Role of Mineral Nutrition in Carbon Allocation and Biomass Production in Bioenergy Plants

Ismail Cakmak
Sabanci University, Istanbul, Turkey

Dependency on Fossil Fuels

Dependency on fossil fuels is still high which cause serious adverse environmental impacts such as high emission of greenhouse gases.

Reducing the dependency on this non-renewable fuel is now an important global challenge.

Alternative to Fossil Fuels

- Converting plant-based biomass into fuel as a renewable energy source (e.g., **biomass-based fuel**) is a promising alternative to fossil fuel.
- Bioethanol and biodiesel are the major biomass fuels, and their widespread usage is expected to mitigate significantly greenhouse gas emissions.

The **sustainability and economics** of the biomass fuel production is dependent on the size of biomass and the concentrations and composition of carbohydrates or oils in the targeted plant biomass.

Role of Mineral Nutrition

Average Crop Yields and Biofuel Production

Crop	Country	Product	Yield	Biofuel
			(t ha^{-1})	(L ha^{-1})
oil palm	Indonesia	Biodiesel	17.8	4092
sugarcane	India	Bioethanol	60.7	4522
maize	China	Bioethanol	5.0	1995
cassava	Nigeria	Bioethanol	10.8	1480

Connor and Hernandez, 2009. In: R.W. Howarth and S. Bringezu; Biofuels:……: http://cip.cornell.edu/biofuels

Role of Mineral Nutrition

Productivity of plants (e.g., size of biomass) is dependent on

i) the capacity of plants to fix atmospheric carbon into organic carbon through photosynthesis,

ii) ii) translocation of the assimilated carbon from source into sink organs, and

iii) iii) utilization of assimilated carbon in the sink organs for growth.

All these steps are greatly influenced by the mineral nutritional status of plants

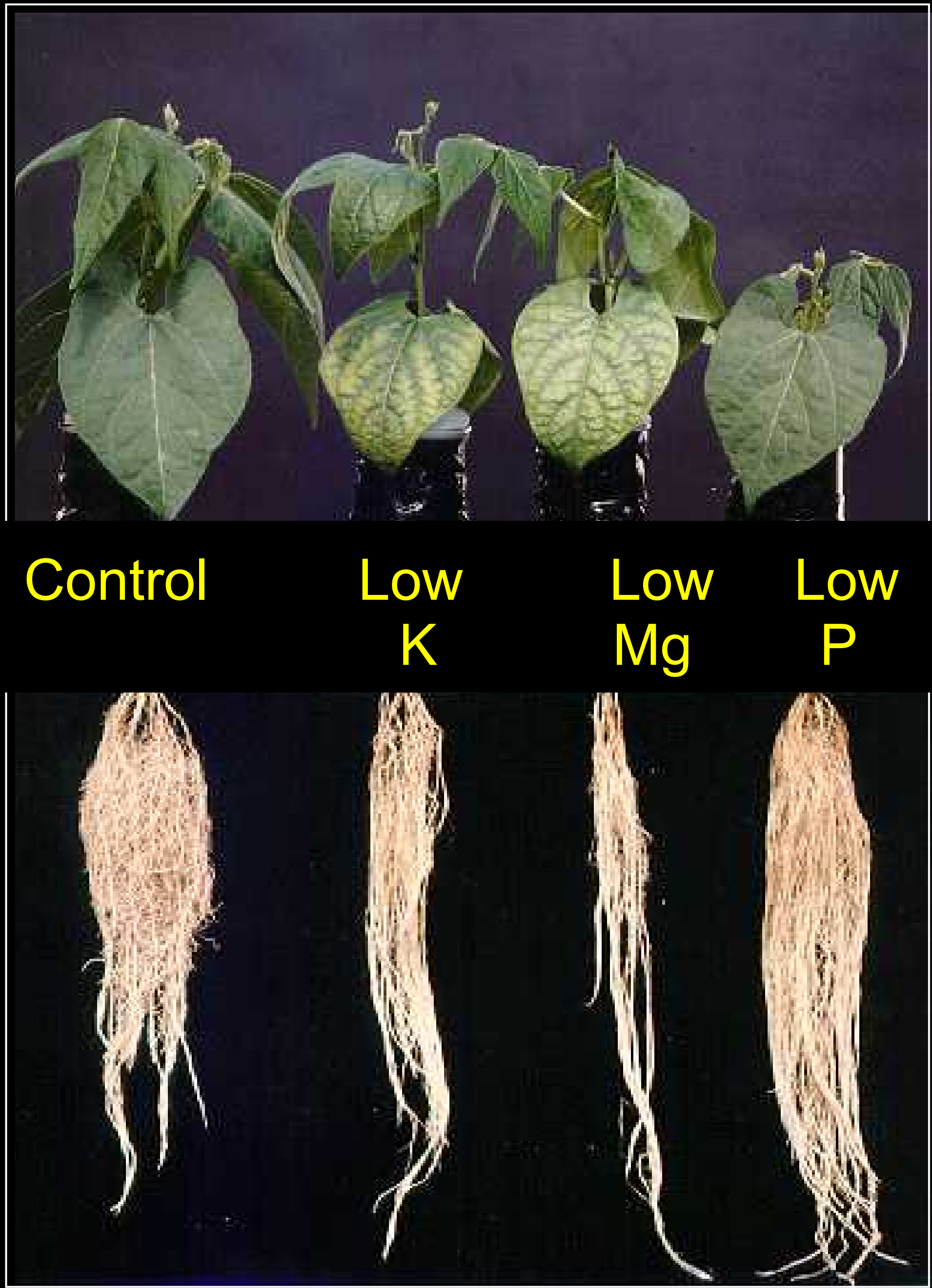
Dry matter and carbohydrate composition and potential ethanol yield in various crops and crop residues

