. *Marschner* (1986) reported that C excretion by corn roots amounts to 5%-7% of the total dry-matter production by the plant, and in young wheat plants 10%-25%, depending on the root environment. Root respiration was reported to be 30%-65% of all carbohydrates translocated to the roots, or 10%-50% of total photosynthesis, depending on species and growth conditions (*Andre* et al., 1978; *Lambers* et al., 1996; *Kuzyakov* and *Domanski*, 2000). Information on root senescence under field conditions is meager, but according to the global pattern of root turnover (*Gill* and *Jackson*, 2000), grassland fine roots have a sloughing rate of 53%, which increases with temperature (Q_{10}=1.6). The current F_{Ri} for respiration, excretion, and sloughing were

assigned values within the above ranges (Tab. 1) that generated the aforementioned range of carbon release from roots (40%- 80% of root mass).

Simplifying assumptions affecting model predictions neglect C_o leaching, employ a single homogenous soil layer (usually 0-40 cm), and neglect soil processes occurring below this layer. These simplifications overestimate CO_2 efflux from soil, but the error is affecting both the control and added-K treatment, and the K-induced ACS is calculated based on the difference between them.

4.3.3 Applicability assessment

At any K-fertilization level, simulated C efflux from soil exceeded the C influx to it (=negative C sequestration). This relationship stems from a sufficiently large soil-to-atmosphere CO_2-concentration gradient and soil CO_2 diffusivity, the latter being strongly dependent on soil mulching and tillage (embodied in h, Eq. 5, Tab. 1). The role of no-till in enhancing soil CO_2 sequestration has been widely discussed and confirmed in the literature (*e. g.*, *Lal*, 2004b), and tested variations in the parameter h indeed provided simulated differences in soil CO_2 sequestration that were comparable with afore-cited empirical results (not presented herein).

The ACS became less negative upon K fertilization because C_o flow into soil through roots increased and exceeded the CO_2 released from soil. Apparently, a certain site-specific soil-air CO_2 concentration exists at which the CO_2 efflux equals the C-addition rate to soil (mole C per unit-area basis), and steady-state soil C concentration is obtained. When soil air and aboveground air CO_2 concentrations are equal (*e. g.*, under soil plastic mulch), the soil C-sequestration rate equals the C-input rate (zero CO_2 efflux). The time needed to obtain CO_2 steady state, or zero efflux from soil, depends on soil, crop, management, and weather conditions.

The predicted K-induced ACS results (for Tab. 1 parameters) can be compared with scarce, indirect literature field data. According to *Schlesinger* (2000), the rate of C accumulation in arable soils transformed into forest or forage soils is ≈34 g C m^{-2} y^{-1} (=1 210 kg CO_2 ha^{-1} y^{-1}), and the estimated maximum sequestration rate is 100 g C m^{-2} y^{-1} (=3 667 kg CO_2 ha^{-1} y^{-1}). Our K-induced ACS data (Tab. 4) can be expressed per ha instead of per kg K by multiplying the latter by a conventional K dose (100 kg ha^{-1}). The transformed ACS results vary between 470 and 2 410 kg CO_2 ha^{-1} $season^{-1}$, depending on crop and experimental conditions, and averaging 1 256 kg CO_2 ha^{-1}. No simulated result exceeded 65% of the afore-mentioned maximum C-sequestration rate. *Hooker* et al. (2005) reported that after 28 y of continuous management in corn, no-till increased SOC by 60.1 g C m^{-2} y^{-1} over conservative tillage, both with residue removal. This increase is equivalent to 2 200 kg CO_2 ha^{-1} y^{-1} and is within the range of our simulated K-induced ACS, which proves that the K contribution to C sequestration is of the same order of magnitude as no-till *vs.* conventional tillage.

According to *Bolinder* et al. (1999), about 17% of corn root C is retained as SOM. The ratio in our simulations (=ACS/PCS, both expressed per kg K) can be calculated from data in Tab. 2. The results show (calculated ratios not presented) that the simulated C-retention percentage was much higher (≈ 65%), but this number includes the C_i transformed species that account for 20%- 80% of total C retention, depending on soil pH, Ca^{2+} concentration in soil solution, and bicarbonate/ carbonate adsorption capacity. Another comparison with velvet grass (*Holcus lanatus*) root-respiration data (*Lambers* et al., 1996) shows that the CO_2-respiration rate along the day varies between 45 and 90 nmol CO_2 (g DM root)$^{-1}$ s^{-1}. Assuming 860 kg DM roots ha^{-1} and 100 d growth, the above respiration rate is equivalent to 294 kg CO_2 ha^{-1} $season^{-1}$. In corn simulations under conditions defined in Tab. 4, the CO_2 released by root respiration was ≈800 kg CO_2 ha^{-1} $season^{-1}$ (data not presented). The difference between the two respiration values is expected in view of the difference between the DM productions by the two plants.

5 Conclusions

The integrated model (ICSM) is a new tool suitable for analyzing quantitatively the interrelated effects of K fertilization, soil, plant, weather, and management on soil CO_2 sequestration, and predicting crop growth and yield. The contribution of conventional K fertilization (100 kg ha^{-1} K) is predicted to be similar to the reported effect of no-till relative to conventional till on the C binding in soil (0.1 - 1 t C ha^{-1} y^{-1}; *Lal*, 2004a), the latter agro-technique being confirmed as mitigating CO_2 buildup in the atmosphere. Moreover, the predicted soil CO_2 sequestration per kg fertilizer K exceeds considerably the CO_2 emission per kg K in industrial potash production (14 - 24 *vs.* the industry-reported 0.2 - 0.6 kg CO_2[kg K]$^{-1}$). Simulated K-induced soil CO_2 sequestration could not be validated *versus* direct experimental measurements because they are not yet available, but the logical predictions merit initiating field work to test their validity. Adopting the model to P fertilization is possible, while predicting N-fertilizer effects on soil CO_2 sequestration is more tedious because N affects microbial activity and soil pH directly in addition to its effect on plant growth.

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钾肥对土壤碳固定影响的模拟

摘　要:至今,田间管理对土壤碳固定的影响研究仅局限于耕作和氮肥的施用方面。本文的目的是通过数学建模来评估钾肥施用对耕作土壤 CO_2 固定的影响。已建成的模型涵盖了 3 个子块:(1)已有的模拟器,模拟对 N、P、K 肥作响应的作物干物质生产情况,其干物质情况不分区;(2)已有的土壤-作物-大气模型,通过 N 肥而不是 K 肥的施用来预测作物产量以及分区干物质量;(3)原创模型,用于计算有机无机碳的转化、无机碳反应及在土壤中的运输、CO_2 扩散、土壤碳固定等,该模型描述了钾肥的施用对碳在土壤中固定的影响,包括土壤 pH、土壤溶液中钙离子浓度、土壤水性质、气温、作物干物质积累及分区等的特征。从黏土上生长的玉米、沙土上生长的小麦来看,根据模型计算出的施用 100 kg/hm^2 钾引起的 CO_2 固定量分别约为 14.5 kg CO_2/kg K 和 24 kg CO_2 / kg K。当玉米种植在砂土而不是黏土上,其 CO_2 固定量下降了 8%。当温度比温暖半干旱地区的通常温度增加 10℃后,CO_2 固定量会下降 20%。根据模型预测结果,施用每公斤钾肥可以固定的 CO_2 量大约是工业上生产 1 kg 钾肥排放出的 CO_2(0.6 kg/kg K)的 30 倍。

关键词:CO_2 扩散;碳酸盐;玉米;矿化;有机碳;小麦

钾对不同基因型甘蔗生长、光合特性及叶绿素荧光参数的影响①

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摘　要：采用溶液培养的方法，设置 4 个钾水平（0、0.1、3.0 和 6.0 mmol/L），研究钾对不同基因型甘蔗生长、光合特性及叶绿素荧光参数的影响。结果表明，K^+ 浓度在 0～3.0 mmol/L 范围内，不同基因型甘蔗生物量、叶绿素含量、净光合速率（*Pn*）、蒸腾速率（*Tr*）、*PS*Ⅱ最大光化学效率（*Fv/Fm*）及实际光化学效率（*ΦPS*Ⅱ）随 K^+ 浓度升高而显著增加；但在 3.0～6.0 mmol/L 时，不同基因型甘蔗间存在差异，YT55 和 BC2-32 的上述指标呈下降趋势，而 ROC22 和 YT60 的仍有所上升，但差异不显著。相关分析表明，不同基因型甘蔗的生物量与叶绿素 a 含量、*Pn*、气孔导度（*Gs*）、*Tr*、*Fv/Fm*、*ΦPS*Ⅱ和光化学猝灭系数之间极显著正相关，与非光化学猝灭系数显著正相关。总之，在一定范围内（0～3.0 mmol/L），钾能明显促进甘蔗株高、茎径和叶片生长，增加叶片叶绿素含量，增强 *PS*Ⅱ反应中心活性，提高光化学效率，极大改善叶片光合特性，从而积累较高的生物量，为高产奠定了基础。

关键词：甘蔗；钾；生物量；光合特性；叶绿素荧光

中图分类号：Q945.11；Q945.12

甘蔗是禾本科甘蔗属植物，原产于热带、亚热带地区，是我国主要经济作物之一，常年种植面积在 2 000万亩左右。甘蔗是一种高光效和喜钾的作物，光饱和点高，光合强度大，生物产量高，因此对钾的需要量大并且十分敏感，按照亩产 6.5 t 计算，种植甘蔗每年从土壤中带走的钾为 16～20 kg/亩。

钾在作物生理生化过程中有着极为重要的功能，被誉品质元素[1-2]。近年来，中国缺钾耕地面积已占耕地总面积的 56%，尤其是甘蔗主栽区砖红壤及赤红壤地区是我国最缺钾的土带。粤西是广东省最大甘蔗产区，甘蔗年种植面积 180 万亩左右，是我国甘蔗三大优势生产区域之一，虽然具有甘蔗生长得天独厚的南亚热带气候条件和土地资源，但由于长期的高温多雨，土壤中钾的淋溶流失严重，加上长期以来农民普遍存在重氮、磷轻钾肥的施肥理念，致使土壤中钾的携出大于收入，出现了严重的缺钾现象[3-5]，这已成为粤西蔗区甘蔗生产的重要限制因素。因此，有关作物钾营养与合理施钾的研究一直是植物营养与施肥研究的热点之一。钾肥用量也是决定甘蔗生长状况、产量和糖分的一个重要元素。有关氮、磷、硅、钼等对甘蔗光合特性方面的研究已有报道[6-9]，本研究则着重探讨在营养液培养条件下，不同钾水平对甘蔗拔节期生长、光合特性和叶绿素荧光参数的影响，旨在找出甘蔗拔节期生长的最适钾肥用量，为甘蔗合理施肥提供理论依据。

1　材料与方法

1.1　试验设计

试验于 2011 年 8 月至 12 月在广州甘蔗糖业研究所温室进行。以具有代表性的甘蔗基因型：新台糖 22 号（ROC22）、粤糖 60 号（YT60）、粤糖 55 号（YT50）和甘蔗斑茅杂种二代 BC2（BC2-32）为供试材料。挑选长势一致、靠近生长点的健康种茎，斩成长短一致的单芽苗，经 300～400 倍多菌灵稀释液浸泡 5～7 min后，摆放于装有河沙的育苗盘内，待第 4 片真叶完全展开后，选取生长一致的甘蔗幼苗，移栽到营养液中培养。试验设 4 个钾处理，即营养液中 K^+ 为 0、0.1、3.0、6.0 mmol/L，分别以 K0、K1、K2 和 K3

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表示，每个处理 4 个重复。K 由 KNO_3 提供。所有的处理都采用改进的 1/2 浓度 Hoagland 营养液：7.5 mmol/L N 用 NH_4NO_3、KNO_3 或 $Ca(NO_3)_2$ 提供，0.5 mmol/L P 用 KH_2PO_4 提供，3.0 mmol/L Ca 用 $Ca(NO_3)_2$、$Ca(H_2PO_4)_2$ 或 $CaCl_2$ 提供，1.0 mmol/L Mg 用 $MgSO_4$ 提供，微量营养元素分别为 46.26 μmol/L B(H_3BO_3)，20.06 μmol/LFe(EDTA-Fe)，9.15 μmol/L Mn($MnCl_2 \cdot 4H_2O$)，0.77 μmol/L Zn($ZnSO_4 \cdot 7H_2O$)，0.32 μmol/L Cu ($CuSO_4 \cdot 5H_2O$)和 0.39 μmol/L Mo($H_2MoO_4 \cdot 4H_2O$)，0.2 mmol/L Si(Na_2SiO_3)。为保证在各元素浓度一致的条件下进行单独供钾试验，为去除因 KNO_3 造成的各处理中 NO_3^- 量的不一致，用$Ca(NO_3)_2$ 调节，而 Ca^{2+} 的不一致用 $CaCl_2$ 调节。营养液用通气泵间隔 2 h 通气 30 min。所有处理的营养液 pH 值控制在 5.8～6.2，并且保持每周完全更换一次营养液。待幼苗长至拔节期时，测定株高、茎径、叶绿素含量、光合参数以及叶绿素荧光参数并采样。

1.2 测定项目及方法

1.2.1 株高、茎径及生物量的测定

用直尺测量株高、游标卡尺测定茎径。

收获时将植株分为叶、茎和根三部分，叶片和茎用湿纱布轻轻擦拭干净，根用去离子水洗净后用吸水纸吸干，所有样品经杀青(105℃，30 min)后 75℃烘至恒重，分别称重，为样品的干重(DW)。

1.2.2 叶绿素含量的测定

叶绿素的提取参照舒展等[10]方法，略有改动。以甘蔗＋2 叶的叶片为材料，鲜叶用蒸馏水洗净后用滤纸吸干揩净，除去中脉，剪碎、混匀，准确称取 0.2 g。切成长约 5 mm、宽约 1 mm 的细丝。将叶片细丝投入含 5 mL 80%丙酮的刻度试管中，封管口后于暗中振荡提取至细丝完全变为白色为止(过夜即可)。用 80% 丙酮将上述提取液稀释一定的倍数，然后将管内溶液轻轻倒入比色杯中。按照 Arnon[11]方法用上海菁华公司制造的 752 紫外可见分光光度计分别测定波长为 663 nm 和 645 nm 的吸光度。叶绿素含量即可按下列公式计算：

$$\text{叶绿素 a} = (12.7A663 - 2.69A645) \times V/(1\,000 \times W)$$

$$\text{叶绿素 b} = (22.9A645 - 4.68A663) \times V/(1\,000 \times W)$$

$$\text{叶绿素总含量} = \text{叶绿素 a 含量} + \text{叶绿素 b 含量}$$

其中 A663、A645 分别为波长 663 nm 和 645 nm 处的吸光度值；V 为提取液体积；W 为材料鲜重。

1.2.3 光合参数测定

在天气晴朗情况下，于上午 9：00—11：00，用美国 LI-COR 公司生产的 LI-6400 便携式光合系统，选用其中红蓝光源叶室测定甘蔗＋2 叶片相同部位的相关参数，每次重复 4～5 次，取平均值。测定条件为：CO_2 浓度(390±5)μmol/mol，测定光强 800 μmol/(m^2 · s)，净光合速率(Pn)、气孔导度(Gs)、胞间 CO_2 浓度(Ci)、大气 CO_2 浓度(Ca)、蒸腾速率(Tr)等光合参数由仪器自动给出。

1.2.4 叶绿素荧光参数的测定

与光合参数同时测定，采用便携式调制叶绿素荧光仪 PAM-2005(泽泉科技有限公司)。测定条件为：CO_2 浓度(390±5)μmol/mol，温度设置为 30℃。叶片暗适应 20 min 后，测定暗适应下最大荧光(Fm)、初始荧光(Fo) 以及作用光为 450 μmol/(m^2 · s) 光适应下稳态荧光(Fs)、初始荧光(Fo')、最大荧光(Fm')等荧光参数。计算 PSⅡ最大光化学效率 (Fv/Fm) = ($Fm - Fo$)/Fm，PSⅡ实际光化学效率 ($\Phi PS\,\text{Ⅱ}$) = ($Fm' - Fs$)/Fm'，光化学猝灭系数 (qP) = ($Fm' - Fs$) /($Fm' - Fo'$)，非光化学猝灭系数 (NPQ) = ($Fm - Fm'$)/Fm'。每处理选用的叶片与重复同光合参数的测定。

1.3 数据分析

所有数据均采用 DPS7.05 和 Microsoft Excel 2003 软件进行统计分析，方差分析采用 Fisher's-test (LSD)。

2 结果与分析

2.1 钾对甘蔗生长形态指标的影响

不同基因型甘蔗缺钾(0 mmol/L，K0)和低钾处理(0.1 mmol/L，K1)都出现缺钾症状，老叶叶片中

脉出现赤红色，但出现症状的时间和数量有所不同，YT55 症状出现的时间比其他基因型迟，症状较轻。这说明 YT55 耐低钾胁迫的能力更强。随着甘蔗生育进程的推进，各处理的株高、茎径及干物质都在增加，处理间差异逐渐明显。从长势情况来看，正常钾处理（3.0 mmol/L，K2）的最佳，K0 和 K1 处理的都出现症状，生长矮小，老叶白色中脉的上表皮出现赤红色，老叶干枯严重。正常钾和高钾（6.0 mmol/L，K3）处理的株高、茎径及干物质均明显优于低钾和缺钾处理。

表 1　钾对不同基因型甘蔗株高、茎径及干物质的影响

Table 1　Plant height, stalk diameter and dry weight of different sugarcane varieties in relation to potassium