Crop	Dry matter	Carbohydrates	Ethanol yield
	(%)	(%)	(L kg^{-1} dry wt)
Corn	86.2	73.7	0.46
Corn stover	78.5	58.3	0.29
Wheat	89.1	35.9	0.40
Wheat straw	90.1	54.0	0.29
Sugarcane	26.0	67.0	0.50
Sugarcane Bagasse	71.0	67.0	0.28

Kim and Dale, 2004, Biomass and Bioenergy, 26: 361-375

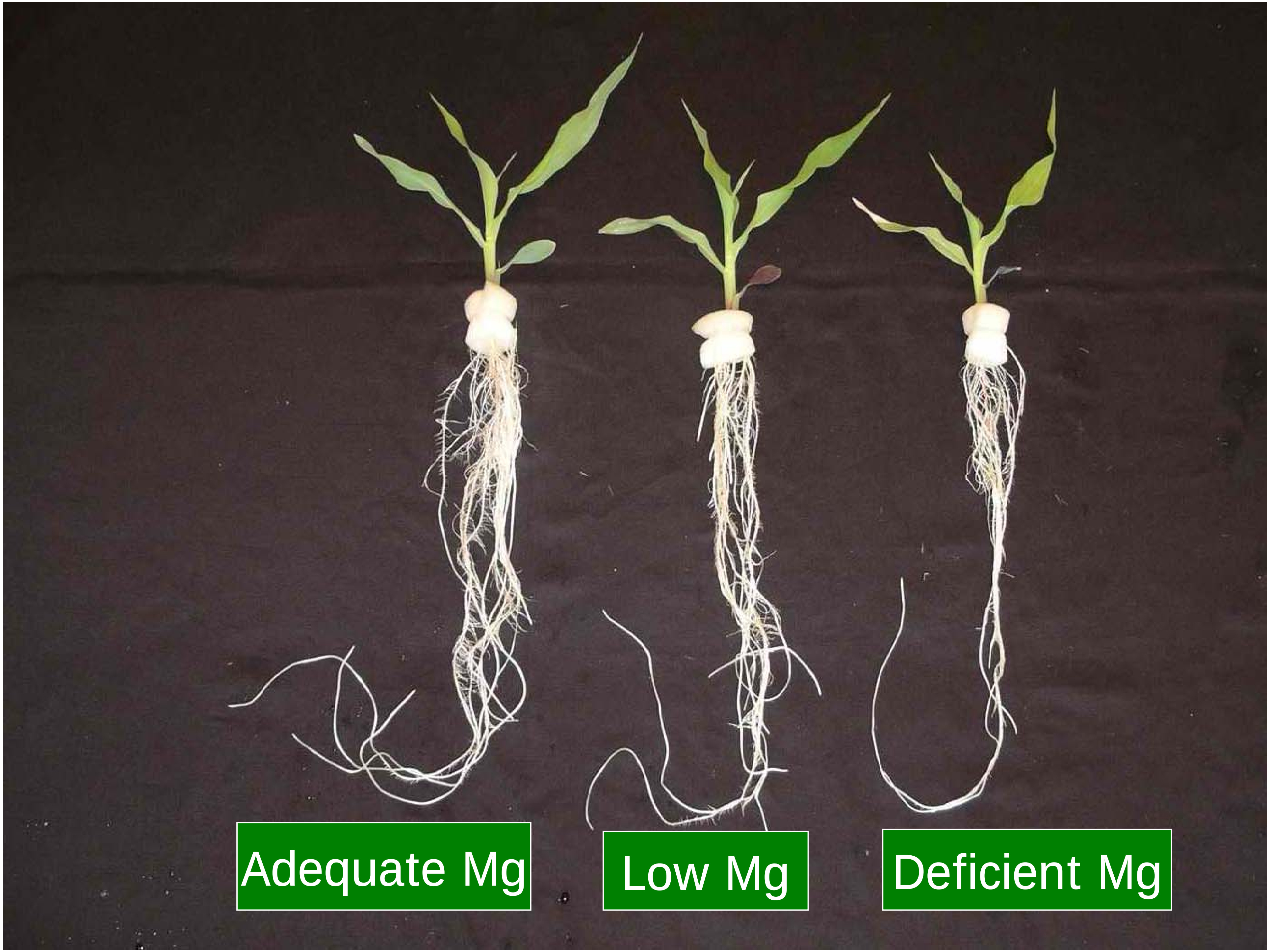
Mineral Nutritional Status of Biofuel Plants

In this presentation several examples will be presented which suggest that a **particular attention should be paid to mineral nutritional status of biofuel plants** to achieve high biomass production and to maximize partitioning of the assimilated carbon in the desired plants organs (e.g., grains, stems or roots).