项目 Items	品种（系） Genotypes (lines)	处理 Treatments			
		K0	K1	K2	K3
植株干重 Plant dry weight (g)	ROC22	25.43±2.62a	54.35±3.47b	87.70±8.13b	91.13±2.12b
	YT60	25.49±1.45a	64.68±3.45ab	93.21±3.39b	114.19±8.08a
	YT55	23.81±6.31a	67.18±4.93a	142.43±11.71a	123.49±6.03a
	BC2-32	16.07±2.21a	39.99±3.61c	98.48±10.57b	88.03±9.55b
根系干重 Root dry weight (g)	ROC22	2.99±1.10a	8.77±1.25a	9.53±0.49ab	10.54±0.75a
	YT60	2.50±0.55a	7.98±0.41a	8.31±1.00b	8.42±0.91a
	YT55	2.69±0.69a	6.93±0.38a	11.97±0.28a	7.86±1.30a
	BC2-32	2.69±0.68a	4.30±0.67b	11.04±1.66ab	9.34±0.44a
地上部干重 Shoot dry weight (g)	ROC22	22.44±2.85a	45.58±2.57b	78.17±7.79b	80.59±2.57b
	YT60	22.99±1.03a	56.70±3.18a	84.90±3.12b	105.78±7.61a
	YT55	21.12±9.76a	60.25±4.83a	130.46±11.42a	115.63±6.20a
	BC2-32	13.38±1.95a	35.69±3.17b	87.44±9.31b	78.69±9.14b
株高 Plant height (cm)	ROC22	44.50±4.17ab	60.50±2.50b	90.25±5.38a	84.25±3.07a
	YT60	50.50±2.10a	74.75±4.25a	86.00±0.58a	91.00±5.31a
	YT55	41.67±11.79ab	69.50±4.41ab	97.50±6.59a	92.50±3.66a
	BC2-32	30.25±3.07b	45.50±2.84c	66.00±3.37b	65.50±2.63b
茎径 Stalk diameter (mm)	ROC22	11.51±0.71a	13.69±0.28c	17.68±0.66a	18.87±0.43a
	YT60	11.82±0.45a	15.79±0.26a	19.73±1.12a	19.96±0.52a
	YT55	10.40±1.34a	14.95±0.32b	19.72±0.48a	19.36±0.54a
	BC2-32	8.15±0.35b	12.33±0.22d	17.83±0.97a	17.44±1.29a

注：图中字母表示 $p<0.05$ 水平显著性差异（下同）。

从表 1 看出，在 0～3.0 mmol/L 范围内，不同基因型甘蔗株高、茎径、根系干重、地上部干重和整株干重均随着钾水平的提高而增加，特别是 K2 处理，YT55 和 BC2-32 的株高、茎径、根系干重、地上部干重和整株干重均为最大值，YT55 的较 K0 处理分别增加 133.98%、89.42%、344.98%、723.61% 和 498.19%；BC2-32 的较 K0 处理分别增加 118.18%、119.75%、310.41%、553.51%和 512.82%。但当浓度超过 3.0 mmol/L 时，以上参数则随着钾水平的提高而有所下降，但差异不显著；ROC22（除株高外）和 YT60 则在 6.0 mmol/L 处理才达到最大值，ROC22 的较 K0 处理分别增加 89.33%、63.94%、252.51%、259.14%和 258.36%；YT60 的较 K0 处理分别增加 80.20%、69.49%、236.80%、360.11% 和 347.98%。可见，适量的钾水平（3.0 mmol/L）能较好地促进甘蔗根系和地上部的生长，增加株高、茎径和干物质重，为甘蔗的高产奠定基础。

不同基因型甘蔗干物质的累积量在同一钾水平处理下存在一定的基因型差异（见表 1）。极端缺钾（K0）胁迫下，各基因型差异不显著；低钾胁迫（K1）下，BC2-32 显著低于其他基因型；YT55 和 YT60 在低钾胁迫和正常供钾水平下，生物量显著高于 BC2-32，表现出较强的耐低钾胁迫能力。

2.2 钾对甘蔗生理指标的影响

2.2.1 钾对不同基因型甘蔗叶绿素含量的影响

在0～6.0 mmol/L范围内，除BC2-32叶绿素a和叶绿素(a+b)含量在K3处理较K2处理有所下降外，不同基因型甘蔗功能叶片叶绿素含量均随供钾水平的提高而增加。其中，在K3处理，ROC22、YT60和YT55叶绿素a、叶绿素b及叶绿素(a+b)的含量均为最大值，与K0处理相比达到极显著水平，ROC22的较K0处理分别增加59.81%、46.58%和56.45%，YT60的较K0处理分别增加182.49%、127.48%和166.77%，YT55的较K0处理分别增加141.23%、88.46%和126.17%。BC2-32叶绿素a和叶绿素(a+b)含量在K2处理达到最大值，较K0处理分别增加297.71%和245.91%，叶绿素b在K3处理达到最大值，较K0处理增加170.32%（见表2）。

同一钾水平处理下，不同基因型甘蔗叶片叶绿素a和叶绿素(a+b)的含量存在一定差异（见表2）。K2处理下，BC2-32的叶绿素a和叶绿素(a+b)含量均显著高于ROC22，而在K0处理，却显著低于ROC22，说明缺钾严重伤害BC2-32叶片叶绿体结构。其他处理下基因型间没有显著性差异。可见，营养液中钾含量为3.0 mmol/L或6.0 mmol/L时有利于甘蔗叶片光合色素的形成，使甘蔗叶片光合作用能力增强。

表2 钾对不同基因型甘蔗叶绿素含量的影响

Table 2 Effects of potassium stress on chlorophyll content of different sugarcane varieties

项目 Items	品种(系) Genotypes (lines)	处理 Treatments			
		K0	K1	K2	K3
叶绿素a chl. a (mg/g FW)	ROC22	2.14±0.36a	2.68±0.10a	2.84±0.24b	3.42±0.10a
	YT60	1.25±0.31ab	2.67±0.24a	3.29±0.13ab	3.52±0.09a
	YT55	1.39±0.53ab	2.77±0.26a	3.34±0.16ab	3.36±0.04a
	BC2-32	0.86±0.11b	2.52±0.19a	3.43±0.14a	3.28±0.11a
叶绿素b chl. b (mg/g FW)	ROC22	0.73±0.10a	0.89±0.03a	0.92±0.06a	1.07±0.04a
	YT60	0.50±0.10a	0.91±0.08a	1.06±0.05a	1.13±0.04a
	YT55	0.56±0.14a	0.91±0.07a	1.02±0.04a	1.05±0.01a
	BC2-32	0.41±0.02a	0.87±0.06a	0.97±0.08a	1.11±0.05a
叶绿素a+b chl. a+b (mg/g FW)	ROC22	2.87±0.46a	3.57±0.12a	3.76±0.31b	4.49±0.14a
	YT60	1.74±0.42ab	3.57±0.32a	4.35±0.18ab	4.65±0.13a
	YT55	1.95±0.67ab	3.69±0.33a	4.36±0.20ab	4.41±0.05a
	BC2-32	1.27±0.13b	3.38±0.25a	4.40±0.17a	4.39±0.10a

2.2.2 钾对不同基因型甘蔗光合特性的影响

从表3可知，在0和0.1 mmol/L(K0和K1)处理下，不同基因型甘蔗叶片净光合速率(*Pn*)、气孔导度(*Gs*)和蒸腾速率(*Tr*)较3.0 mmol/L和6.0 mmol/L(K2和K3)处理显著下降，说明营养液3.0 mmol/L或6.0 mmol/L的K^+浓度较有利于水培甘蔗光合产物的积累。胞间CO_2浓度(*Ci*)的变化则表现出一定的差异。在0～3.0 mmol/L范围内，ROC22、YT60和YT55的*Ci*随着钾浓度的下降表现为先下降后上升的趋势，而BC2-32则一直升高，说明不同基因型甘蔗对低钾胁迫的响应机制有所不同。前人的研究认为叶片气孔导度的减少及RuBP酶活性的降低是造成低钾胁迫下植物叶片光合能力下降的最主要原因。这表明了在低钾处理下，ROC22、YT60和YT55叶片有可能通过*Gs*的减小进而降低*Ci*，从而导致光合速率的下降。然而在K0处理，伴随着*Pn*、*Gs*和*Tr*的下降，*Ci*却呈现出增高的趋势，说明缺钾导致水培甘蔗*Pn*、*Gs*和*Tr*的降低，但净光合速率的下降主要不是由气孔因素引起的。

表3表明，在同一钾水平处理下，不同基因型甘蔗光合特性有一定的差异。BC2-32叶片的*Pn*无论在哪个钾水平处理下都低于其他基因型，在K0和K1处理达显著水平，其他基因型间无显著差异。BC2-32叶片的*Gs*和*Tr*在0～3.0 mmol/L钾处理范围内低于其他基因型。说明在水培条件下，BC2-32光合能力较弱，而ROC22、YT60和YT55光合能力较强，初步解释了水培条件下不同基因型甘蔗干物质累积量存在差异的原因。

表 3　钾对不同基因型甘蔗光合参数的影响

Table 3　Effects of potassium on photosynthetic parameters of different sugarcane varieties

项目 Items	品种(系) Genotypes (lines)	处理 Treatments			
		K0	K1	K2	K3
净光合速率 Net photosynthetic rate [μmol/(m² · s)]	ROC22	14.11±0.91a	19.39±1.94a	24.02±0.68a	24.96±1.23a
	YT60	11.86±0.96a	15.19±1.19ab	24.93±1.32a	25.26±0.82a
	YT55	11.18±2.52ab	18.65±1.60a	25.98±1.18a	23.38±2.52a
	BC2-32	7.23±1.15b	11.98±0.79b	23.36±1.32a	22.49±1.78a
气孔导度 Stomatal conductance [mol H_2O/(m² · s)]	ROC22	0.12±0.01a	0.15±0.02a	0.20±0.01a	0.16±0.04a
	YT60	0.12±0.02a	0.11±0.01a	0.20±0.02a	0.19±0.03a
	YT55	0.12±0.02a	0.13±0.03a	0.24±0.02a	0.22±0.03a
	BC2-32	0.06±0.01b	0.11±0.00a	0.20±0.02a	0.22±0.02a
胞间 CO_2 浓度 Intercellular CO_2 content (μmol CO_2/mol)	ROC22	182.05±5.26b	125.93±21.36a	129.51±6.03a	125.40±7.19b
	YT60	191.20±12.12ab	116.02±9.49a	127.55±3.79a	136.60±5.57b
	YT55	218.49±13.61a	105.44±26.99a	150.82±8.25a	206.16±32.26a
	BC2-32	181.27±6.66b	164.00±19.90a	135.10±16.67a	175.69±13.44ab
蒸腾速率 Transpiration rate [mmol H_2O/(m² · s)]	ROC22	3.18±0.11a	3.52±0.29a	4.28±0.19a	4.18±0.30b
	YT60	2.92±0.35a	2.88±0.19ab	4.40±0.30a	4.65±0.17b
	YT55	2.97±0.45a	3.39±0.36ab	5.01±0.28a	5.02±0.38a
	BC2-32	1.59±0.19b	2.66±0.08a	4.29±0.40a	4.78±0.33ab

2.2.3　钾对不同基因型甘蔗叶绿素荧光参数的影响

为了进一步探讨低钾胁迫下光合能力下降的内部原因和光合防御机制，我们测定了叶绿素荧光参数。表 4 显示在正常供钾条件下不同基因型甘蔗 *PS*Ⅱ最大光化学效率(*Fv/Fm*)的值保持较高的水平(约 0.77)。而在 K0 处理下，YT60 和 BC2-32 较 K3 处理显著降低，分别降低 27.27%和 19.23%，表明缺钾胁迫下 YT60 和 BC2-32 叶片 *PS*Ⅱ反应中心受到破坏，最大光能转化效率降低，可用于光合碳同化的能量不如正常供钾植株充足。YT55 的 *Fv/Fm* 在低钾胁迫下没有显著下降，其 *PS*Ⅱ反应中心的破坏程度较轻，进一步表明了 YT55 耐低钾胁迫的能力较强。

由表 4 可以看出，*PS*Ⅱ实际光化学效率(*ΦPS*Ⅱ)和光化学猝灭系数(*qP*)的变化在不同基因型甘蔗中表现不同，ROC22 和 YT55 各处理间没有显著差异，而 YT60 和 BC2-32 则随着钾水平的升高而增加，YT60 的 K3 处理较 K0 处理分别增加 128.57%和 42.11%，BC2-32 的 K3 处理较 K0 处理分别增加 125.00%和 77.78%，差异达到显著或极显著水平。说明适当提高钾浓度，有利于 YT60 和 BC2-32 叶片将捕获的激发能转换为光化学反应，从而有利于叶片实际光化学效率的提高。

从表 4 可知，与正常供钾相比，钾胁迫条件下，YT55 的非光化学猝灭系数(*NPQ*)没有明显的变化，这样可以维持有较多的光能通过热耗散逸散，有效地避免或减轻因 *PS*Ⅱ吸收过多光能而引起的光抑制和光氧化，从而保护 *PS*Ⅱ，使之免受或减轻光抑制和光破坏的作用，而 BC2-32 较 K3 处理却显著下降，说明在低钾胁迫下，BC2-32 叶片捕获的光能中，过多的光能无法通过非辐射能量的耗散，导致光合器官严重受损，光合效率较低。

表 4　钾对不同基因型甘蔗叶绿素荧光参数的影响

Table 4　Effects of potassium on chlorophyll fluorescence parameters in leaf of different sugarcane varieties

项目 Items	品种(系) Genotypes (lines)	处理 Treatments			
		K0	K1	K2	K3
Fv/Fm	ROC22	0.727±0.010a	0.761±0.001a	0.770±0.004a	0.779±0.006a
	YT60	0.556±0.105a	0.634±0.049a	0.726±0.008b	0.773±0.001a
	YT55	0.722±0.036a	0.706±0.056a	0.760±0.006a	0.765±0.023a
	BC2-32	0.635±0.032a	0.566±0.096a	0.765±0.003a	0.784±0.001a

续 表

项目 Items	品种(系) Genotypes (lines)	处理 Treatments K0	K1	K2	K3
ΦPSⅡ	ROC22	0.136±0.004a	0.136±0.007a	0.160±0.001a	0.136±0.011a
	YT60	0.072±0.016b	0.131±0.003a	0.141±0.007ab	0.162±0.015a
	YT55	0.128±0.017a	0.140±0.015a	0.146±0.008ab	0.162±0.017a
	BC2-32	0.082±0.004b	0.075±0.013b	0.132±0.007b	0.184±0.031a
qP	ROC22	0.248±0.010a	0.246±0.014ab	0.281±0.004a	0.237±0.021a
	YT60	0.189±0.024b	0.282±0.031a	0.254±0.007ab	0.268±0.022a
	YT55	0.225±0.016ab	0.265±0.027a	0.245±0.015b	0.270±0.026a
	BC2-32	0.180±0.006b	0.183±0.012b	0.236±0.010b	0.317±0.051a
NPQ	ROC22	1.23±0.15a	1.57±0.04a	1.55±0.02a	1.62±0.03a
	YT60	1.06±0.07a	0.93±0.08b	1.14±0.09b	1.25±0.05b
	YT55	1.05±0.13a	1.14±0.06b	1.14±0.05b	1.19±0.12b
	BC2-32	1.08±0.07a	0.90±0.22b	1.59±0.06a	1.63±0.03a

2.3 甘蔗生物量、叶绿素含量、光合参数以及叶绿素荧光参数的相关分析

不同基因型甘蔗植株干重与叶绿素 a 含量(Chl. a)、光合参数和叶绿素荧光参数之间相关系数列于表5。植株整株干重与叶片 Chl. a、*Pn*、*Gs*、*Tr*、*Fv/Fm*、*ΦPS*Ⅱ和 *qP* 之间极显著正相关,与 *NPQ* 显著正相关。叶绿素 a 除与 *Ci* 成极显著负相关外,与其他之间均存在极显著正相关关系。表明随着钾浓度的适当提高,叶绿素 a 含量升高,叶片捕获的能量增加,用于光化学反应的比例相应增大,光合作用增强,因此光合产物的累积量就增大。另外,光合参数之间,除 *Ci* 与 *Pn* 成极显著负相关,与 *Gs* 和 *Tr* 之间不存在显著相关外,其他参数之间均存在极显著正相关关系。叶绿素荧光参数之间,除 *qP* 与 *Fv/Fm* 成显著正相关,与 *NPQ* 相关不显著外,其他参数间极显著正相关。

表 5 甘蔗生物量、叶绿素含量、光合参数以及叶绿素荧光参数的相关分析

Table 5 Correlation analysis among sugarcane dry weight, chlorophyll content, photosynthetic and chlorophyll fluorescence parameters

	Chl. a	*Pn*	*DW*	*Gs*	*Ci*	*Tr*	*Fv/Fm*	*ΦPS*Ⅱ	*NPQ*	*qP*
Chl. a	1									
Pn	0.780**	1								
DW	0.775**	0.815**	1							
Gs	0.645**	0.821**	0.742**	1						
Ci	−0.343**	−0.368**	−0.222	−0.018	1					
Tr	0.696**	0.901**	0.796**	0.928**	−0.049	1				
Fv/Fm	0.517**	0.554**	0.454**	0.447**	−0.188	0.490**	1			
*ΦPS*Ⅱ	0.589**	0.638**	0.545**	0.507**	−0.239	0.600**	0.684**	1		
NPQ	0.390**	0.424**	0.293*	0.275*	−0.239	0.305*	0.545**	0.414**	1	
qP	0.433**	0.459**	0.386**	0.321*	−0.267*	0.421**	0.190	0.826**	0.272*	1

注(Note):样本数为 48,* 表示显著相关,** 表示极显著相关。

3 讨论

叶绿素作为光合色素,参与光合作用中光能的吸收、传递和转化,在植物光合作用中起着关键性的作用。本研究表明,缺钾和低钾(0 和 0.1 mmol/L)胁迫显著降低了不同基因型甘蔗叶绿素 a、b 和 a+b 含量,叶绿素 a 的含量下降幅度远大于叶绿素 b,可见叶片中叶绿素的下降主要是由于叶绿素 a 含量的下降引起的,而叶绿素 a 被称为天线色素,是吸收光能的主要色素,其含量的降低势必影响到叶片对光能的捕获。大豆受铝毒胁迫时也发现叶绿素含量降低,且叶绿素 a 的下降幅度大于叶绿素 b[12]。这种叶绿素含