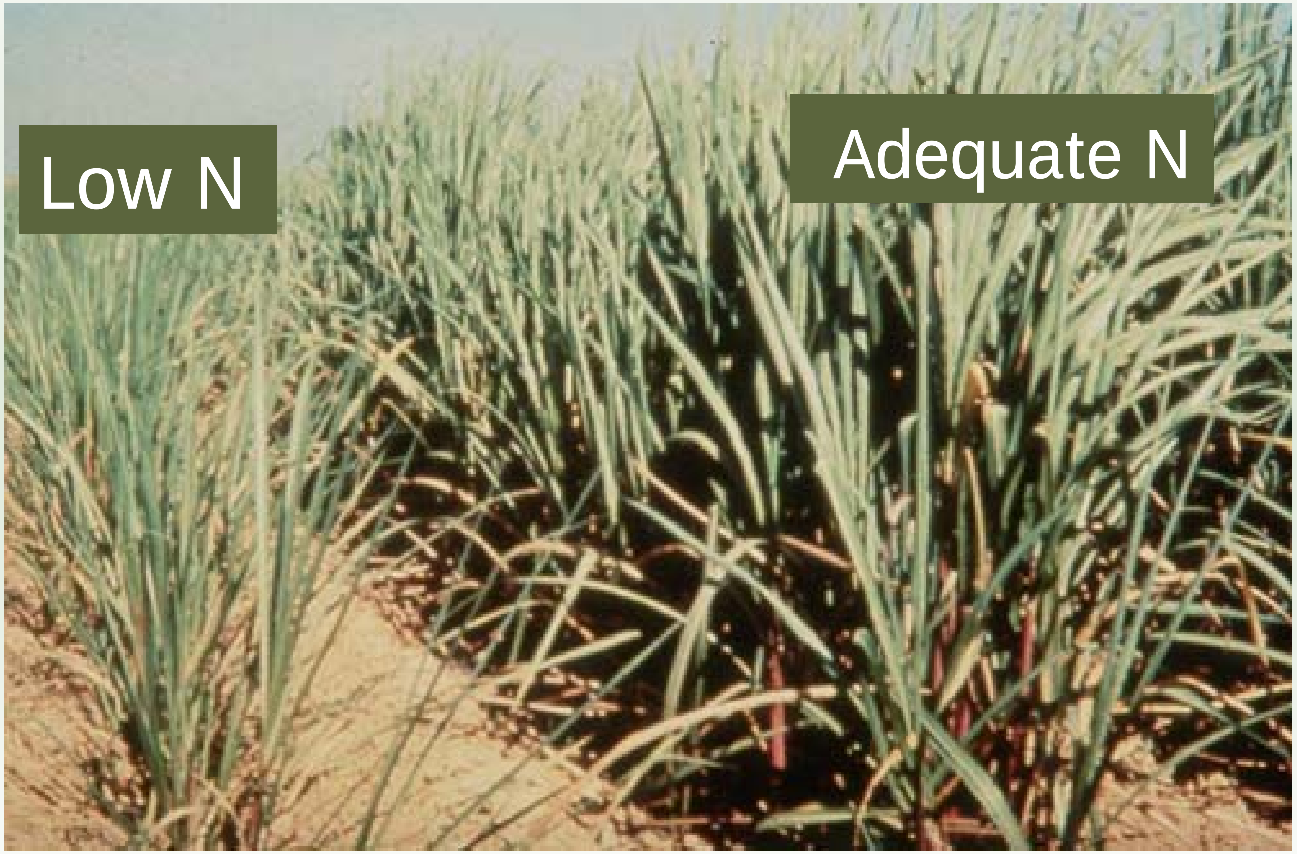


Effect of deficiencies of various mineral nutrients on shoot and root dry weight

Cakmak et al., 1994a
J. Exp. Botany


Adequate Mg
Low Mg
Deficient Mg

Nitrogen deficiency on sugarcane in Brazil



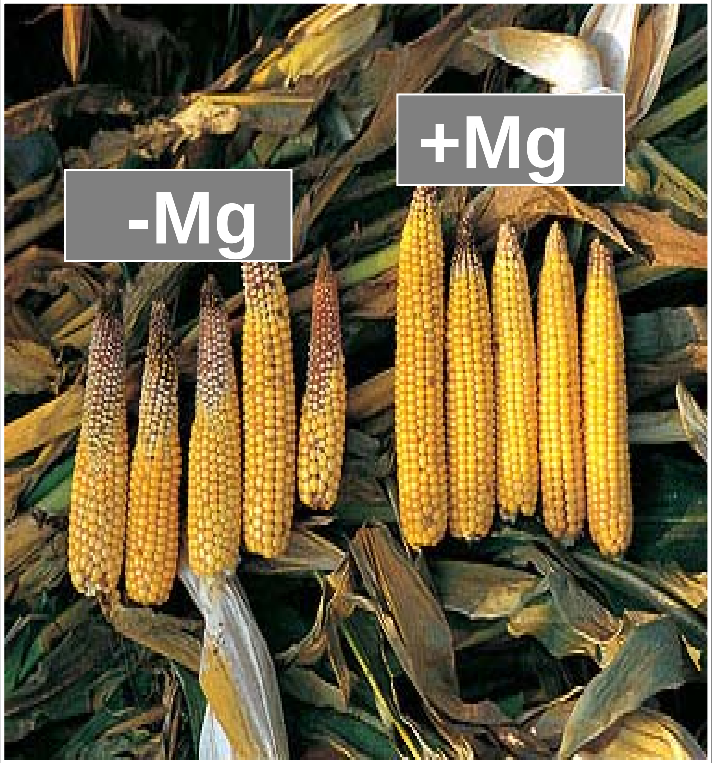
www.potashcorp.com

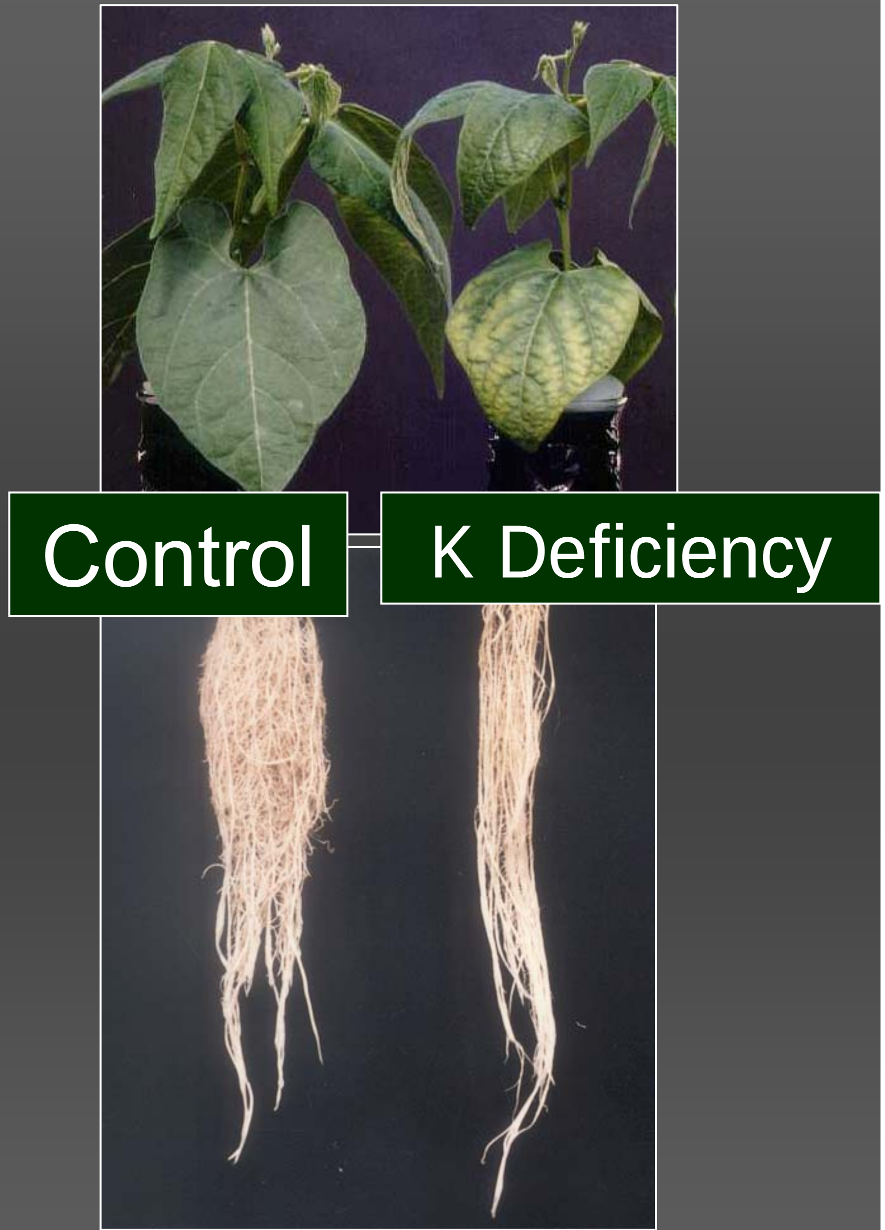
Effect of N P K combinations on root/tuber production in in Potatoes