量的降低是由于叶绿素降解加强造成的，还是由于合成叶绿素原初物质减少而导致的，有待进一步研究。

引起 *Pn* 下降的原因主要分为两类：一类为气孔因子，主要受气孔数量、气孔孔径、气孔开度等的影响；因为气孔是 CO_2 进入叶片胞内的途径，K^+ 能调节其开闭，所以钾营养对叶片气孔导度的影响很大，从而影响光合作用。另一类为非气孔因子，主要受内部的酶活力和光合组分控制[13]。本试验结果表明，缺钾和低钾胁迫下，不同基因型甘蔗 *Pn* 都明显降低，一方面是由于气孔导度减小限制了气体与水分的内外交换；另一方面，叶绿素 a 含量的显著降低也减小了叶片对光能捕获的机会；此外，反应中心捕获的光能被耗散的比例增加，而用于传递的能量减少，说明光合电子传递过程也在钾胁迫下遭到一定程度的破坏，由此可见，缺钾和低钾胁迫对不同基因型甘蔗光合效率的影响是多方面的。许大全[14]研究认为当 *Pn* 和 *Gs* 持续降低时，根据 *Ci* 变化方向可判断光合速率降低是受气孔限制还是受非气孔限制，即当 *Pn*、*Gs* 和 *Ci* 浓度均呈下降趋势时，*Pn* 降低可归结为受气孔限制；而当 *Pn* 和 *Gs* 持续下降，其 *Ci* 却呈增加趋势时，则归结为受非气孔限制。试验中在低钾处理下，三者变化趋势一致，因此，可以认为气孔限制是导致光合速率下降的一个原因；而在缺钾条件下，*Pn*、*Gs* 和 *Tr* 都显著低于其他处理，*Ci* 却高于其他处理，说明气孔因子并非 *Pn* 下降的主导因子。乔建磊等[15]研究结果也表明，在低钾胁迫的初期，叶片 *Pn* 的下降主要是由气孔限制引起，但随着胁迫时间的进一步延长，非气孔限制也逐渐成为净光合速率下降的主要原因。

由于具有快速、灵敏和非破坏性等优点，叶绿素荧光技术已经广泛应用于植物光合生理状况及各种外界因子对其细微影响的研究[16]。研究表明，营养胁迫对植物荧光参数的影响是十分明显的，缺钾胁迫下，水稻叶片升高 *Fo*，*Fv* /*Fm* 显著降低[17]。初始荧光 *Fo* 增加表明 *PS* Ⅱ反应中心出现可逆的失活或出现不易逆转的破坏，也可能是植物叶片类囊体膜受到损伤。本研究结果表明，在缺钾和低钾胁迫下 *Fo* 显著增加，说明其 *PS* Ⅱ反应中心受到严重的破坏，类囊体膜受损严重，这是阻碍光合电子传递的一个重要因素。而 *Fv* /*Fm*、*ΦPS* Ⅱ却显著降低，说明其 *PS* Ⅱ反应中心结构与功能受到不同程度的损伤与破坏，反应中心活性降低，原初光能转化效率减小，这对于叶绿体把光能转化为化学能极为不利，反应中心吸收的光能被耗散掉的比例增加，用于电子传递的能量则显著减少，导致光合速率降低。同时，光合速率下降可能还与 Rubisco 及光合机构其他组分一起降解的过程有关[18]，且翁晓燕和毛伟华[19]的研究表明 Rubisco 活化酶和 Rubisco 活性与 *Pn* 显著相关。

本试验结果显示甘蔗植株干重与叶绿素 a 含量、*Pn*、*Gs*、*Tr*、*Fv*/*Fm*、*ΦPS* Ⅱ和 *qP* 之间极显著正相关，与 *NPQ* 显著正相关，与相关研究结果一致[20-22]。陈昆等[23]研究表明，营养液中 K^+ 为 6.0 mmol/L 时能较好地促进大蒜苗期假茎粗度的增加，使植株生长健壮；还可以增加叶片叶绿素含量、光合速率、蒸腾速率和气孔导度；对烟草的研究表明，施钾通过增加叶片气孔开度、提高蒸腾速率，从而提高光合速率，此外，蒸腾速率的提高可以促进烟株整体的物质运输和代谢，促进植株生长，并最终获得较高的干物质积累[24]。

综上可知：本试验条件下，营养液 K^+ 浓度为 3.0 mmol/L 时，设施水培不同基因型甘蔗拔节期茎径和叶片健壮，株高较高，生长最佳，叶绿素含量、净光合速率以及生物量较高，为后期高产奠定了基础。

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Effects of potassium on growth, photosynthetic and chlorophyll fluorescence parameters of different sugarcane varieties

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Abstract: A hydroponic experiment was conducted to investigate the effects of potassium on growth, photosynthetic characteristics and chlorophyll fluorescence parameters of different sugarcane varieties. There were four different K^+ contents, 0, 0.1, 3.0 and 6.0 mmol/L, in the experiment. The results indicated that in the range of 0 - 3.0 mmol /L, the biomass, chlorophyll content, net photosynthetic rate (Pn), transpiration rate (Tr), PSⅡ maximum photochemical efficiency (Fv/Fm), and PSⅡ actual photochemical efficiency (ΦPSⅡ) were significantly increased with increasing concentration of K^+. However, there were genotypic differences in the change of above index with the increasing of K^+ between 3.0 - 6.0 mmol/L. The above index of Yuetang 55 and BC2-32 were decreased, while ROC22 and Yuetang 60 were just the opposite. Correlation analysis showed that the biomass of different sugarcane varieties was positively correlated with chlorophyll content, Pn, stomatal conductance (Gs), Tr, Fv/Fm, ΦPSⅡ and photochemical quenching coefficients (qP) at $p < 0.01$ level, and with non-photochemical quenching coefficients (NPQ) at $p < 0.05$ level, respectively. In conclusion, potassium could promote the growth of sugarcane stem, stalk diameter and leaves, chlorophyll content, photosynthetic characteristics, and improve the accumulation of sugarcane biomass at the elongation stage, which lays the foundation for sugarcane high yield. And the best promotion effect is under 3.0 mmol/L K^+ concentration.

Key words: Sugarcane, potassium, biomass, photosynthetic characteristics, chlorophyll fluorescence

Assessment of economic and environmental impacts of two typical cotton genotypes with contrasting potassium efficiency §

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Abstract: It is essential to produce optimal crop yields while reducing adverse environmental impacts of over fertilization. Therefore, nutrient-efficient plants may play a major role in improving the efficiency of fertilizer use whilst increasing crop yields. This field trial was conducted to study the differences on absorption and utilization of nitrogen (N), phosphorus (P), and potassium (K) of K-efficient cotton genotype 103 and K-inefficient cotton (*Gossypium hirsutum L.*) genotype 122 and their environmental and economic effects. The results show that seed cotton yield was significantly different between K-efficient cotton genotype 103 and K-inefficient cotton genotype 122; the yields of genotype 103 were 39.2%, 33.8%, and 25.0% higher than those of genotype 122 with no K fertilizer (K0), 112 kg K ha^{-1} K (K1), and 224 kg K ha^{-1}(K2), respectively. Even when no K fertilizer was applied, the yield of genotype 103 was still 7.9% higher than the yield of genotype 122 at the highest K level (K2). Further economic benefit analysis revealed that the value cost ratio (VCR) of genotype 103 was significantly higher than 122 at K0 and K1, and harvest index (HI) of genotype 103 was significantly higher than that of genotype 122 at all three K levels. In addition, when fertilized with K, partial factor productivity of applied K (PFP_K) of genotype 103 was dramatically higher than that of genotype 122, demonstrating that genotype 103 had stronger ability to utilize K. Besides, the N- and P-use efficiencies of genotype 103 were also higher than those of genotype 122. It is concluded that: (1) genotype 103 gives better profit than genotype 122 and (2) genotype 103 uses fertilizer more efficiently and reduced fertilizer inputs will alleviate environmental risks.

Key words: economics/environment/field trial/Gossypium hirsutum/potassium fertilizer

1 Introduction

Potassium (K) plays important roles during plant growth. It is widely accepted that K can activate enzymes of plants, increase photosynthesis, and promote translocation of photosynthates (*Marschner*, 2012), In addition, the International Potash Institute reviewed more than 2 000 studies and found that 70% and 69% of them reported beneficial effects of K against fungal and bacterial diseases, respectively, and 63% found benefits against insects and mite infections (*Amtmann* et al., 2008). In 1998, scientists from the International Plant Nutrition Institute summarized the reasons why K can increase crop yields, which included increased root growth and improved drought resistance, it activates many enzyme systems, it helps to maintain turgor, and it reduces water loss and wilting.

The earth's crust contains around 2.6% K, but K deficiency is prevalent in large areas of agricultural land in the world (*Alemán* et al., 2011) because the majority of K is dehydrated and coordinated to oxygen atoms in soils and is not available to plants. Typical concentrations in the soil solution vary between 0.1 and 1 mM K. Plant growth is usually stimulated by additional supplying K, and potash fertilization is common practice in many crop producing areas (*Maathuis*, 2009). Global K consumption has increased 4.4% per year from 1999 to 2005 (*Alemán* et al., 2011), and the amount of potash consumption was increased every year in the last decade.

To improve yield, the amount of mineral-fertilizer input in agriculture has been increased year by year. In China, the total crop-planting area increased by 7.0% from 1978 to 2010, but the fertilizer rate

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has increased 5.3 fold, while the total grain output only increased by 80% (*China National Bureau of Statistics*, 2011). Zhang et al. (2008) analyzed 1 333 experimental sites in the key irrigated grain-producing areas of China, and found that the average nutrient efficiencies (kg nutrient taken up per kg nutrient applied) of major cereal crops were 27.5% for N, 11.6% for P, and 31.3% for K, which was far below the global levels. This might be due to excessive nutrient supply to soils (*Zhu and Chen*, 2002), which can cause serious environment risk and ecological disruption (*Sharpley* et al., 1987; *Vitousek* et al., 1997; *Tilman* et al., 2001; *Beebe* et al., 1997; *Galloway and Cowling*, 2002).

To coordinate agricultural development with environment protection, one important approach is to screen and use nutrient-efficient crop genotypes (*Lynch*, 1998). The purpose of screening nutrient-efficient genotypes is to increase production under poor nutrient conditions (*Beebe* et al., 1997). As for K-efficient germplasm resources, much work has been done recently (*Brouder and Cassman*, 1990; *George* et al.,2002; *Tian* et al., 2008; *Wang and Chen*, 2012). However, the relationship between K efficiency of crops and its environmental and economic effects is often ignored, especially for cotton, which does require a great amount of nutrients to maintain its growth and development.

The objectives of this work, using two typical cotton (*Gossypium hirsutum L.*) genotypes, K-efficient genotype 103 and K-inefficient genotype 122, were to study: (1) the difference in utilization of nitrogen (N) and phosphorus (P) between these two cotton genotypes differing in K efficiency and (2) the economic and environmental effects of the two cotton genotypes.

2 Material and methods

2.1 Cotton varieties

Two cotton (Gossypium hirsutum L.) genotypes were used, K-efficient genotype 103 and K-inefficient genotype 122. These genotypes were selected from 86 cotton genotypes from four different groups including Stoneville, King, Coker and Deltapine (*Jiang* et al., 2005). A number of studies have been carried out on these two genotypes in this laboratory since 2001, including the pattern of absorption and distribution of K (*Xia* et al., 2011; *Jiang* et al., 2008), root morphology (*Hao* et al., 2011) and physiological indicators related to the absorption and utilization of potassium (*Jiang* et al., 2007, 2013). The cotton genotypes were provided by the Cotton Research Institute, Chinese Academy of Agricultural Sciences, and Huazhong Agricultural University, Wuhan, Hubei province, China.

2.2 Experimental site and basic soil physiochemical properties

A field experiment was conducted at Datonghu Farm, Hubei province, China (latitude 29°55′- 30°08′N, longitude 113°34′- 113°49′E). During cotton growth season in 2010, this region's average temperature was 24.1℃. The monthly temperature were 21.5℃ (11.8℃- 33.2℃) in May, 25.2℃ (16.4℃- 35.2℃) in June, 28.5℃ (22.9℃- 35.2℃) in July, 28.6℃ (19.8℃- 38.1℃) in August, 24.1℃ (13.8℃- 36.2℃) in September, and 16.7℃ (3.5℃- 27.9℃) in October. The total rainfall was 939.2 mm during the growth season. The field basic soil physiochemical properties were as follows: pH (soil-to-H_2O ratio=1∶2.5)∶8.2, organic matter: 17.5 g kg^{-1}, alkali-hydrolyzable N: 38.5 mg kg^{-1}, Olsen P: 4.01 mg kg^{-1}, and 1 M NH_4OAC-extractable K: 171.7 mg kg^{-1}.

2.3 Experimental design and plant management

Three K levels were applied: no K fertilizer (K0), 112 kg Kha^{-1}(K1), and 224 kg K ha^{-1}(K2) factorially on the two genotypes, and abbreviated as follows: 103K0; 103K1; 103K2; 122K0; 122K1; 122K2. All these treatments were applied with equal amounts of N and P fertilizers with 300 kg N ha^{-1} and 39 kg P ha^{-1}. The fertilizers used in this experiment were urea (N 46%), diammonium phosphate (15-42-0), potassium chloride (K_2O 60%). Nitrogen was applied four times during the growth season: split 45% at sowing, 10% at seedling stage, 30% at flowering stage, and 15% at bolling stage; P was applied as DAP at sowing; K was applied two times: 60% at sowing and 40% at flowering stage. Each

treatment had four replications, and they were randomly arranged with a size of 20 m^2. The field management was conducted according to conventional agronomic practices. Cotton seedlings were planted in the nursery on April 4, and then the seedlings were transplanted to the field on May 8. Yield of cotton from each plot was recorded respectively before the October 11, 2010.

2.4 Plant and soil analyses

The plant samples were separated into roots, main stem, branches, boll shells and leaves. Then the samples were dried at 60℃ for at least 72 h. The dry weight of each part of the cotton was measured. Samples were ground, a 0.15 g subsample was weighed, and this was digested by addition of H_2SO_4—H_2O_2. N and P concentrations were measured using a flow injection analyzer (Sweden FIAstar 5 000) and K with a flame spectrophotometer (FP 640, Shanghai Precision & Scientific Instrument Co.).

Soil samples were collected from the field, plant debris and stones were removed, then the soil was air-dried and ground through 0.84 mm and 0.15 mm sieves. The following determinations were made according to *Bao* (2000). Soil pH was measured using a 1∶2.5 soil-to-water ratio with a FiveEasy 20 pH electrode, organic matter was measured by potassium dichromate titration, alkali-hydrolyzable nitrogen was measured by 1/2 H_2SO_4 titration, Olsen-P was measured after 0.5 M $NaHCO_3$ extraction with Mo-Sb colorimetry, and available K was measured after 1M NH_4OAC extraction and using a flame photometer.

2.5 Parameter calculation and Statistical Analyses

The following parameters were calculated:

(1) Value cost ratio (VCR)=yield of seed cotton × price of seed cotton/fertilizer inputs. The price of seed cotton used was 1.465 $ kg^{-1}, urea price 0.264 $ kg^{-1}, diammonium phosphate 0.417 $ kg^{-1}, and potassium chloride 0.366 $ kg^{-1}.

(2) Harvest index (HI)=(yield of seed cotton/total biomass) × 100%

(3) Partial factor productivity of applied potassium (PFP_K)=yield of seed cotton / application amounts of potassium fertilizer.

(4) Partial factor productivity of applied nitrogen (PFP_N)=yield of seed cotton/ application amounts of nitrogen fertilizer.

(5) Partial factor productivity of applied phosphorus (PFP_P)=yield of seed cotton/ application amounts of phosphorus fertilizer.

Statistical analysis and figure development were performed using SAS software (least significant difference, LSD at $p<5\%$; t test, $p<5\%$) and Originpro 8.5 (OriginLab Corporation, USA).

3 Results

3.1 Effects of potassium application on dry matter production and its distribution in two cotton genotypes

Table 1 Yields of various organs of two cotton genotypes under different K treatments. Values within columns followed by the same letter are not different at $p<5\%$ by LSD.

Treatments	Dry weight(kg ha^{-1})						
	Root	Main stem	Branch	Leaf	Bell shell	Seed cotton	Total
103K0	600c	1 175c	921bc	NL§	530ab	1 845abc	5 071bc
103K1	760abc	1 649ab	1 439a	NL	661a	2 064ab	6 573a
103K2	846ab	1 925a	1 665a	NL	687a	2 138a	7 261a
122K0	710bc	1 307bc	730c	391a	239c	1 325d	4 702c
122K1	888a	1 618ab	988bc	583a	319bc	1 543cd	5 939abc
122K2	906a	1 586ab	1 090b	711a	394bc	1 710bc	6 397ab

§ NL: there were no leaves left when cotton was harvested.

With the increasing amount of K, the total dry weight increased in every part of cotton (Tab. 1).

Compared to K0, seed cotton yields of genotype 103 were increased by 219 kg ha^{-1}, and 293 kg ha^{-1}, equivalent to 11.9% and 15.9%. Genotype 122 was increased by 218 kg ha^{-1} and 385 kg ha^{-1} at K1 and K2 levels, equivalent to 16.4% and 29.0%. When these two genotypes were treated with the same amount of K fertilizer, genotype 103 had relatively lower root dry weight, while the dry weights of branch, bell shell, seed cotton and the whole plant were higher than those of genotype 122. The yields of the bell shell for genotype 103 were 2.2, 2.1, and 1.7 times higher than those of genotype 122 at the three K levels, and the yields of seed cotton for genotype 103 were 39.2%, 33.8%, and 25.0% greater than those of genotype 122 at K0, K1, and K2 respectively. In addition, the whole plant dry weight of 103 was higher than 122 at each K level.

Table 2 Effect of different K treatments on the distribution of dry matter production of two cotton genotypes at harvest. Values within columns followed by the same letter are not different at $p < 5\%$ by LSD.

Treatments	Distribution of dry matter production (%)					
	Root	Main stem	Branch	Leaf	Bell shell	Seed cotton
103K0	11.8b	23.2b	18.2b	NL§	10.4a	36.4a
103K1	11.6b	25.1ab	21.9a	NL	10.0a	31.4ab
103K2	11.7b	26.5a	22.9a	NL	9.5a	29.4b
122K0	15.1a	27.8a	15.5b	8.3a	5.1b	28.2b
122K1	15.0a	27.2a	16.6b	9.8a	5.4b	26.0b
122K2	14.2a	24.8ab	17.0b	11.1a	6.2b	26.7b

§ NL: there were no leaves left when cotton was harvested.