at 92 (Expt 1) and 58 days (Expt 2) after emergence

Treatment combinations	Root dry wt fraction (%)		Tuber number per plant		Tuber wt. (g $plant^{-1}$)	
	Expt 1	Expt 2	Expt 1	Expt 2	Expt 1	Expt 2
high N P K	2.0	2.9	11.2	27.5	701	629
low N / high P K	2.0	3.1	11.5	21.3	370	465
low P / high N K	2.1	2.4	11.0	27.3	490	587
low K / high N P	1.6	2.2	10.8	17.8	338	418

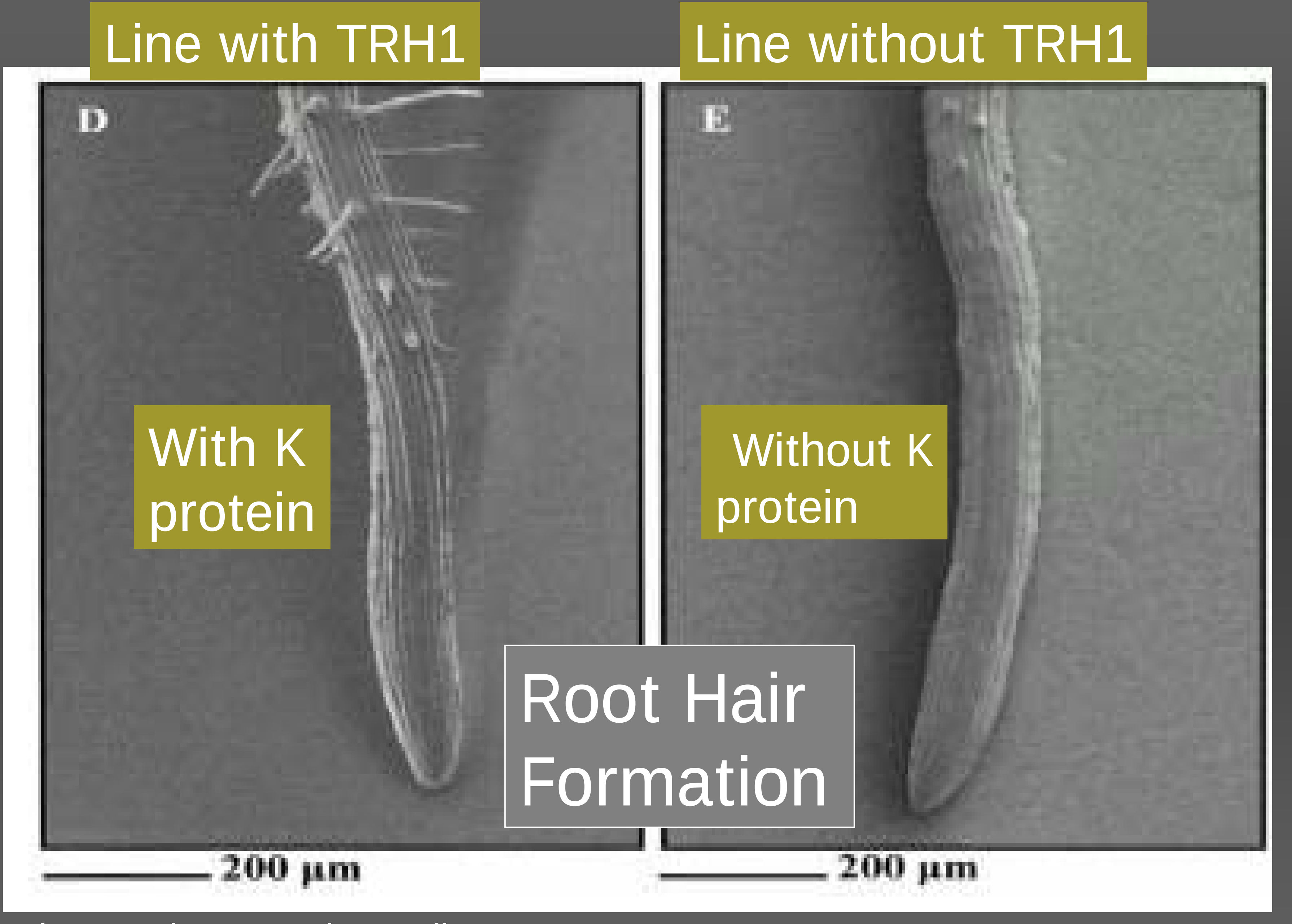
Jenkins and Mahmood, 2002, Ann. App. Biology





Sink Organs are very sensitive to Mg and K deficiencies

Cakmak and Kirkby, 2008, Physiol. Plant.



Rigas et al., 2001, Plant Cell, 13: 139-151

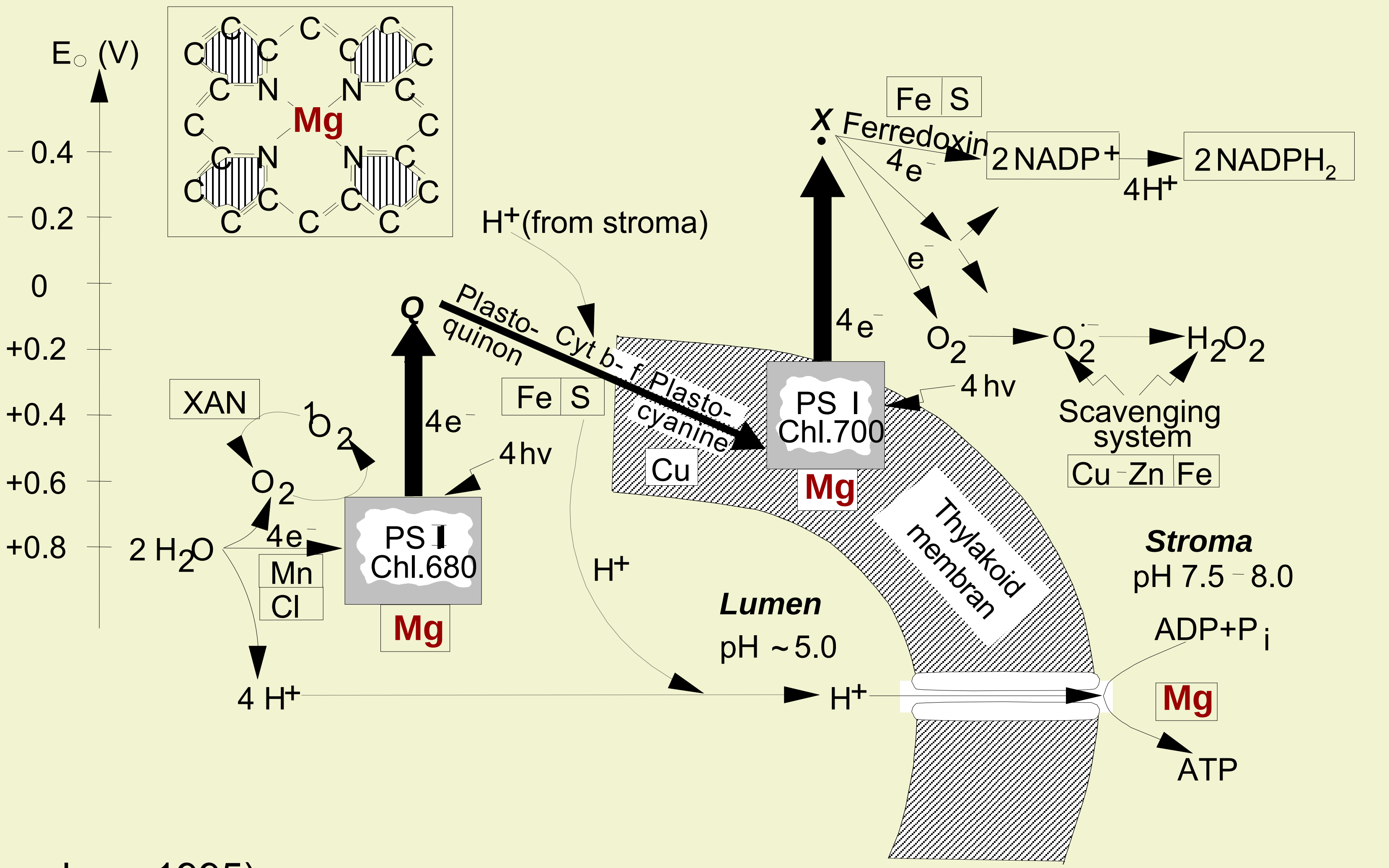
Mineral nutrients behave more or less similarly in their final effect on total dry matter production of plants, but distinctly differently in their final effect on dry matter partitioning between shoot and root organs,