With K application, it appeared that dry matter was more accumulated in stem and leaf and less in the roots (Tab. 2). Dry matter allocation rate in branch, bell shell, and seed cotton allocations were evidently higher for genotype 103. Further analysis revealed that the dry-matter accumulation in bell shell and seed cotton of genotype 103 accounted for 46.8%, 41.4%, and 38.9% of the whole plant at the three K-fertilization levels, while those percentages were only 33.3%, 31.4%, and 32.9% for genotype 122. Moreover, K application had little effect on dry-matter allocation in genotype 122, but the dry-matter allocation in main stem and branch of genotype 103 was evidently affected by K application.

Table 3 N, P, and K concentrations in different tissues of two cotton genotypes. Values within columns followed by the same letter are not different at $p < 5\%$ by LSD.

Treatments	N concentration (%)					P concentration (%)					K concentration (%)				
	Root	Main stem	Branch	Leaf	Bell shell	Root	Main stem	Branch	Leaf	Bell shell	Root	Main stem	Branch	Leaf	Bell shell
103K0	1.0a	1.0b	1.4a	—	1.5ab	0.13a	0.17a	0.21a	—	0.26a	0.68bc	0.8b	0.93b	—	1.98b
103K1	1.1a	1.1ab	1.6a	—	1.4ab	0.14a	0.23a	0.22a	—	0.25a	0.83a	0.95a	1.13a	—	2.18ab
103K2	1.1a	1.1ab	1.6a	—	1.7a	0.14a	0.19a	0.19a	—	0.23ab	0.78ab	0.95a	1.15a	—	2.25a
122K0	1.0a	1.2a	1.6a	2.3a	1.0c	0.15a	0.21a	0.19a	0.29a	0.17bc	0.68bc	0.78b	0.93b	0.50a	2.28a
122K1	0.9a	1.0b	1.5a	2.2a	1.0c	0.13a	0.22a	0.21a	0.26a	0.15c	0.73ab	0.83b	1.03ab	0.53a	2.35a
122K2	0.9a	1.0b	1.6a	2.3a	1.2bc	0.13a	0.19a	0.19a	0.26a	0.18bc	0.60c	0.68c	0.93b	0.5a	2.35a

Concentrations of N, P, and K were not consistently affected by K-fertilizer application (Tab. 3). Concentrations of N and P of the two genotypes showed no significant difference between K levels, whereas K concentrations of genotype 103 in K1 and K2 were significantly higher than in K0. Concentrations of K of genotype 122 did not differ with K additions. In addition, N and P concentrations in the bell shell were significantly higher in genotype 103 and the K concentration was significantly lower than that of genotype 122.

3.2 Effect of potassium on the economic efficiency of two cotton genotypes

The Value Cost Ratios (VCRs) of genotype 122 were significantly lower than the VCRs of genotype 103 at K0 and K1 (Fig. 1). Compared to K0, the VCRs of genotype 103 were decreased by 15.5% and 29.1% when K application was increased. The value of VCR for genotype 122 was significantly lower at K2 than at K0. At this K2 level genotypes 122 and 103 had similar VCR values.

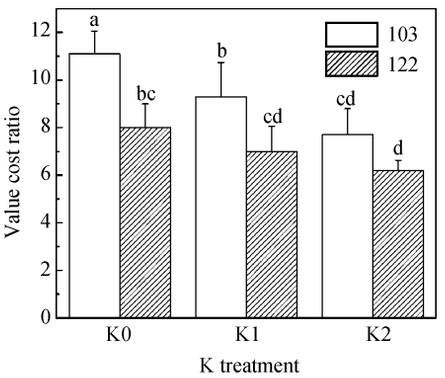

Figure 1 Effect of different K treatments on the value cost ratio of two cotton genotypes. Bars assigned the same letter are not significantly different at $p < 5\%$ by LSD.

Harvest Indices (HIs) of genotype 103 decreased as K application increased (Fig. 2). For genotype 122, HIs at three K levels were not significantly different but were lower than those of genotype 103 at K0.

3.3 Effect of potassium on K efficiency and utilization of N and P of two cotton genotypes

Partial factor productivity of fertilizer is defined as grain yield per unit fertilizer inputs (Olk et al., 1998). For cotton, the yield parameter was seed cotton yield. Fig. 3 shows that the partial factor productivity for K (PFPK) was decreased by 48.4% for 103 and 44.7% for 122 with increased K application. However, the PFPK of genotype 103 was significantly higher than that of genotype 122 in the same K supply level; the PFPKs were 1.3 times than those of genotype 122 at the K1 level and 1.2 times at the K2 level.

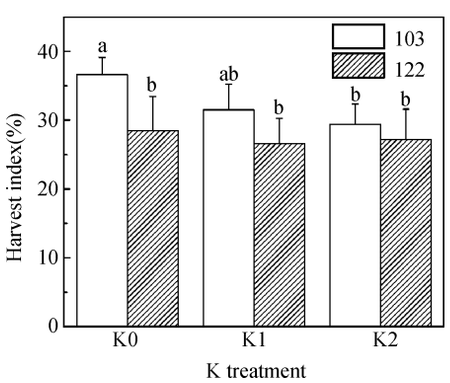

Figure 2 Effect of different K treatments on the harvest index of two cotton genotypes. Bars assigned the same letter are not significantly different at $p < 5\%$ by LSD.

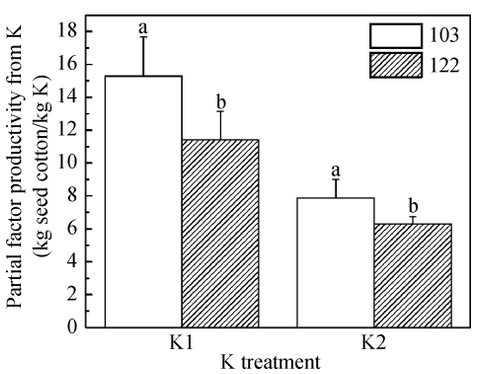

Figure 3 Effect of different K treatments on the partial factor productivity of K in two cotton genotypes. Bars assigned the same letter are not significantly different at $p < 5\%$ by t test.

Figures 4 and 5 show increasing trends of partial factor productivity for N and P (PFPN and PFPP) with increasing K application for the two cotton genotypes. Compared with the PFPN and the PFPP values of genotype 122 at same K level, the PFPN values of genotype 103 were 1.4, 1.4, and 1.2 times greater than the PFPN of genotype 122 at K0, K1, and K2 levels, respectively, and the PFPP values of 103 were 1.4, 1.3, and 1.2 times greater than the PFPP values of genotype 122 at these K levels, the differences were significant. The results also show that the contribution of N and P to seed cotton yield increases with K application, implying that K addition may interactively improve utilization of N and P in cotton.

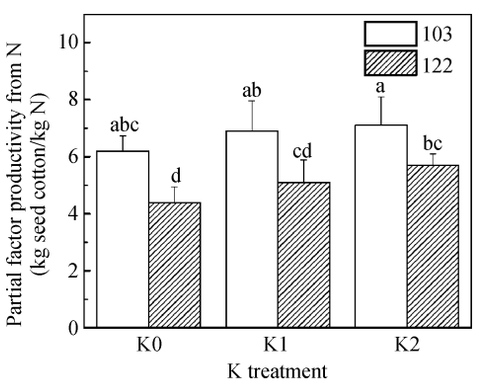

Figure 4 Effect of different K treatments on partial factor productivity of N in two cotton genotypes. Bars assigned the same letter are not significantly different at $p < 5\%$ by LSD.

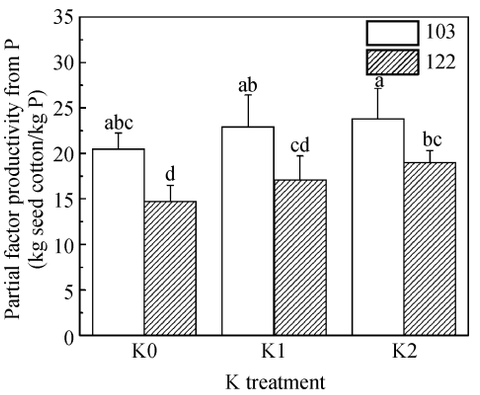

Figure 5 Effect of different K treatments on partial factor productivity of P in two cotton genotypes. Bars assigned the same letter are not significantly different at $p < 5\%$ by LSD.

4 Discussion

4.1 Yield and synergistic effect of N, P, and K utilization in two cotton genotypes

The bell is the gateway for photosynthates transported from vegetative organs to lint and seed. Parenchymal cells of young fluid bell are the temporary repository for organic compounds such as soluble sugar, protein, and pectin. A high concentration of K in the bell should benefit the translocation of organic materials from vegetative to economic parts of the crop (*Benedict* et al., 1973). In this research, K concentration in the bell was obviously higher in genotype 122 than genotype 103 (Tab. 3), which might be one of the reasons why genotype 122 gave bigger bolls and higher single-boll weight in our investigation (data not shown) as well as in previous research (*Jiang* et al., 2011). But, genotype 122 had lower yield (Tab. 1), which is due to many squares and bolls shedding during the reproductive stage, and this shedding was less in genotype 103 (*Jiang* et al., 2008). N, P, and K have interactive effects on plants. Onuwaje and Uzu (1982) reported that the growth response of rubber seedlings to N and K was enhanced by the presence of P. He et al (1998) believed N, P, and K had interactive effects on nutrient absorption of plants. In this experiment, every plot was given the same N and P fertilizer with different K levels, and the K efficient cotton genotype 103 had a higher yield than genotype 122 (Tab. 1), which indicated that K-efficient genotype 103 could use NP fertilizers more efficiently, and genotype 103 might be an N- and P-efficient genotype simultaneously.

4.2 Nutrient efficiency, environmental and economic effects of two cotton genotypes

Nutrient efficiency is defined in many ways. Rengel and Damon (2008) indicated that high-efficiency genotypes can not only use nutrients in soil efficiently, but also realize high crop yields, consequently reducing chemical fertilizer inputs into the environment. Zhang et al. (2008) found that many nutrient-efficient crop varieties can achieve yields 10%–20% higher than conventional varieties. Fertilizer-use

efficiency, which measures the relationship between fertilizer, soil, and plants, might be far more complex than nutrient efficiency. In this research, partial factor productivity from applied fertilizer, which is calculated as yield per unit fertilizer supply (*Zou* et al., 2011), was used to determine N, P, and K efficiency of two cotton genotypes. Results of this study showed that genotype 103 gave higher NPK-fertilizer efficiency in all treatments (Figs. 3-5). Genotype 103 produced higher yield under each fertilizer treatment, and particularly showed higher production with no K application (Tab. 1), which might be due to its excellent root system for absorbing nutrients (*Hao* et al., 2011; *Wang and Chen*, 2012). Early research about root formation of these two genotypes indicated that genotype 103 had superior environmental adaptability and more fine roots (*Hao* et al., 2011), and the number of fine roots, which were important in nutrient absorption, increased when the K supply in the environment was poor (*Wang and Chen*, 2012; *Jungk*, 2001). The number of coarse roots, which help anchor the plant, increased when K was sufficient (*Hao* et al.,2011).

The harvest index (HI) is an indicator of partitioning of assimilates to economic sinks. A high HI is fundamental to efficient utilization of all resources taken up by the plant (*Rengel and Damon*, 2008). Harvest index of genotype 103 was significantly higher than of 122 with no K supplied, and showed a similar (but nonsignificant) trend with K application. Genotype 103 clearly has higher potential for economic benefits at the same fertilization conditions.

5 Conclusions

The K-efficient genotype 103 grew better and gave higher yields than the K-inefficient genotype 122. In addition, the value cost ratio (VCR) and harvest index (HI) of genotype 103 were higher, and N, P, and K utilization were greater than of the genotype 122. This indicates that genotype 103 could require less fertilizer input and give higher cotton production and economic benefit. Results of this research demonstrate that nutrient-efficient genotypes of crops can be used to give better economic and environmental benefits in the future.

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两种典型不同钾效率棉花基因型环境经济效益分析

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摘　要：研究如何在增加作物产量的同时减少由过量施肥引起的环境问题至关重要，而养分高效品种无疑在解决这一问题中扮演着重要角色。本实验研究了钾高效棉花基因型103和钾低效棉花基因型122氮磷钾养分的吸收利用及其环境经济效益的差异。设置K0（不施钾肥），K1（施钾112 kg/hm^2）和K2（施钾224 kg/hm^2）三个处理，结果显示两种基因型棉花的产量差异显著，基因型103各处理的产量分别比基因型122高39.2%、33.8%和25.0%，基因型103甚至在K0处理时的产量比基因型122在K2处理时的产量高7.9%。进一步进行经济效益分析发现，K0和K1处理下，基因型103的产投比显著高于基因型122；三个钾肥处理下，基因型103的收获指数均显著高于基因型122。对环境效应的分析发现，基因型103的氮磷钾偏生产力均高于基因型122。因此，本研究认为钾高效棉花基因型103在获得较高产量的同时，能更有效力利用土壤中的氮磷钾肥，在未来农业种植中，可以选用养分高效品种实现较少的肥料投入，获得较高的经济效益。

关键词：经济效益；环境效益；大田试验；棉花；钾肥

甘蔗及其近缘属植物钾效率差异研究[①②]

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摘　要：本研究对39份甘蔗及其近缘属植物进行钾效率评价分析，旨在探讨不同基因型甘蔗种质钾效率差异，从而为筛选、培育耐低钾的甘蔗品种提供种质材料。研究结果表明：在低钾水平下，甘蔗及其近缘属植物地上部生物量（F地上部生物量＝161.86***）、钾吸收效率（F钾累积量＝179.01***）和钾利用效率（F钾利用效率＝58.47***）存在显著基因型差异；不同甘蔗及其近缘属属间地上部生物量（F地上部生物量＝174.23***）、钾吸收效率（F钾累积量＝254.44***）和钾利用效率（F钾利用效率＝80.87***）也存在显著属间差异。另外，通过对供试材料的钾效率评价，发现部分斑茅材料不仅具有较高的生物量，同时也具有较高的钾素利用效率，可为甘蔗钾效率的定向改良提供优良种质。

关键词：甘蔗；基因型差异；钾吸收效率；钾利用效率

钾是作物生长发育所必需的大量元素之一，它在维持细胞内物质正常代谢调节，促进光合作用，光合产物的运输，蛋白质合成及增强植物的抗逆性等方面发挥着重要作用[1]。根据中国钾盐（肥）行业分会发布的统计数据，2011年国内钾肥总产量380.3万t，全年进口量达378.0万t，进口依存度达50%[2]。随着钾肥资源的短缺问题日益严重化，有关植物钾营养基因型差异的研究受到人们的重视和关注，并得到了迅速发展[3-8]。植物钾效率的基因型差异和遗传变异的多样性为人们合理选育钾高效作物品种提供了可能。近年来人们对植物营养性状的改良日益重视，从植物营养性状的改良入手，通过挖掘、利用钾高效植物，以补充代替传统方法所需的钾素资源，这对于缓解我国钾资源危机，提高作物产量具有重要意义[9]。

甘蔗是C4作物，生物量大，钾需求量大，但目前关于甘蔗钾高效基因型筛选和利用、钾素营养相关生理机制的研究较少，且缺乏系统深入的研究，不利用甘蔗产业的可持续健康发展。因此，有必要挖掘、利用我国丰富的甘蔗种质资源，筛选钾高效的甘蔗基因型，通过常规育种和生物技术方法培育出钾高效的优良甘蔗品种，将是充分利用土壤钾素资源，缓解缺钾问题的长久有效途径之一。

甘蔗及其近缘属植物王草、象草、斑茅、割手密等长期生长在自然土壤环境中，长期的进化过程令其产生了对环境的高度适应性，且抗逆性强、宿根性好、生势强、耐养分协迫，并蕴藏着较大的遗传变异性，是甘蔗养分高效育种的重要基因源。本研究以广东省甘蔗种质资源库中王草、象草、斑茅、割手密等39份种质为材料，通过田间小区试验筛选钾高效基因型种质，以期为选育钾高效甘蔗基因型提供材料，探索缓解甘蔗钾需求提供新途径。

1　材料与方法

1.1　供试材料

供试材料选用保存于广东省甘蔗种质资源库中来自不同地区的王草、象草、斑茅、割手密等39份甘蔗及其近缘属材料。其中包括王草1份，象草1份，斑茅8份，割手密19份，具体见表1。

表1　供试材料

编号	材　料	种　　属
1	紫色王草	Saccharum Sinese
2	象草82-21	Pennisetum purpureum Schumach

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续 表

编号	材 料	种 属
3	广西 87-3	Erianthus arundinaceus (Retz.) Jeswiet
4	崖城 3 号	Erianthus arundinaceus (Retz.) Jeswiet
5	广东 51 号	Erianthus arundinaceus (Retz.) Jeswiet
6	云南 82-85	Erianthus arundinaceus (Retz.) Jeswiet
7	四川 79-I-9	Erianthus arundinaceus (Retz.) Jeswiet
8	江西 83-4	Erianthus arundinaceus (Retz.) Jeswiet
9	海南 92-109	Erianthus arundinaceus (Retz.) Jeswiet
10	贵州 78-Ⅱ-14	Erianthus arundinaceus (Retz.) Jeswiet
11	越南三号	Succharum spontaneum L.
12	海南 92-76	Succharum spontaneum L.
13	羊栏 9 号	Succharum spontaneum L.
14	四川 92-2	Succharum spontaneum L.
15	简阳 6 号	Succharum spontaneum L.
16	印度 1 号	Succharum spontaneum L.
17	印度 2 号	Succharum spontaneum L.
18	79 不详号	Succharum spontaneum L.
19	福建 89-I-7	Succharum spontaneum L.
20	金山割手密	Succharum spontaneum L.
21	江西 79-17	Succharum spontaneum L.
22	泰国二号	Succharum spontaneum L.
23	海南 92-44	Succharum spontaneum L.
24	广东 81 号	Succharum spontaneum L.
25	贵州 78-I-27	Succharum spontaneum L.
26	云南 82-16	Succharum spontaneum L.
27	贵州 78-Ⅱ-10	Succharum spontaneum L.
28	四川 92-13	Succharum spontaneum L.
29	浙江割手密	Succharum spontaneum L.
30	海南 92-41	Succharum spontaneum L.
31	广东 29 号	Succharum spontaneum L.
32	越南 1 号	Succharum spontaneum L.
33	四川 79-I-4	Succharum spontaneum L.
34	湖南割手密	Succharum spontaneum L.
35	崖城 12 号	Succharum spontaneum L.
36	云南 82-114	Succharum spontaneum L.
37	泰国一号	Succharum spontaneum L.
38	广西割手密	Succharum spontaneum L.
39	印度二号割手密	Succharum spontaneum L.

1.2 供试土壤

试验于 2009 年 12 月—2010 年 9 月在广州甘蔗糖业研究所海南育种场进行，供试土壤为酸性红壤土。土壤理化性质为：pH 5.52，有机质 1.52%，全氮 0.73 g/kg，有效氮(N)81.72 mg/kg，速效磷(P_2O_5)16.32 mg/kg，速效钾(K_2O)66.23 mg/kg。

1.3 试验方法

试验采用田间小区试验，每区面积为每个水泥圈内面积，水泥圈内径 0.75 m，下不封底，面积 0.44 m^2。试验处理为不施肥处理(N0－K0－P0)，39 个甘蔗及其近缘属材料，3 次重复，共 117 小区。供试材料斩成双芽苗，用 50%多菌灵 1 000 倍稀释液浸泡 5 min，每小区种植 10 个双芽苗，种植时间为 2009 年 12 月中旬。试验中浇水量及管理条件保持一致，并进行必要的病虫害防治。

1.4 田间取样及相关指标的测定方法

(1) 样品田间取样

试验在 2010 年 8 月中旬取样，取样时，选取一株具有代表性的植株剪取地上部，将剪取的地上部茎和叶分开成两部分后放于烘箱，在 105℃下杀青 30 min，然后于 75℃恒温烘干后称取茎、叶干物重和地上部

生物量。

(2) 植株、土壤养分测定项目及方法

植株烘干称重后，测定其体内氮、磷、钾养分含量。植株全钾含量采用火焰光度法测定[11]；植株全氮、全磷含量采用法国 Alliance 连续流动分析仪测定。

土壤 pH 采用电位法，按水：土＝5：1 的比例混匀，静置澄清后用 pH 计测定；有机质采用高温外热重铬酸钾氧化-容量法测定；有效氮用碱解扩散法测定；全磷经浓硫酸-高氯酸消煮后，用钼蓝比色法测定；土壤速效磷采用氟化铵—盐酸浸提，钼蓝比色法测定[11]；土壤全氮经混合加速剂-浓硫酸消煮后，采用法国 Alliance 连续流动分析仪测定；土壤全钾：经氟化氢-高氯酸消化后，用 1：1 HCl 溶解残渣，定容，采用火焰光度法测定。

(3) 钾效率表示方法及分类标准

Gerloff(1983)认为：在等量的胁迫下，养分效率高的基因型应是那些能取得较高产量或生物量的基因型[12]。在本研究中，以地上部钾的累积量代表植物钾的吸收效率。以地上部组织内单位钾含量所产生的地上部干重代表植物钾的利用效率。本研究根据植物的生物量和利用效率高低对甘蔗的钾效率进行分类和钾效率综合评价，供试材料钾效率可分为四个不同的类型。Ⅰ：低产、低效利用型；Ⅱ：高产、低效利用型；Ⅲ：高产、高效利用型；Ⅳ：低产、高效利用型。

1.5 数据处理和分析

本试验所有数据均用 Microsoft® Excel(Microsoft Company，USA)进行平均数和标准差等计算，并且利用 SAS(SAS Institute Inc.，Cary，NC，USA)统计软件进行方差分析。

2 结果与分析

2.1 甘蔗及其近缘属营养效率性状的变异分析

对 39 份甘蔗种质的 10 个养分效率性状相关指标进行统计分析。从表 2 中单因素方差分析结果可以看出，地上部生物量的基因型差异达极显著水平(F 地上部生物量＝161.86***)。同时结果也表明，供试材料不同基因型间对钾的吸收效率(F 钾累积量＝179.01***)和利用效率(F 钾利用效率＝58.47***)也表现出显著基因型差异。以上结果表明，不同基因型之间对养分的吸收、积累、利用存在着很大的基因型差异，不同基因型在同一肥力水平下产量效应相差很大，这种差异是不同基因型对环境适应性差异的具体表现，为养分高效优良基因型的筛选、开发利用提供了前提和基础。

表 2 钾效率相关性状的变异分析

钾效率性状	最大值	最小值	极差	标准差	变异系数(%)	F 值
地上部生物量(g/株)	1 027.57	32.98	994.59	189.26	96.65	161.86***
钾含量(%)	2.98	0.48	2.50	0.56	43.11	5.52***
钾利用效率	210.52	33.55	176.97	45.84	48.36	58.47***
钾累积量 (g/株)	30.62	0.41	30.21	4.92	174.52	179.01***

注：*：$0.05 > p > 0.01$；** $0.01 > p > 0.001$；***：$p < 0.001$。

对 39 份材料 10 个营养性状的变异分析表明(见表 2)，钾的吸收效率变异幅度最大，为 0.41～30.62 g/株，变异系数高达 174.52%。其次是地上部生物量，变异系数达 96.65%。钾含量的变异系数最小，但也达 43.11%。由此可见，甘蔗及其近缘属不同基因型间的钾效率性状具有较大的遗传变异和选择潜力。

2.2 甘蔗及其近缘属属间钾效率差异

本试验选用王草、象草、斑茅、割手密等甘蔗及其近缘属植物共 39 个不同基因型。通过用低钾处理下地上部生物量表现来评价植株的钾效率发现(见表 3)，钾效率在不同的甘蔗及其近缘属间存在着显著的属间差异(F 地上部生物量＝174.23***)，具体表现为王草的钾效率最高，然后依次为斑茅、象草，而割手密的钾效率在属间表现最差。用低钾水平下甘蔗及其近缘属间钾的吸收量(钾累积量)来评价其对钾的吸收效率发现，钾的吸收效率在不同的甘蔗及其近缘属存在着显著的属间差异(F 钾累积量＝254.44***)，

具体表现为王草的钾吸收效率最高，然后依次是象草、斑茅和割手密。同时，从表 3 可以看出，不同的甘蔗及其近缘属间的钾素利用效率存在着显著的属间差异（F 钾利用效率＝80.87***）。具体表现为斑茅的钾素利用效率最高，植株体内单位钾含量所产生的地上部分干物质的重量最大，为体内每克钾可产生 106.56 g 的干物质，然后依次为割手密、象草和王草，其植株组织内每克钾分别可产生干物质 94.64 g、66.72 g 和 33.55 g。

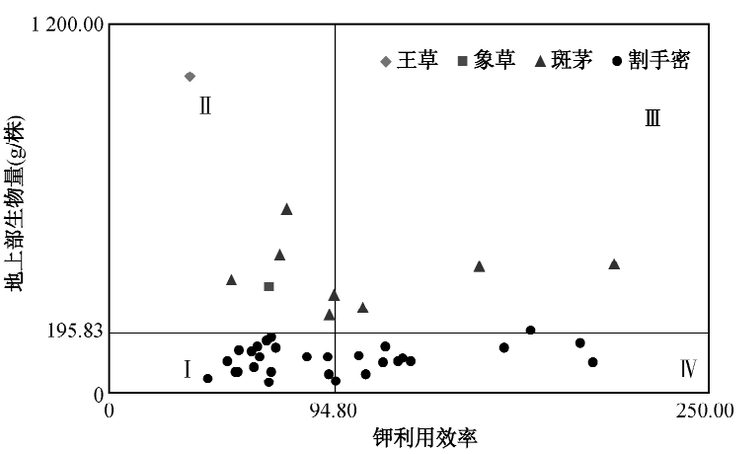
表 3　不同类型材料钾效率差异

钾效率性状	种属				F value
	王草	象草	斑茅	割手密	
地上部生物量（g/株）	1 027.54±56.48	343.87±18.90	386.91±1.99	109.33±6.01	174.23***
钾含量（%）	2.98±0.01	1.51±0.07	1.14±0.06	1.27±0.05	302.24***
钾利用效率	33.55±0.13	66.72±3.09	106.56±5.80	94.64±4.32	80.87***
钾累积量（g/株）	30.62±1.60	5.20±0.51	4.46±0.25	1.33±0.09	254.44***

注：表中数据为三次重复的平均值，符号“±”后为相应的标准误差；*：$0.05>p>0.01$；**：$0.01>p>0.001$；***：$p<0.001$。

2.3　甘蔗及其近缘属不同基因型钾效率评价

采用地上部生物量和钾素利用效率二个指标在低钾条件下的表现来综合评价甘蔗及其近缘属不同基因型植物的钾效率，可将供试材料划分为四种不同的类型Ⅰ：低产、低效利用型；Ⅱ：高产、低效利用型；Ⅲ：高产、高效利用型；Ⅳ：低产、高效利用型。其中Ⅰ类为生物量和钾利用效率均低于供于材料的平均值，Ⅱ类生物量高于供试材料的平均值，但钾利用效率效率低于平均值，Ⅲ类不仅具有较高的生物量，同时具有较高的钾素钾利用能力，Ⅳ类的生物量较低，但具有较高的钾素钾利用效率。从图 1 可知，王草、象草及部分斑茅基因型分布在Ⅱ区，具有较高的生物量和较低的钾素利用能力，为高产、钾低效利用型，表现为植物体内的钾素利用能力较弱，但具有较高的生物量；部分斑茅基因型分布在Ⅲ区，具有较高的生物量和钾素利用效率，为高产、高效利用型，表现为对植株体内钾素利用能力强的同时具有较大的生物量；而割手密主要分布在Ⅰ和Ⅳ区，总体表现出较低生物量，但基因型间的利用效率在高效和低效区都有分布，表明可在割手密材料中筛选出部分对钾素高效利用的基因型，但较难筛选到生物量较高的基因型。



Ⅰ：低产、低效利用型；Ⅱ：高产、低效利用型；
Ⅲ：高产、高效利用型；Ⅳ：低产、高效利用型

图 1　供试甘蔗材料钾效率评价

3　结论

（1）甘蔗及其近缘属钾效率性状的基因型差异

不同植物种类或同种植物（作物）的不同品种对于土壤缺钾的生理反应以及对钾元素的吸收利用效率存在明显差异，同时这种钾营养效率差异是可以向子代稳定遗传的，是由遗传基因控制的[12-13]。随着人们对资源和环境问题严峻性认识的不断加深，以节省资源、保护环境为前提的农业持续发展热潮波及全球，植物营养性状的遗传改良也越来越受重视，许多国家都把植物营养性状的改良列为农业基础研究的前沿课题和优先发展领域，第 15 届国际土壤学会把这一研究提高到“优化养分循环，减少养分投入，提高养分利用效率，促进农业持续发展”的高度，认为通过改良作物的营养性状来提高作物产量、改善品质、提高

生产效率是作物育种工作的努力方向。甘蔗是需钾量大的作物，但甘蔗钾效率性状的遗传改良还没得到应有的重视，甘蔗钾效率的基因型差异及遗传变异等方面都缺少相应研究，使得甘蔗钾效率的营养遗传改良进展缓慢。植物钾素营养性状遗传改良的第一步也是关键的一步是遗传材料的获得。本研究通过田间试验对甘蔗及其近缘属 39 个基因型进行钾效率筛选研究，研究发现，甘蔗及其近缘属不同基因型植物之间对养分的吸收、积累、利用存在着很大的基因型差异；甘蔗及其近缘属不同基因型间养分效率相关性状具有丰富多样性和遗传变异及选择潜力，可供选择的范围较广。试验结果表明了甘蔗不同基因型在钾效率特性方面存在较大的遗传变异，是受基因控制的，这为通过遗传手段改良钾效率提供了巨大的潜力。在本研究中，由于考虑试验场地、工作量等多种因素，重点挖掘了低钾胁迫下甘蔗及其近缘属基因型的钾效率性状差异和遗传变异，而不同基因型间对钾肥施用的敏感程度则缺少研究，有待对从中筛选出的部分钾特异种质进一步深入研究。

(2) 甘蔗及其近缘属植物在甘蔗钾效率改良中的利用价值

植物营养性状研究的最终目的是为了培育能够在特定的土壤环境下获得高产、高效、优质的作物品种，这种植物类型称为营养高效基因型。对于植物营养性状改良而言，商业种和改良品种通常不是理想的遗传资源，这一方面是因为现代品种往往没有将植物营养性状列入育种目标中，只是强调高产、优质等农艺性状，而忽略了对不良土壤环境的适应性，另一方面，现代育种过程令现有栽培群体遗传变异性下降，往往导致一些抗逆基因的流失，因此，从现有品种中进行植物营养性状的改良潜力是不大的[9]。王草、象草、斑茅、割手密等甘蔗及其近缘属植物生长在自然土壤中，长期的进化过程令其产生了对环境的高度适应性，蕴藏着较大的遗传变异。本研究筛选出来的部分材料，具有钾效率性状的优势，适合作为某一理想特性的供体。本研究对 39 个甘蔗及其近缘属基因型钾效率综合评价发现，王草、象草具有较高的生物量和钾素吸收效率，但钾素利用效率较低；而割手密一般具有较低的生物量和钾素吸收效率，但部分割手密材料具有较高的钾素利用效率；斑茅钾素效率在各个类型都有分布，具有丰富的多样性。研究结果表明，从该批材料中难以筛选出兼具高产、钾吸收高效、钾利用高效三方面优势的基因型。但是通过筛选，可以筛选到具有高产、钾高效吸收基因型，如王草、象草和部分斑茅植物；也可筛选出具有高产、钾高效利用基因型，如部分斑茅植物。这些材料可以为甘蔗相关钾效率性状的定向改良提供相应遗传资源。不同的地区，由于环境条件和栽培水平等不同，钾效率育种目标应有所不同，在一些土壤钾素水平高，钾肥可投入量大的地区，钾效率育种目标主要倾向于高产和钾高效吸收，以追求较高的产量水平；而对于土壤钾素水平低，钾肥可投入量较少的地区，在追求高产的同时亦需重点考虑植物钾素的利用效率，以减少由于甘蔗收获所带走的钾素，从而减少钾肥投入和维持土壤钾素平衡。在我国蔗区，一方面土壤缺钾现状严重，另一方面钾肥资源匮乏，筛选高产和钾利用效率高的种质更具有现实意义，以期为甘蔗钾高效育种提供优良种质。近年年，广州甘蔗糖业研究所将钾高效(高产、钾高效利用)特异种质斑茅材料同栽培种进行杂交利用，创制出斑茅杂交后代系列材料，目的是将斑茅中所具有的抗逆基因和钾高效基因导入到栽培种中，取得了一定的进展。

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The differences of potassium efficiency among different genotypes of sugarcane and its related genera

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Abstract: In this study, a field experiment was carried out to explore the difference in potassium efficiency with 39 sugarcane and related genera genotypes, so as to screen and provide materials for breeding low-potassium tolerant sugarcane genotypes. The results showed that there was significant difference in plant biomass ($F_{\text{shoot biomass}} = 161.86^{***}$), potassium uptake efficiency ($F_{\text{k accumulation}} = 179.01^{***}$) and potassium utilization efficiency ($F_{\text{k utilization efficiency}} = 58.47^{***}$) among difference genotypes; significant difference also existed in plant biomass ($F_{\text{shoot biomass}} = 174.23^{***}$), potassium uptake efficiency ($F_{\text{accumulation}} = 254.44^{***}$) and potassium utilization efficiency ($F_{\text{k utilization efficiency}} = 80.87^{***}$) among different genus. In addition, some materials of *Erianthus arundinaceus* (*Retz.*) *Jeswiet* with high biomass and high K utilization efficiency have been found in this experiment which might provide sugarcane germplasm for breeding high K efficiency sugarcane.

Key words: Sugarcane, genotype difference, K uptake efficiency, K utilization efficiency

内蒙古马铃薯施肥效应及养分利用率研究[①②]

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摘　要：本文整理了内蒙古2002—2011年进行的15项次马铃薯施肥田间试验，结果表明：马铃薯施用NPK肥分别增产26.3%、22.8%和20.1%，每kg N、P_2O_5、K_2O增产马铃薯40.7、70.4、44.7 kg。施肥增产效果：氮肥＞磷肥＞钾肥。施用氮磷钾肥的N、P_2O_5、K_2O的养分利用率分别为35.9%、15.6%、50.4%。生产1 t马铃薯吸收N、P_2O_5、K_2O分别为5.32、1.42、6.01 kg。缺素区马铃薯吸收N、P_2O_5、K_2O养分量分别为126.3、38、152.1 kg/hm^2。试验结果为该地区马铃薯推荐施肥提供了科学参数。马铃薯NPK吸收积累量呈“S”型生长曲线变化规律，即前期慢、中期快、后期又慢，吸收积累的高峰期在出苗后60 d左右，之后积累量逐渐放缓，到收获时日积累量有小幅下降，特别是磷和钾的积累。吸收的NPK前期主要供给叶片的生长发育，在收获时70%～80%的氮素，80%～90%的P_2O_5和K_2O转移到了块茎中。出苗后60 d是马铃薯水肥需要关键期，此时期保证水肥供应是获得高产的关键。

关键词：马铃薯；NPK化肥；养分吸收规律；平衡施肥

中图分类号：S532　　**文献标识码**：A

马铃薯（*Solanum tuberosum L.*）俗称土豆，为茄科茄属的草本植物，由于营养丰富，适宜栽培，产量较高，在世界各地广泛种植，是世界上仅次于稻、麦、玉米的四大粮食作物之一[1]。我国马铃薯栽培起步虽晚，但发展较快，播种面积是仅次于大豆的第五大作物。2008—2010年我国马铃薯的种植面积平均为498.3万hm^2，单产每hm^{2}达15.1 t，总产量达7 518万t，占世界总产量的25%左右，是世界上最大的马铃薯生产国。内蒙古自治区是我国马铃薯主产区之一，马铃薯已成为自治区仅次于玉米、大豆的主栽作物。2010年，全区马铃薯播种面积达到69.1万hm^2，占全区粮食作物播种面积的12.24%，马铃薯总产量855万t，占全国马铃薯总产量的10%以上[1]。对中国而言，马铃薯之所以重要不仅是因为它能够作为主粮，而且它还是土壤贫瘠的山区农民的经济作物[4]。在我国592个扶贫工作重点县中有549个县种植马铃薯。