an effect that needs a particular attention in production of bio-energy crops

Question: why mineral nutrient deficiencies greatly effect both

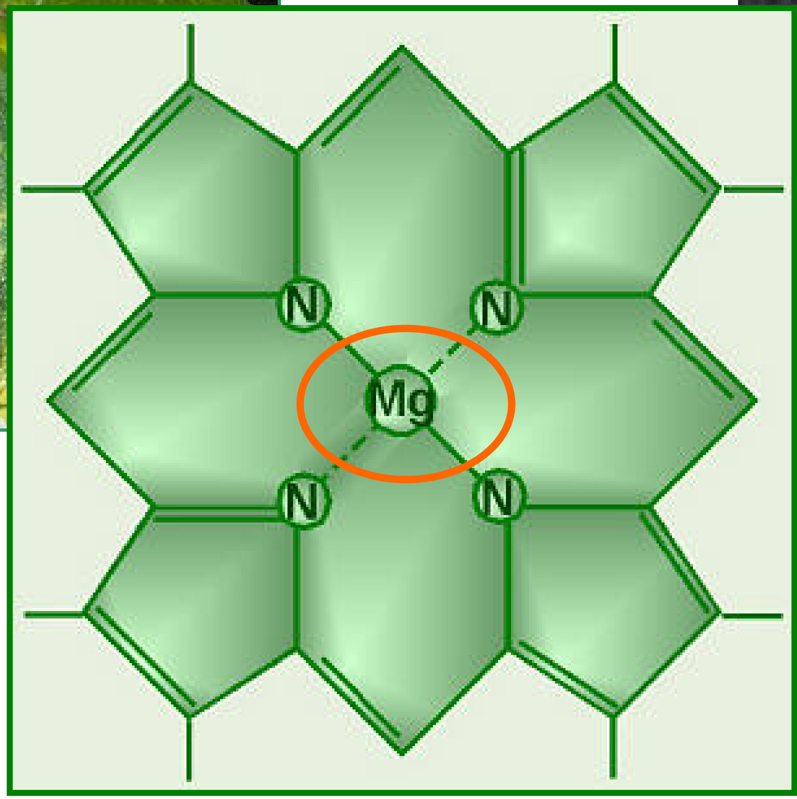
- total amount and
- allocation of biomass/carbon within plants

Several steps of photosynthetic electron transport are affected by various mineral nutrients



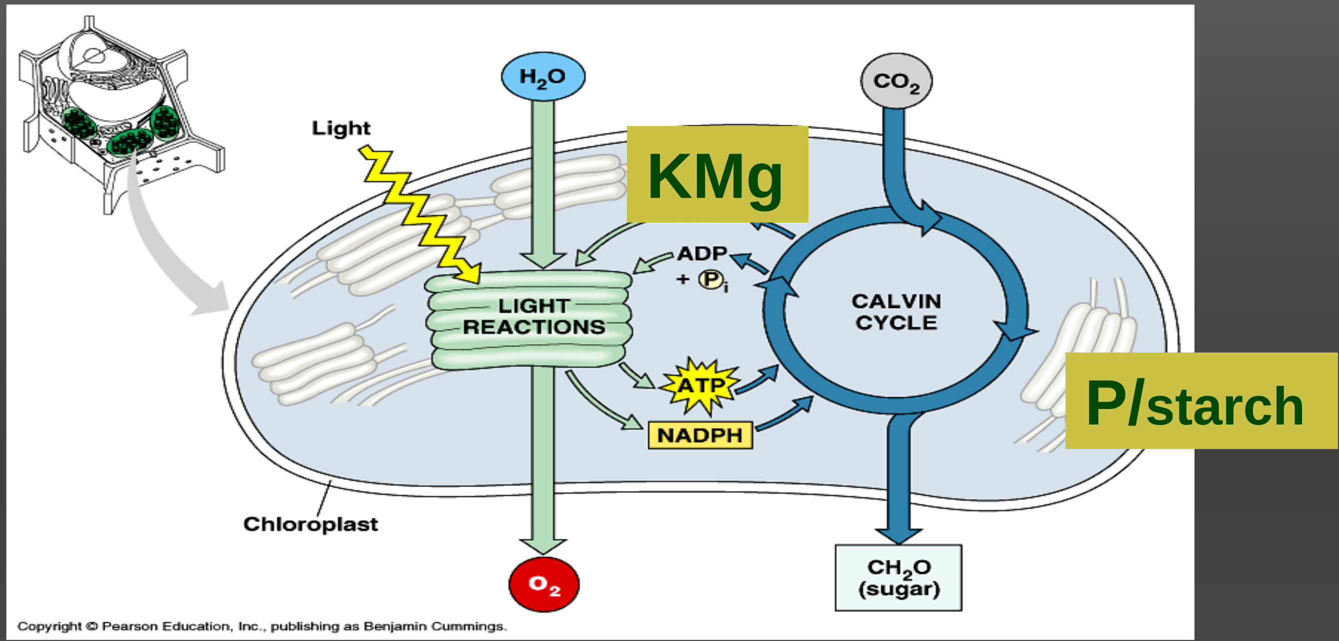
(Marschner,1995)

Nitrogen/Magnesium: central ions of chlorophyll. their deficiencies cause chlorosis



www.rothamsted.ac.uk/

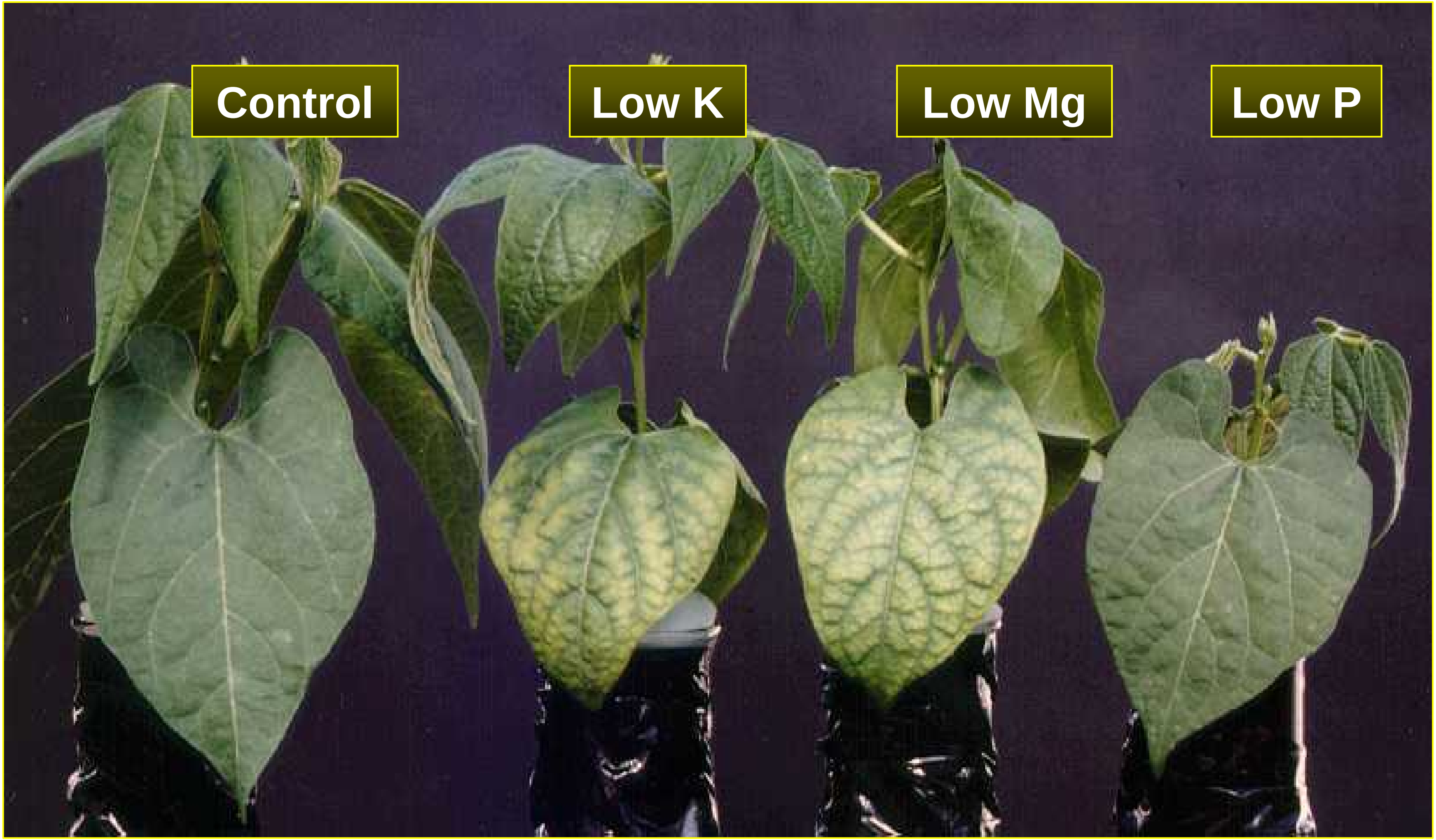
Photosynthesis :
light reactions and carbon-fixation reactions



K and Mg primarily affect production of ATP and reducing equivalents during the photosynthetic e-transport and activity of the enzymes required for fixation of CO2 in chloroplasts.

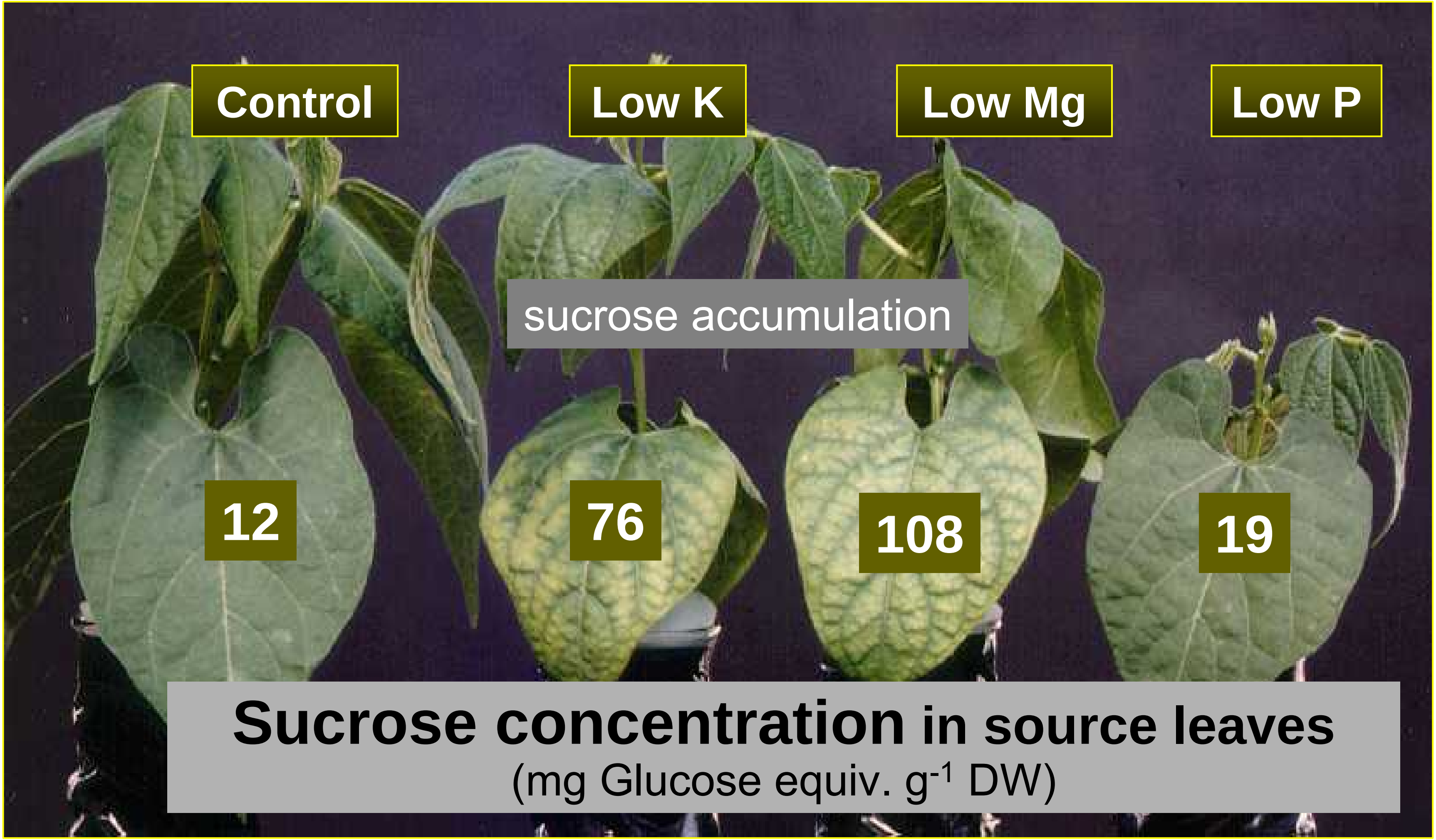
One of the well-documented effects of P in photosynthetic carbohydrate metabolism is its direct effect on biosynthesis of starch.