科学合理施肥是保证产量、降低投入、增加品质的重要途径。在马铃薯生长发育过程中矿质元素通过参与同化物的合成、转运和分配过程，对马铃薯的生长发育及产量形成有着重要作用。肥料充足、养分配比合理时，生物产量和块茎产量都可达到最高，同时可以提高马铃薯的品质[3]。

马铃薯对氮、磷、钾养分有严格的需求，缺乏其中之一都会使生长和发育减缓，产量减少和质量降低。氮、磷、钾肥配合施用增产效果明显，表现在结薯个数多，大中薯比例高，单株产量明显提高等特性[5,6]。因各地自然条件、栽培管理等差异，N、P、K肥施用量和施肥配比存在很大差异。关于马铃薯平衡施肥的研究比较多，如甘肃省景泰县、内蒙古达拉特旗和河北省沽源县3个马铃薯生产基地进行的研究结果表明，在氮、磷、钾肥用量和比例为180、180、225 kg/hm^{2}施肥处理时，其经济效益较高[5]。贵州六盘水市马铃薯在N、P_2O_5、K_2O用量为45、45、75 kg/hm^{2}处理下可以较低的投入获得较高的产出[6]。在浙江土壤肥力较高的灰泥田上种植马铃薯，N、P_2O_5、K_2O用量为150、60、225 kg/hm^{2}较适宜[7]。

马铃薯是喜钾作物，对钾的消耗很大，增施钾肥不但使其产量有所提高，而且还能改善品质，增加抗逆性及淀粉含量。研究报道过钾肥在黑龙江省主要土壤上对马铃薯生长发育、产量及质量的影响[3]。Dow（1978）报道，块茎产量54～95 t/hm^2，块茎移走钾量为230～445 kg/hm^2[9]。钾素营养影响块茎的大小、干物质的百分比、淀粉含量、黑心病、耐储性和抗机械损害。钾也提供抵抗有害物、疾病、干旱和霜冻的能力。N、P、K比例的严重不平衡和施肥利用率低是马铃薯产量低的重要原因[10]。

马铃薯对氮素的吸收速率在整个生育期间呈单峰曲线变化，峰值出现在块茎快速增长期（出苗后

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51 d 左右）。氮在植物体内很容易流动，块茎形成后，大量的氮素转移到块茎中，用于块茎的建成和营养贮存。马铃薯植株在淀粉积累开始后，各器官中氮素加快向块茎转移，使叶片和地上茎的衰老进一步加剧。因此，在马铃薯高产栽培实践中，须注重氮、磷、钾的适量与配合施用，使之既能满足块茎的形成与生长的需要，又可防止植株生长过旺或后期发生早衰[11]。

磷在物质代谢和能量代谢中起重要作用，可促进光合物质的合成、转运和分配。同时磷对氮代谢有明显促进作用，从而进一步扩大了“源”的供应能力和同化物的转运效率。马铃薯生育前期光合物质主要用于茎叶形态建成，适当的氮磷有利于茎叶的形态建成；生育中期伴随光合器官生长的同时，块茎逐渐形成并不断膨大，生育后期“块茎”成为生长中心，磷钾有利于同化物质向块茎运输，并促进可溶性同化物转变形成淀粉[9]。

磷元素在马铃薯植株体内的流动性较大，磷营养水平与块茎膨大密切相关，块茎是磷素的最终贮存库。马铃薯对磷素（P_2O_5）吸收速率较低，在整个生育期内吸收速率呈单峰曲线变化，峰值出现在块茎增长期[12]。

马铃薯钾素（K_2O）积累量在淀粉积累期达到峰值，块茎形成后，地上茎中的 K_2O 的分配率始终高于叶片，这有利于保持地上茎的高效运输、直立与抗性；块茎形成后，K_2O 的分配率逐渐增加，对于块茎体积的增长和淀粉的积累具有重要意义[13]。

每生产 1 t 马铃薯，植株吸收的氮磷钾量因品种和栽培条件的不同而有差异。高炳德（1984）研究认为同薯 8 号每生产 1 t 鲜薯植株吸收 N、P、K 分别为 4.38、0.79、6.55 kg，其中以钾吸收量最大[2]。刘克礼等研究认为在适量施肥组合下，每生产 500 kg 马铃薯块茎需要纯 N 2.65～3.02 kg[11]，需吸收磷素 0.80 kg[12]，需吸收钾素 4.10 kg[13]。吴旭银等研究认为马铃薯（克新 1 号）块茎产量在 38 718 kg/hm^2 水平下，生产 1 t 块茎植株需吸收 N 5.65 kg，P_2O_5 1.17 kg，K_2O 5.19 kg，质量比为 1.00∶0.21∶0.92[14]。

施肥是马铃薯增产的物质基础，科学合理施肥不仅能增加马铃薯产量、改善品质，也可减少肥料的浪费。为此，我们开展了马铃薯施肥肥效和养分吸收利用的研究，旨在明确马铃薯吸肥规律和最佳养分管理技术，为马铃薯推荐施肥提供技术参数，为马铃薯最佳养分管理提供技术支撑。

1 材料与方法

试验从 2002 年开始在内蒙古武川县上秃亥乡、察右中旗黄羊城乡等地进行。土壤为栗钙土，土壤养分状况见表 1。

试验均设置 4 个基本处理：OPT（NPK），OPT－N，OPT－P，OPT－K。

①OPT（NPK）：N、P、K 化肥配合施用的最优施肥处理（由中加合作实验室推荐），肥料具体用量见表 2；②OPT－N：不施氮肥处理，既在 OPT 的基础上减去 N 肥；③OPT－P：不施磷肥处理，既在 OPT 的基础上减去 P 肥；④OPT－K：不施钾肥处理，既在 OPT 的基础上减去 K 肥。

供试马铃薯品种为脱毒紫花白。试验用氮肥为尿素，含 N 46%；磷肥为重过磷酸钙，含 P_2O_5 46%；钾肥为氯化钾，含 K_2O 60%。磷钾肥全部做基肥一次深施，40%基施，60%在生育期间追施。田间管理同一般生产田。

收获时各处理分别收获记产，并随机取样 3 株，测定茎叶、花盘和籽实干物质重量，混匀后粉碎测定全 N、全 P 和全 K 含量。

NPK 测定方法：采用 H_2SO_4－H_2O_2 消煮法，植物全氮用凯氏法测定；全磷采用钒钼黄吸光光度法测定；全钾用火焰光度法进行测定。

表 1 供试土壤养分状况

Table 1 Analysis result of soil nutrient on experimental site

地点 Site	年份 Year	pH	OM	NH_4-N	NO_3-N	P	K
			%	mg/L			
武川 Wu Chuan County	2002	8.3	0.66	8.7		14.7	76.5
	2003	8.35	1.1	10.3		18.5	83.45
	2004	8.4	1.2	7.9		10.25	54.75
	2005	8.35	1.45	30.1		9.65	66.45

续 表

地 点 Site	年 份 Year	pH	OM	NH_4-N	NO_3-N	P	K
			%		mg/L		
	2006	7.9	0.4	7.9		20.9	58.65
	2007	8.42	1.45	41.4		24.9	108.8
	2008	8.48	1.27	3.4	47.9	18.9	123.5
	2009	8.37	1.28	11.4	31.4	26.8	137
	2010	8.44	0.85	6.8	27.4	19.8	80.6
		8.42	0.44	19.3	6.9	14.3	54.2
	2011	8.12	1.29	0.0	19.9	14.3	80.4
察右中旗 Cha You Zhong Banner	2008	8.76	0.72	3.7	20.6	5.5	79
		8.94	0.33	9.8	23.1	12.1	98.8
		8.55	2.52	7.3	11.9	7.5	138
	2009	8.49	1.26	7.6	16	37.5	90.1

注：土壤分析结果由中加合作实验室进行，采用 ASI 方法。

2 结果与分析

2.1 马铃薯的养分积累分配规律

2011 年对武川试验站进行的马铃薯施肥试验的 OPT 处理从出苗后开始每隔 15 d 左右取样一次（每次每处理取样 3 株），测定茎、叶和块茎鲜重，样品风干后测定干物质重并测定 NKP 养分含量，各器官和全株的 NPK 养分吸收积累结果见图 1。

马铃薯 NPK 吸收累积量呈“S”型，即“前期慢、中期快、后期又慢”的生长曲线变化规律，吸收积累的高峰期在出苗后 60 d 左右，之后日积累量逐渐放缓，到收获时日积累量有小幅下降，特别是钾素的积累。NPK 的积累量均以出苗后 60 d 左右最高。此时，茎叶等吸收积累的养分开始下降，而块茎的养分积累量超过茎叶并快速增加，马铃薯茎叶等同化器官吸收积累的养分开始向块茎转移，块茎快速膨大，这时正是马铃薯开花期，是马铃薯生长最快的时期，此时期保证水肥供应是获得高产的关键。

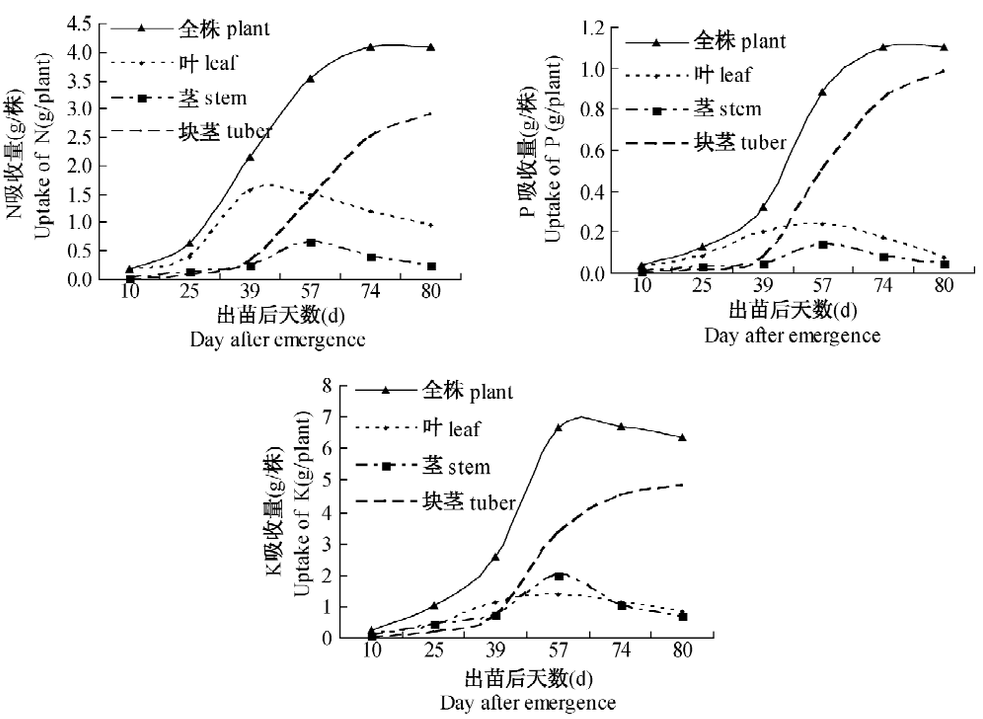

图 1 施肥对马铃薯 NPK 养分积累的影响

Fig. 1 Effect of NPK fertilizer for nutrient accumulation in irrigation Potato

吸收的氮素前期主要供给叶片的生长发育，在出苗后 40 d 叶片吸收的氮素占总量的 73%，在收获时大部分氮素转移到块茎中，积累量占总吸收量的 71%，叶片占 23%，茎秆占 6%。吸收的 P_2O_5 前期也是主要供给叶片，在出苗后 40 d 叶片吸收的 P_2O_5 占总吸收量的 62%，到收获时绝大多数 P_2O_5 转移到了块茎中，块茎的积累量占总量的 89%。吸收的 K_2O 前期主要供给茎秆生长需要，在出苗后 40 d 茎秆吸收的 K_2O 占总吸收量的 43%，而叶片占总量的 28%。到收获时绝大多数 K_2O 转移到了块茎中，块茎的积累量占总量的 76%。

2.2 马铃薯施肥平衡与养分利用率

整理了 2002—2011 年进行的 15 项次水浇地马铃薯田间试验结果，见表 2、表 3。

2002—2011 年进行的 15 项次试验结果表明，采用推荐施用氮肥(N)量基本能够满足马铃薯吸收氮素的需求，供需基本平衡，亏缺仅为 5.2 kg/hm²；推荐施用的 P_2O_5 量基本大于马铃薯吸收的 P_2O_5 量，盈余 22.9～63.7 kg/hm²，平均盈余 44 kg/hm²；在内蒙古富钾地区推荐的钾肥用量是不能满足马铃薯的养分需求的，亏缺 84.9 kg/hm²，需要向土壤中补充。

缺素(N、P、K)处理的养分吸收量反映了试验土壤供应氮磷钾养分的能力。进行的 15 项次试验结果表明，缺 N 区(OPT-N)马铃薯吸收 N 量为 71～180 kg/hm²，平均为 126.3 kg/hm²；缺 P 区(OPT-P)马铃薯吸收 P_2O_5 量为 16.2～82.0 kg/hm²，平均为38.0 kg/hm²；缺 K 区(OPT-K)马铃薯吸收 K_2O 为 72.1～253.4 kg/hm²，平均为 152.1 kg/hm²。

在施磷钾肥基础上施用氮肥的养分利用率(N)为 28.5%～50.4%，平均 35.9%；在施氮钾肥的基础上施用磷肥的养分利用率(P_2O_5)为 10.6%～20.6%，平均 15.6%；在施氮磷肥的基础上施用钾肥的养分利用率(K_2O)为 38.3%～65.4%，平均 50.4%。

表 2 水地马铃薯施肥的养分吸收量和养分利用率

Table 2 Effect of fertilization for nutrient uptake and NUE on irrigation potato

年份 Year		OPT 施肥量 Fertilizer rate (kg/hm²)			OPT 养分吸收量 OPT uptake (kg/hm²)			养分平衡 Nutrient balance (kg/hm²)			缺素区养分吸收量 Deficiency treatments uptake (kg/hm²)			养分利用率 NUE(%)		
		N	P_2O_5	K_2O	N	P_2O_5	K_2O	N	P_2O_5	K_2O	N	P_2O_5	K_2O	N	P_2O_5	K_2O
2002	武川	128	90	90	202.6	48.5	168.3	−74.6	41.5	−78.3	166.1	37.1	131.3	28.5	12.6	41.1
2003		143	92	120	184.8	38.0	182.7	−41.4	54.0	−62.7	132.9	26.2	136.7	36.2	12.8	38.3
2004		120	90	120	126.9	26.3	151.0	−6.9	63.7	−31.0	89.1	16.2	98.8	31.5	11.2	43.5
2005		120	90	120	165.2	59.3	248.7	−45.2	30.7	−128.7	118.0	41.4	181.4	39.3	19.8	56.1
2006		150	90	120	217.4	50.9	249.1	−67.4	39.1	−129.1	173.0	35.6	197.6	29.6	17.0	42.9
2007		180	60	120	231.7	37.1	288.9	−51.7	22.9	−168.9	169.4	30.8	231.8	34.6	10.6	47.6
2008		150	75	105	208.5	50.7	202.4	−58.5	24.3	−97.4	146.3	35.6	144.6	41.5	20.1	55.0
2009		210	90	165	151.7	58.0	205.9	58.3	32.0	−40.9	85.5	47.7	121.4	31.5	11.4	51.3
2010		240	90	165	151.5	35.4	198.0	88.5	54.6	−33.0	71.0	17.5	100.3	33.5	19.8	59.2
2010		300	120	150	272.7	62.4	337.3	27.3	57.6	−187.3	158.0	37.7	253.4	38.2	20.6	55.9
2011		240	90	165	253.3	42.3	302.3	−13.3	47.7	−137.3	132.3	27.1	194.3	50.4	16.9	65.4
2008	中旗	180	90	120	152.0	58.1	132.2	28.0	31.9	−12.2	89.5	41.2	72.1	34.7	18.8	50.1
2008		180	90	120	159.0	36.6	162.8	21.0	53.4	−42.8	95.9	23.7	105.0	35.0	14.4	48.2
2009		210	150	150	170.2	90.0	188.2	39.8	60.0	−38.2	87.4	70.2	108.6	39.4	13.2	53.1
2009		300	150	225	282.1	103.9	311.4	17.9	46.1	−86.4	180.0	82.0	203.4	34.1	14.6	48.0
MEAN.		190.1	97.1	137.0	195.3	53.2	221.9	−5.2	44.0	−84.9	126.3	38.0	152.1	35.9	15.6	50.4

2.3 马铃薯施肥肥效与单位产量养分吸收量

进行的 15 项次试验表明(见表 3)，马铃薯 OPT 处理的产量水平为 24.4～60.2 t/hm²，平均为 37.4 t/hm²。OPT-N 的产量为 18.0～47.8 t/hm²，平均 29.9 t/hm²。OPT-P 为18.1～44.2 t/hm²，平均 30.6 t/hm²。OPT-K 为 19.6～47.2 t/hm²，平均 30.6 t/hm²。

施用氮肥增产 11.4%～51.7%，平均为 26.3%，每 kg N 增产马铃薯 26.0～70.3 kg，平均为 40.7 kg；施用磷肥增产 3.6%～47.3%，平均为 22.8%，每 kg P_2O_5 增产马铃薯 13.3～133.3 kg，平均为 70.4 kg；

施用钾肥增产 2.3%～43.4%，平均为 20.1%，每 kg K_2O 增产马铃薯 8.6～93.7 kg，平均为 44.7 kg。施肥增产效果：氮肥＞磷肥＞钾肥。

生产 1 t 马铃薯吸收 N 4.04～7.58 kg，平均为 5.32 kg；吸收 P_2O_5 0.94～2.51 kg，平均为 1.42 kg；吸收 K_2O 3.56～9.44 kg，平均为 6.01 kg。

表 3　水地马铃薯施肥肥效和养分吸收量

Table 3　Effect of fertilization for potato yield and nutrient uptake rate on irrigating potato

年份 Year		产量 Yield(t/hm²)				增产率 Yield increasing(%)			农学效率 AE(kg/kg)			1t 马铃薯吸收量 Nutrient uptake(kg/t)		
		OPT	OPT-N	OPT-P	OPT-K	N	P_2O_5	K_2O	N	P_2O_5	K_2O	N	P_2O_5	K_2O
2002	武川 WuChuan	34.4	30.9	33.2	33.6	11.4	3.6	2.3	27.4	13.3	8.6	5.89	1.41	4.89
2003		32.4	27.9	27.9	29.6	16.1	16.0	9.3	31.2	48.5	23.0	5.71	1.17	5.64
2004		26.0	20.4	23.7	23.8	27.2	9.9	9.3	46.3	26.0	18.5	4.88	1.01	5.81
2005		37.5	31.3	31.3	34.0	20.0	19.7	10.3	52.1	68.5	29.2	4.40	1.58	6.63
2006		31.5	25.6	25.4	25.3	22.9	24.1	24.5	39.1	67.9	51.6	6.91	1.62	7.91
2007		30.6	23.8	24.9	25.9	28.3	23.0	18.1	37.5	95.4	39.1	7.58	1.21	9.44
2008		38.7	29.7	30.6	30.3	30.3	26.4	28.0	60.0	107.9	80.6	5.38	1.31	5.22
2009		37.0	29.5	32.7	33.9	25.5	13.3	9.0	35.8	48.3	18.6	4.10	1.57	5.56
2010		37.5	28.2	32.1	30.1	32.9	16.7	24.3	38.6	59.4	44.3	4.04	0.94	5.29
2010		60.2	47.8	44.2	47.2	25.8	36.2	27.4	41.1	133.3	86.4	4.53	1.04	5.61
2011		44.3	38.0	38.9	39.6	16.4	13.9	11.9	26.0	60.0	28.6	5.72	0.95	6.82
2008	中旗 Cha You Zhong Banner	37.1	24.5	25.2	25.9	51.7	47.3	43.4	70.3	132.6	93.7	4.09	1.56	3.56
2008		24.4	18.0	18.1	19.6	35.8	34.7	24.5	35.8	70.0	40.0	6.51	1.50	6.66
2009		35.9	27.0	26.1	26.6	32.9	37.4	35.1	42.3	65.2	62.2	4.74	2.51	5.24
2009		53.2	45.2	44.2	42.9	17.7	20.4	24.1	26.7	60.0	45.9	5.30	1.95	5.85
MEAN.		37.4	29.9	30.6	31.2	26.3	22.8	20.1	40.7	70.4	44.7	5.32	1.42	6.01

2.4　马铃薯推荐施肥量的确定

马铃薯推荐施肥量(kg/hm²)＝(目标产量(t/hm²)×单位产量养分吸收量(kg/t)－土壤养分供应量(kg/hm²))/养分利用率(%)

土壤养分供应量(kg/hm²)＝缺素区养分供应量(kg/hm²)

例如：某水浇地地块计划产量 45 t/hm²(亩产 3 t)，施肥量为：

马铃薯推荐施 N 量(kg/hm²)＝(45 t/hm²×5.32 kg/t－126.3 kg/hm²)/(35.9/100)＝315 kg/hm²

马铃薯推荐施 P_2O_5 量(kg/hm²)＝(45 t/hm²×1.42 kg/t－38 kg/hm²)/(15.6/100)＝166 kg/hm²

马铃薯推荐施 K_2O 量(kg/hm²)＝(45 t/hm²×6.01 kg/t－152.1 kg/hm²)/(50.4/100)＝235 kg/hm²

3　结论与讨论

马铃薯 NPK 吸收累积量呈“S”型生长曲线变化规律，即前期慢、中期快、后期又慢，吸收积累的高峰期在出苗后 60 d 左右，之后积累量逐渐放缓，到收获时日积累量有小幅下降，特别是磷和钾的积累。出苗后 60 d 是马铃薯水肥需要关键期，此时期保证水肥供应是获得高产的关键。

吸收的 NPK 前期主要供给叶片等同化器官[11, 12, 13]的生长发育，在收获时 70%～80%的氮素、近 90%的 P_2O_5 和 80%K_2O 转移到了块茎中。

马铃薯施用 NPK 肥均有增产效果，分别增产 26.3%、22.8%和 20.1%，施肥增产效果：氮肥＞磷肥＞钾肥。每 kg N、P_2O_5、K_2O 增产马铃薯 37.9、65.6、41.1 kg。施肥的养分利用率：N、P_2O_5 和 K_2O 分别为 35.6%、14.9%、49.9%。生产 1 t 马铃薯吸收 N、P_2O_5、K_2O 分别为 5.56、1.48、6.21 kg。缺素区马铃薯吸收 N、P_2O_5、K_2O 养分量分别为 120.6、36.8、146.6 kg/hm²。

有关马铃薯施肥的增产效果、养分利用率、单位产量的养分吸收量在相关参考文献中都有报道，但是通过多年多点试验取得的资料较少，本文总结 10 年 15 项次马铃薯试验并提出的养分推荐参数有重要的

实用价值，可以作为该地区马铃薯推荐施肥的技术参数。

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Fertilization effect and nutrition use efficiency of potato in Inner Mongolia

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Abstract: In order to investigate the effects of fertilization and the fertilizer use efficiency on the potato in Inner Mongolia, 15 field experiments were carried out on irrigated land in 2002-2011. The results on irrigated farmland showed that the potato yield increased by 26.3%, 22.8% and 20.1%, respectively, when the nitrogen (N) and phosphorus (P) and potassium (K) fertilizer were used. Per kg N, P_2O_5 and K_2O increased potato by 40.7 kg, 70.4 kg, and 44.7 kg, separately, and the NUE was 35.9%, 15.6%, and 50.4%, respectively. 5.32 kg N, 1.42 kg P_2O_5, and 6.01 kg K_2O were needed to produce 1 ton potato. The absorption amount of NPK by potato increased as an "S" curve and accumulated slowly in the early period then fast in the middle stage and slowly again at the end. The absorption peak occurred about 60 days after emergence, so it is a critical period for potato growing and adequate water and nutrition is the key to obtain high yields. The nutrient NPK supplied leaf growth mainly in the early period, and 70%-80% N and 80%-90% P_2O_5 and K_2O were transferred to the tuber by time of harvest.

Key words: Potato, NPK fertilizer, nutrition absorption, balanced fertilization

不同钾肥用量对生姜生长和营养品质的影响[①②]

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摘　要：采用田间试验研究不同施钾水平对生姜产量和品质及经济效益的影响。结果表明，施用不同数量的钾肥对生姜块茎产量及品质有明显的影响，合理施钾能显著增加块茎产量，改善其营养及安全食用品质，提高施肥效益。生姜块茎产量表现为随施钾量的加大先增加后降低，呈一元二次抛物线关系，所有处理中，中等钾肥用量的 K450 获得了最高块茎产量。品质分析结果显示，施用适量钾肥能明显提高生姜块茎蛋白质、维生素 C 和糖分含量，有效降低硝酸盐含量。维生素 C、粗蛋白质、可溶性糖和还原糖含量，均是 K450 处理最高。施用不同数量的钾肥后，生姜块茎硝酸盐含量下降 24.0%～34.4%，平均降低 30.2%，K450 处理最低。施钾增收 27 086～40 659 元/hm^2，施用钾肥的产投比高达(5.16～24.63)∶1。

关键词：钾肥用量；生姜；产量；品质；经济效益

生姜为我国名特蔬菜品种，其地下块茎含有辛香浓郁的挥发油和姜辣素，是人们日常生活中常用的一种重要调味品和中药材，广泛用于烹调、食品加工和医药卫生等领域[1]。中国是世界生姜主产区，是生姜生产和出口大国，常年栽培面积达 630×10^3 hm^2，仅次于印度，居世界第二，出口量位居世界第一[2]。安徽是我国生姜重要产区之一[1]，全省常年种植面积 20×10^3 hm^2。生姜是重要的出口创汇经济作物。

生姜产量高，需肥量大，是需钾量较多的作物，对钾素营养敏感[1, 3]，仅靠土壤提供的钾素不能完全满足生姜生长发育对钾的需要，还必须通过施肥进行补充。因此，钾肥的合理施用直接影响到生姜的产量、品质、经济效益等。关于施用钾肥对生姜产量和品质的影响，前人已作了一些研究，取得了一定的增产和改善品质的效果[4, 5]。然而，生姜施肥方面还存在不少问题。调查表明，姜农盲目施肥、过量施用氮磷肥、不施或少施钾肥等不合理施肥现象较为普遍，氮磷钾比例失调，生姜病虫害严重，产量低而不稳，块茎品质差，种姜经济效益低下，严重制约了我国生姜产业的发展。同时，与其他作物相比，生姜施肥资料不多，研究的品质性状较少，而且由于供试材料不同，得出的结论也不尽相同，特别是在块茎品质上[5, 6]。为此，开展了本试验，以期为合理施用钾肥以提高生姜产量和改善块茎品质提供科学依据。

1　材料与方法

1.1　供试土壤

试验于 2007 年和 2008 年在安徽省临泉县单桥和范集等乡镇进行，供试土壤为普通砂姜黑土。试验前 0～20 cm 耕层土壤养分状况分别为：有机质含量分别为 16.2、12.1 g/kg，全 N 含量 1.02、0.85 g/kg，碱解 N 含量 112.5、80.1 mg/kg，有效 P 为 25.0、15.5 mg/kg，速效 K 为 138.0、120.5 mg/kg。

1.2　试验设计

试验在施氮(N) 450 kg/hm^2 和磷(P_2O_5) 120 kg/hm^2 的等量氮磷肥基础上进行，设 5 个处理，分别为施钾(K_2O) 0、225、450、675、900 kg/hm^2，以 K0、K225、K450、K675 和 K900 表示，K0 为对照(CK)。供试肥料，氮肥为尿素，磷肥为磷酸二铵，钾肥为氯化钾。施肥方法为：40%的氮肥和钾肥及全部磷肥做基肥开沟深施，余下的 60%氮肥与钾肥作追肥，结合倒沟于 8 月初和 9 月上旬条施。小区面积 20.0、21.0 m^2，3 次重复，完全随机区组排列。供试生姜品种为当地主栽的狮头姜，种植密度 10.5×10^4 株/hm^2。每年 3 月底催芽，5 月初移栽，10 月下旬按小区单独收获计实产。其他栽培管理措施如病虫草害防治同当地一般大田生姜。

1.3　测定项目和分析方法

在生姜收获期调查单位面积株数，每小区采集代表性植株 5 株，调查株高、分枝数、姜球数、单株姜块

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重和地上部茎叶重，保留新鲜块茎样品供测定品质。

分析方法：土壤、姜块品质和养分含量的测定均参照《土壤农化分析》进行[7]，土壤基本性状采用常规法分析。应用2，6-二氯靛酚滴定法测定生姜块茎维生素C含量，可溶性糖的分析采用HCl转化-铜还原-直接滴定法，用酚二磺酸比色法测定姜块硝酸盐含量。生姜块茎烘干磨碎后采用$H_2SO_4-H_2O_2$消煮，开氏定氮法测全N；粗蛋白总量＝全氮×6.25[8]。数据采用Excel软件和SPSS软件进行统计分析，应用最小差异显著法LSD法进行多重比较。

2 结果与分析

2.1 不同施钾量对生姜生长及产量的影响

表1的调查结果说明，在施用氮磷肥的基础上，增施钾肥对生姜的生长发育有较大的促进作用。与不施钾的对照相比，施钾生姜植株高度、茎粗、分枝数、子姜球数、地上部生物量和单株姜块重都有较大幅度的提高，差异达显著水平。施钾量在450 kg/hm²以下时，生姜株高、茎粗、分枝数、子姜球数、单株姜块重和生物量随钾肥用量的加大都有逐渐增加的趋势。田间观察发现，施钾生姜植株叶色浓绿，生长旺盛健壮，抗病虫害能力明显提高。收获时施钾姜块外观色泽好，肥厚鲜嫩。

研究表明，生姜块茎产量主要由收获期单位面积有效株数和单株姜块茎重构成，而单株姜块茎重则与分枝数和子姜球数有关。从表1可看出，不同施钾量对生姜块茎产量及其构成因素有较大的影响。随着施钾量的增加，生姜块茎产量逐渐增加，中等施钾量的K450处理达最大值；施钾量超过450 kg/hm²的K675和K900处理，块茎产量反而又降低。并且不同施钾量间生姜块茎产量存在显著差异，其中施钾各处理较不施钾的对照产量提高22.3%～37.7%，平均增产28.7%，达1%极显著水准；处理K450与K900间产量差异也达1%的极显著水平，与K675间差异达5%显著水准，但与K225间产量差异不显著；同时，K225、K675与K900三处理间产量差异不显著。进一步分析表明，生姜块茎产量与施钾(K_2O)量之间呈极显著的一元二次抛物线关系，其回归方程为 $y=-0.054\,048K^2+50.847\,738K+36\,144.5$，$F=47.03^{**}$，$r=0.942^{**}$，Signif $F=0.000\,0$，回归方程检验结果达1%的极显著水平，建立的回归方程有效，表明生姜块茎产量与施钾量的关系很密切。进一步对自变量在回归方程中作用的大小进行检验，检验结果也达极显著水平，说明生姜产量与钾肥施用量的关系很密切，可作为推断生姜产量的依据。由此可得，施K_2O量470.4 kg/hm²时，生姜块茎产量达到最高，达48 103.7 kg/hm²；根据生姜价格2.00元/kg和K_2O价格6.67元/kg，可进一步求出最佳K_2O施用量为439.6 kg/hm²，最佳施肥量时的生姜块茎产量为48 052.3 kg/hm²，基本接近最高产量。

表1 施钾对生姜生长和块茎产量的影响

Table 1 Effect of potash application rates on ginger growth, yield and its component

处理	株高(cm)	分枝数(个/株)	茎周长(cm)	姜球数(个/株)	姜块鲜重(g/株)	生物量(g/株)	经济产量(t/hm²)	增产(%)
K0	74.5 b	8.0 c	4.70 b	10.1 c	439.5 c	79.7 c	35.38 c C	—
K225	86.0 a	10.0 b	5.05 ab	11.7 b	526.0 ab	98.0 b	45.38 ab AB	28.27
K450	88.5 a	12.5 a	5.50 a	12.8 a	568.0 a	109.6 a	48.72 a A	37.69
K675	92.5 a	11.5 a	5.25 a	12.5 ab	533.2 ab	105.2 ab	44.80 b AB	26.59
K900	90.0 a	9.5 b	4.95 ab	12.3 ab	491.4 b	96.7 b	43.29 b B	22.34

注：小写字母表示差异达5%显著水平，大写字母表示差异达1%显著水平。下同。

2.2 施用钾肥对生姜块茎品质的影响

2.2.1 施用钾肥对姜块蛋白质和维生素C含量的影响

蛋白质和维生素C是衡量蔬菜营养品质的两种重要指标。施用适量的钾肥能有效提高生姜块茎粗蛋白和维生素C含量，改善姜块内在营养品质(见表2)。与块茎产量相似，施钾量较低时，姜块维生素C含量也随钾肥施用量的增加而显著提高，中等施钾量的K450处理达到最高；继续增加钾肥施用量，姜块维生素C含量显著下降，K900处理甚至低于对照K0，只是两者间差异不显著。施用不同数量钾肥对姜块粗蛋白含量的影响与维生素C相似，中低施钾量时，随施钾量的增加，块茎粗蛋白含量也相应显著提高，K450处理达到高峰，K900处理也低于对照K0，表明过量施钾对姜块品质也会产生不利的影响。

表 2　施用钾肥对生姜块茎品质的影响

Table 2　Effect of potash fertilizer application on qualities of ginger rhizome

处理	粗蛋白质		维生素 C		可溶性糖		还原糖		硝酸盐	
	含量（%）	指数（%）	含量（mg/kg）	指数（%）	含量（%）	指数（%）	含量（%）	指数（%）	含量（mg/kg）	指数（%）
K0	11.97 b	100.0	17.23 c	100.0	3.65 b	100.0	2.04 b	100.0	156.1 a	100.0
K225	13.81 a	115.4	20.94 b	121.5	3.90 ab	106.8	2.20 ab	107.8	110.0 bc	70.5
K450	14.14 a	118.1	23.23 a	134.8	4.09 a	112.1	2.46 a	120.6	102.4 c	65.6
K675	13.60 a	113.6	19.58 b	113.6	3.82 ab	104.7	2.37 a	116.2	104.8 c	67.1
K900	11.10 b	92.7	16.50 c	95.8	3.72 b	101.9	2.26 ab	110.8	118.7 b	76.0

2.2.2　施用钾肥对姜块糖分含量的影响

施用不同数量钾肥对生姜块茎可溶性糖和还原糖含量有明显影响（见表 2）。可溶性糖含量表现为随施钾量的增加逐渐升高，K450 处理达最大值，同时不同施钾量间生姜块茎可溶性糖含量存在显著差异。其中施钾各处理较不施钾的对照提高 1.9%～12.1%，平均提高 6.4%，提高的幅度远低于维生素 C，同时仅中等施钾量的 K450 处理与对照 K0 间差异达 5%显著水平，其他施钾处理与 K0 间差异不显著，表明适量施钾才能有效提高生姜块茎可溶性糖含量。不同钾水平对生姜块茎还原糖含量的影响与可溶性糖相似，施用适量钾肥，还原糖含量也显著提高，K450 和 K675 与 K0 间差异达显著水平，而不同施钾量间差异则不显著（见表 2）。

2.2.3　施用钾肥对姜块硝酸盐含量的影响

硝酸盐含量是衡量蔬菜安全食用品质的主要指标[10]。施用不同数量的钾肥对生姜块茎硝酸盐含量有显著影响（见表 2）。从表 2 可看出，增施钾肥后生姜块茎硝酸盐含量均较对照 K0 显著下降。与 K0 比，各施 K 处理相应下降 24.0%～34.4%，平均降低 30.2%，差异均达 5%显著水平，中等施钾量的 K450 处理硝酸盐含量最低，K675 次之，而最高施钾量的 K900 处理硝酸盐下降的幅度则最小，并且 K450 和 K675 处理与高施钾量的 K900 间差异也达 5%显著水平，表明钾肥用量过大也不利于降低生姜块茎硝酸盐含量，对蔬菜的安全食用品质有不利影响。

2.3　生姜施钾的经济效益

表 3 的结果说明，在施用氮磷肥的基础上增施适量的钾肥，可以大幅度提高生姜的总产值，农民种植生姜收入显著增高，种植生姜的经济效益相对较好。与不施钾的不足 9 万元/hm^2 产值的对照相比，施钾处理的产值每公顷都在 10 万元以上，增收 27 086～40 659 元/hm^2，施用钾肥的产投比高达（5.16～24.63）∶1，K225 处理施钾产投比最高超过 24.6∶1；K450 处理效益最好，增收 40 660 元/hm^2。随着施钾量的增加，施用钾肥的产投比逐渐下降；当施钾（K_2O）量超过 450 kg/hm^2 时，产投比降至 10 以下；与此同时，生姜块茎产量下降导致总产值下降，而随钾肥投入量加大施肥成本也快速上升，结果种姜收益降低，施肥的经济效益下滑；其中高施钾量的 K900 处理的产投比只有 5.16∶1，效益很低。说明合理施钾是提高钾肥施用效益的有效和重要途径。

表 3　生姜施用钾肥的经济效益

Table 3　Effect of K application rates on profit and potassium use efficiency of ginger rhizome

处理	平均产量（kg/hm^2）	总产值（元/hm^2）	肥料投入（元/hm^2）	用工费（元/hm^2）	种姜收益（元/hm^2）	增加收入（元/hm^2）	钾肥投入（元/hm^2）	施钾肥产投比
K0	35 382	88 455	2 390	36 000	50 065	—	—	—
K225	45 384	113 460	3 703	36 000	73 757	32 326	1 313	24.63
K450	48 717	121 793	5 015	36 000	80 777	40 659	2 625	15.49
K600	44 789	111 973	6 328	36 000	69 645	30 839	3 938	7.83
K900	43 288	108 220	7 640	36 000	64 580	27 086	5 250	5.16

注：生姜价格＝2.50 元/kg；N 的价格＝4.35 元/kg，P_2O_5 的价格＝4.82 元/kg，K_2O 的价格＝5.83 元/kg；用工费以 60 元/工计算。

3　讨论

施钾量对生姜块茎产量的影响表现为：在一定范围内，随施钾量的增加块茎产量提高，超过一定范围块茎产量增长缓慢，甚至增产不显著[4]。关于施钾量的高限，由于研究条件的差异，不同品种生姜差别较大。

艾希珍[4]在山东的研究结果为 600 kg/hm²，安徽[3]适宜施 K_2O 量为 375～450 kg/hm²，张传珂[9]山东拟合结果为 274～426 kg/hm²。本研究结果表明，生姜块茎产量随施 K 量的加大先增加后降低，两者呈一元二次抛物线关系，K450 处理产量达最高值范围，最高产量施 K_2O 量为 470.4 kg/hm²，最佳 K_2O 施用量为 439.6 kg/hm²，因此当前生产条件下，淮北平原砂姜黑土地区，生姜适宜施钾(K_2O)量为 450 kg/hm² 左右。超过适宜施钾量，氮钾比例不平衡，生姜生长发育受到不利影响，分枝数和姜球数减少，单株块茎重下降，块茎产量显著降低。

姜块蛋白质、维生素 C、糖分和硝酸盐含量是生姜主要的营养及安全食用品质指标。徐坤和艾希珍研究结果表明，适量施用钾肥可显著提高生姜块茎蛋白质含量，并有利于糖和 Vc 的形成[4, 6]。本研究表明，施用不同数量的钾肥均能显著提高生姜块茎粗蛋白、维生素 C 和糖分含量，改善其营养品质，中等施钾量的 K450 处理，粗蛋白质、维生素 C、可溶性糖及还原糖含量最高，还显著高于 K900 或 K225 处理，与 Majumdar 等人的研究结果相似[5]。施用钾肥后，生姜块茎硝酸盐含量较不施钾的对照均显著降低，中等施钾量的 K450 硝酸盐含量最低，较对照的降幅更大，表明适量施钾能有效降低生姜块茎硝酸盐等有害物质的含量。生姜作为调味品，虽然用量相对较少，对饮食安全威胁不大，但是新鲜幼嫩的姜块可作为蔬菜盐渍生食或炒食，硝酸盐含量过高会增加人们对硝酸盐等有害物质的摄入量，对人类健康造成损害。中低施钾量的 K225 处理，硝酸盐含量与其他各施钾处理间差异不显著，适当控制钾肥施用量，既能有效降低硝酸盐含量，使生姜产品硝酸盐含量保持在食品安全范围(低于 432 mg/kg)内，又能显著降低施肥成本，提高钾肥利用效率和施肥的经济效益。

大量研究表明，合理施用肥料才能取得明显的增产增收效果，从而有效提高施肥的经济效益，获得较高的施肥产投比[10-12]。本研究结果表明，在施用氮磷肥的基础上增施适量的钾肥，可以大幅度提高生姜的总产值，使农民种植生姜的收入显著增加。施钾增收 27 086～40 659 元/hm²，施用钾肥的产投比高达(5.16～24.63)∶1，K225 处理施钾产投比最高超过24.6∶1；K450 处理效益最好，增收 40 660 元/hm²。因此，合理施用钾肥对增加生姜产量、改善块茎品质及提高施肥经济效益均具有重要作用。生产上应合理施用钾肥，并采用 NPK 配合施用，以促进生姜对钾素的吸收利用，增加块茎产量，改善品质，提高钾肥利用效率，达到生姜高产优质和环境友好的生产目标。

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Effect of different potash fertilizer application rates on growth and nutrient qualities of ginger

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Abstract: Field experiments were conducted to study the effects of different potash (K) application rates on growth, uptake of potassium, nutrition qualities and profit of ginger (*Zingiber officinale*). Results showed that appropriate K application rates could significantly promote ginger growth, increase rhizome yield, raise K concentration and uptake, and improve nutrition quality and profit. Ginger rhizome yield increased by 13.0%-27.2% and 22.3%-37.7% with averages of 22.5% and 28.7% at two sites two years respectively, with a parabolic relationship between rhizome yield and K application rate, and the highest rhizome yield was obtained by the treatment of medium K application rate of K_{450}. K concentration and K uptake in ginger shoot, rhizome and total plant increased by 33.4%-210.7%, 2.9%-70.8% and 18.4%-139.9%, as well as 64.5%-342.2%, 31.3%-118.7% and 48.5%-209.0% respectively, when different potash rates were applied. The content of rough protein, vitamin C, and soluble sugar in ginger rhizome enhanced obviously and the treatment of K_{450} reached the peak when the suitable K rate was applied. The profit increased by 13,626-23,286 yuan/hm^2 and the value cost ration reached (2.27-12.60) : 1 compared the treatments of K application to the control.

Key words: Different potash application rates, ginger, uptake of potassium, quality, profit

不同钾用量对山东褐土夏玉米产量、效益及钾素平衡的影响

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摘　要：在山东省褐土区夏玉米生产上设计了不同钾肥用量试验。结果表明：各施钾处理玉米产量均比不施钾处理增加，增产幅度为4.97%～5.59%，施钾90 kg/hm² 处理与不施钾处理相比玉米产量增产达到极显著水平，施钾180 kg/hm² 和施钾270 kg/hm² 处理与不施钾处理玉米产量相比增产达到显著水平，各施钾处理玉米产量之间没有显著差异。经计算得出最高产量施用钾量为174.2 kg/hm²，最经济施用钾量为50.6 kg/hm²，从收获后的样品分析，绝大部分钾积累于玉米秸秆中。随着施钾量的增加，秸秆和籽粒中的钾含量都有增加的趋势。从土壤-作物系统内钾素平衡状况看，施钾204 kg/hm² 时可以实现土壤钾素的收支平衡。随着施钾量的增加，钾肥利用率逐渐下降，钾肥当季利用率在17.99%～54.28%。

关键词：钾用量；褐土；夏玉米；钾素平衡；经济效益；钾肥利用率

中图分类号：S143.3；S513

钾是作物必需的大量营养元素之一，施用钾肥对提高作物产量、改善品质以及提高其抗逆性具有明显作用[1]。近年来，随着农业科技的进步与推广，农民提高了对钾的认识，在农业生产中钾肥的用量有了明显增加[2]。不同地区由于自然条件及种植管理措施的差异，在当地生产上的肥料适宜用量而不一致。褐土是山东省的主要土壤类型之一，主要分布于胶济铁路沿线及鲁中南地区，约占全省耕地面积的21.1%。其成土母质为石灰岩风化物、黄土和洪、冲积物。土层深厚、肥力较高[3]，属于传统的农业种植区域，当地农民习惯在生产上投入肥料量较大，以获取高产，但如果肥料施用过量，不仅造成浪费，还会引起环境污染等问题。针对生产现状，在山东省褐土区开展夏玉米钾素适宜用量的研究试验，目的是确定夏玉米生产中钾素的最佳补充量，为合理施肥提供理论依据，以指导农业生产实践。

1　材料和方法

1.1　试验材料

试验于2008年5月至2008年10月在山东省青州市高柳镇廉颇村进行。该试验地块位于鲁北平原南部，处于暖温带半湿润季风气候区。年平均气温13.1℃，年平均降水量641.5 mm，干旱时采用地下水机井浇灌。

供试土壤为褐土，质地为轻壤。玉米种植方式是麦田套播，播种前采取耕层土壤样品(0～20 cm)采用常规法方法分析农化性状[4]。土壤养分状况为：有机质1.58%，碱解氮80.04 mg/kg，有效磷33.71 mg/kg，速效钾151.50 mg/kg。玉米品种为郑单958，播种密度4 000 株/hm²。氮肥为尿素，磷肥为过磷酸钙，钾肥为氯化钾(加拿大)。

1.2　试验方法与过程

试验为随机区组设计，试验设5个处理，重复3次。小区面积40 m²。各处理情况见表1。

表1　玉米各处理肥料用量

Table 1　Fertilizer levels of the treatments of Summer-Maize

处理 Treatments	施肥量 Fertilizer levels (kg/hm²)		
	N	P_2O_5	K_2O
1 K0	180	75	0
2 K45	180	75	45

* 通讯作者：崔荣宗(1964—)，男，山东省青岛市人，研究员，主要从事作物营养与施肥方面研究。E-mail：rzcui@ipni.ac.cn

续 表

处理 Treatments	施肥量 Fertilizer levels (kg/hm²)		
	N	P_2O_5	K_2O
3 K90	180	75	90
4 K180	180	75	180
5 K270	180	75	270

玉米于2008年5月26日麦田内套播，于6月20日第一次追肥，施用全部的磷钾肥和50%的氮肥，另外50%氮肥于7月22日大喇叭口期第二次追施。

成熟期每个小区地上部全部收获计产，分籽粒和秸秆两部分分别记录。并采取各小区有代表性的样品，秸秆整株用粉碎机粉碎，混匀后取样。籽粒和粉碎的秸秆样品80℃烘干至恒重，粉碎过2 mm筛，经$H_2SO_4-H_2O_2$消煮，火焰光度计法分别测定全钾含量。

数据用Excel和DPS软件进行统计分析。

2 结果与分析

2.1 经济产量分析

从经济产量分析表可知，各施钾处理均比不施钾处理玉米产量增加，增产幅度为4.97%～5.59%，其中以施钾90 kg/hm² 处理增产幅度最大，增产玉米377.09 kg/hm²，增产率为5.59%。统计分析显示，施钾90 kg/hm² 处理与不施钾处理玉米产量相比增产达到极显著性水平，施钾180 kg/hm² 和施钾270 kg/hm² 处理与不施钾处理玉米产量相比增产达到显著性水平，各施钾处理玉米产量之间没有明显性差异。以施钾量和产量做出肥料效应方程为$y=-0.020\,2x^2+9.659\,3x+7\,455.5$($R^2=0.937\,6$)，经计算玉米获得最高产量的施钾量为174.2 kg/hm²。计算钾元素的增产效益可知，施钾45 kg/hm² 处理的增产效益最高，每施入1 kg钾可使玉米增产5.99 kg。随着施钾量的增加，每施入1 kg钾元素玉米的增产量逐渐降低。从产值中扣除肥料成本，分析各处理的纯收益，纯收益由高至低的顺序为K45＞K0＞K90＞K135＞K270。经计算最经济的施钾量为50.6 kg/hm²。

表2 不同施钾处理经济产量及收益分析

Table 2 Yield and economic efficiency analysis of different K treatments

处理 Treatments	产量 Yield (kg/hm²)	增产* Increasing yield (kg/hm²)	增产率* Increased rate (%)	钾增产 Yield increment per kg K_2O (kg/kg)	产值 Output (元/hm²)	纯收益 Net income (元/hm²)
1 K0	6 750.10bB	—	—		9 450.14	8 016.14
2 K45	7 019.55abAB	269.46	3.99	5.99	9 827.38	8 091.88
3 K90	7 127.19aA	377.09	5.59	4.19	9 978.06	7 941.06
4 K180	7 097.66aAB	347.56	5.15	1.93	9 936.72	7 598.22
5 K270	7 085.81aAB	335.71	4.97	1.24	9 920.13	7 280.13

注：* 增产(kg/hm²)＝其他处理产量－K_0 产量；

* 增产率(%)＝[(其他处理产量－K_0 产量)/ K_0 产量]×100；

钾增产(kg/kg)施入单位钾养分的增产量；

肥料价格：N＝4.8元/kg，P_2O_5＝7.6元/kg，K_2O＝6.7元/kg；

收获物(玉米)价格＝1.4元/kg。

2.2 土壤钾素平衡及钾素利用率分析

钾在作物体内的吸收、转移、分配是玉米养分利用的重要过程。对收获后的样品分析可以看出(见表3)，秸秆和籽粒中的钾含量差别较大，前者是后者的6～7倍。随着施钾量的增加，秸秆和籽粒中的钾含量都有增加的趋势。从土壤-作物系统内钾素平衡状况看，除K270处理外，其余各处理玉米季生产上土壤钾均表现不同程度的亏缺，不施钾处理亏缺160.44 kg/hm²，随着施钾量的增加，亏缺逐渐减小，施钾180 kg/hm² 时，仅亏缺20.64 kg/hm²，而施钾270 kg/hm² 时则表现为盈余61 kg/hm²。以施入钾量与移走钾量之比作为钾平衡系数，随着施钾量增加，平衡系数逐渐增大，经计算可得出施钾204 kg/hm² 时可以实现

土壤钾素的收支平衡。从钾肥利用率的计算结果看，钾肥当季利用率在 17.99%～54.28%，随着施钾量的增加，钾肥利用率逐渐下降，应根据生产情况，合理确定钾肥用量，提高肥料利用率。

表 3　不同施钾处理土壤钾素平衡及钾素利用率分析

Table 3　Potassium balance and KUE analysis of different K treatments

处理 Treatments	秸秆 Stem 钾含量* K_2O content(%)	籽粒 Grain 钾吸收量 K_2O adsorption (kg/hm^2)	钾含量 K_2O content(%)	钾吸收量 K_2O adsorption (kg/hm^2)	施入土壤钾量 Potassium levels (kg/hm^2)	土壤钾盈亏 Soil Potassium balance (kg/hm^2)	钾平衡系数 Equilibrium coefficient of potassium	钾素利用率 (KUE) (%)
1 K0	2.12	141.21	0.31	19.23	0	−160.44	0	—
2 K45	2.33	162.28	0.35	22.58	45	−139.86	0.24	54.28
3 K90	2.37	169.31	0.37	24.23	90	−103.55	0.47	36.79
4 K180	2.44	173.24	0.42	27.40	180	−20.64	0.90	22.33
5 K270	2.51	180.35	0.44	28.65	270	61.00	1.29	17.99

注：* 钾含量以 K_2O 计。

3　讨论与结论

本研究中收获后测定玉米秸秆和籽粒中钾的含量结果显示两者差异非常大，与前人的很多研究报道不一致[5-7]，可能与玉米品种不同或样品收集处理方式有关，可进一步探讨。从玉米收获移走钾量分配看，绝大部分钾保留在玉米秸秆中，如果通过秸秆还田或其他方式及时返回到土壤中，则只需补充少量的钾肥就可以实现土壤钾素平衡。

从试验结果看，在山东省褐土上施钾有助于玉米增产，施钾量在 0～90 kg/hm^2 时，随着施钾量的增加，玉米增产幅度也变大，施钾量在 90～270 kg/hm^2 时，玉米的增产幅度随着施钾量的增加而逐渐降低。从养分的增产效益可以看出，随着施钾量的增加，钾元素的增产效益逐渐下降，当施钾量在 45 kg/hm^2 时钾元素的增产效益最高。由于受当年肥料价格较高因素的限制，增施钾肥虽然增加了产量，但纯收益却没有一定增加。在本试验条件下，夏玉米获得最高产量的施钾量为 174.2 kg/hm^2；考虑到当年肥料价格，最经济的施钾量为50.6 kg/hm^2；从计算土壤钾素平衡结果显示，施钾 204 kg/hm^2 时可以实现土壤钾素的收支平衡。江丽华等 2001 年在褐土区的试验结果表明当地夏玉米生产上钾肥适宜用量在 75～225 kg/hm^2[8]，本试验研究结果与之基本一致。

由于玉米生产及钾肥施用效果受土壤肥力、土壤类型、气候及品种等多个因素的影响，不同地区、不同地类之间肥料用量也具有一定的差异。应根据各地区的具体情况进行肥料施用量的合理优化，以实现玉米高产、优质和高效。

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Effects of potassium levels on the yield, efficiency and K balance of summer-maize in cinnamon soil of Shandong Province

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Abstract: The study of different potassium(K) levels was conducted on summer-maize production in cinnamon soil area of Shandong Province. Results showed that the maize yields of K treatments were all increased compared to no K treatment by an amplitude of 4.97% to 5.59%. The difference between the treatment with 90 kg/hm^2 K_2O and no K treatment was very obvious, the differences between the treatment of 180 kg/hm^2 K_2O, 270 kg/hm^2 K_2O and no K treatment were obvious, but there were no obvious differences among maize yields of the K treatments. According to the calculations, the K_2O level of the highest maize yield was 174.2 kg/hm^2, the highest economic K_2O level was 50.6 kg/hm^2. The main K_2O accumulated in maize straws according to sample analysis. The K_2O contents in straw and grain increased with the increase of K_2O levels. From the point of potassium balance between soil and crop, 204 kg/hm^2 K_2O was needed to balance the income and output of soil potassium. But the potassium (K) use efficiency (KUE) was decreased with the increase of potassium level. The KUE ranged from 17.99% to 54.28% in the experiment.

Key Words: K level, cinnamon soil, summer-Maize, potassium balance, economic efficiency, potassium use efficiency (KUE)

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