Growth of bean plants under low supply of K, Mg or P



Cakmak et al., 1994a, J. Exp. Bot.

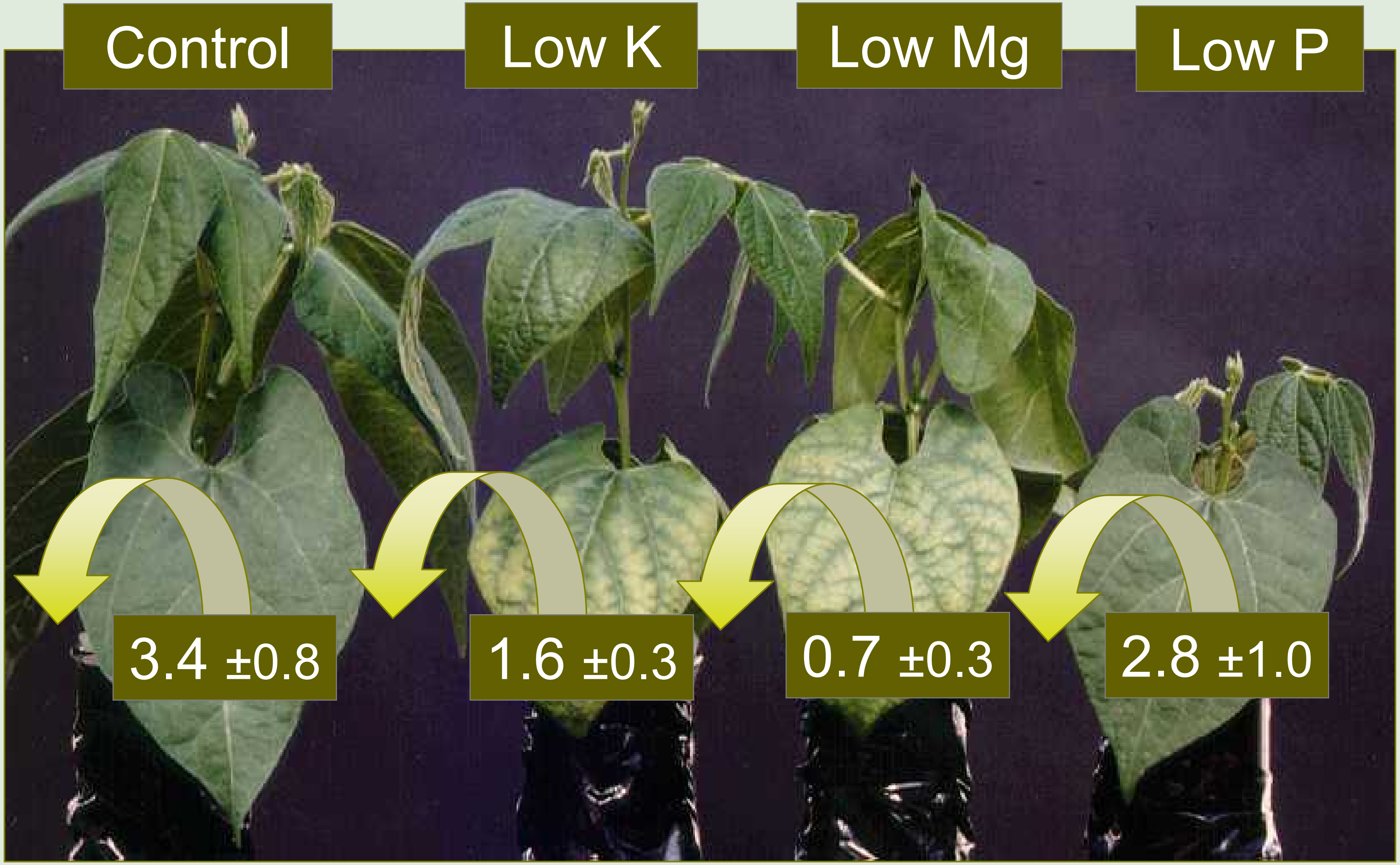
Inhibited phloem loading in K and Mg deficient leaves results in sucrose accumulation in shoot and reduced availablility of photo-assimilates for root growth.



Cakmak et al., 1994b, J. Exp. Bot.

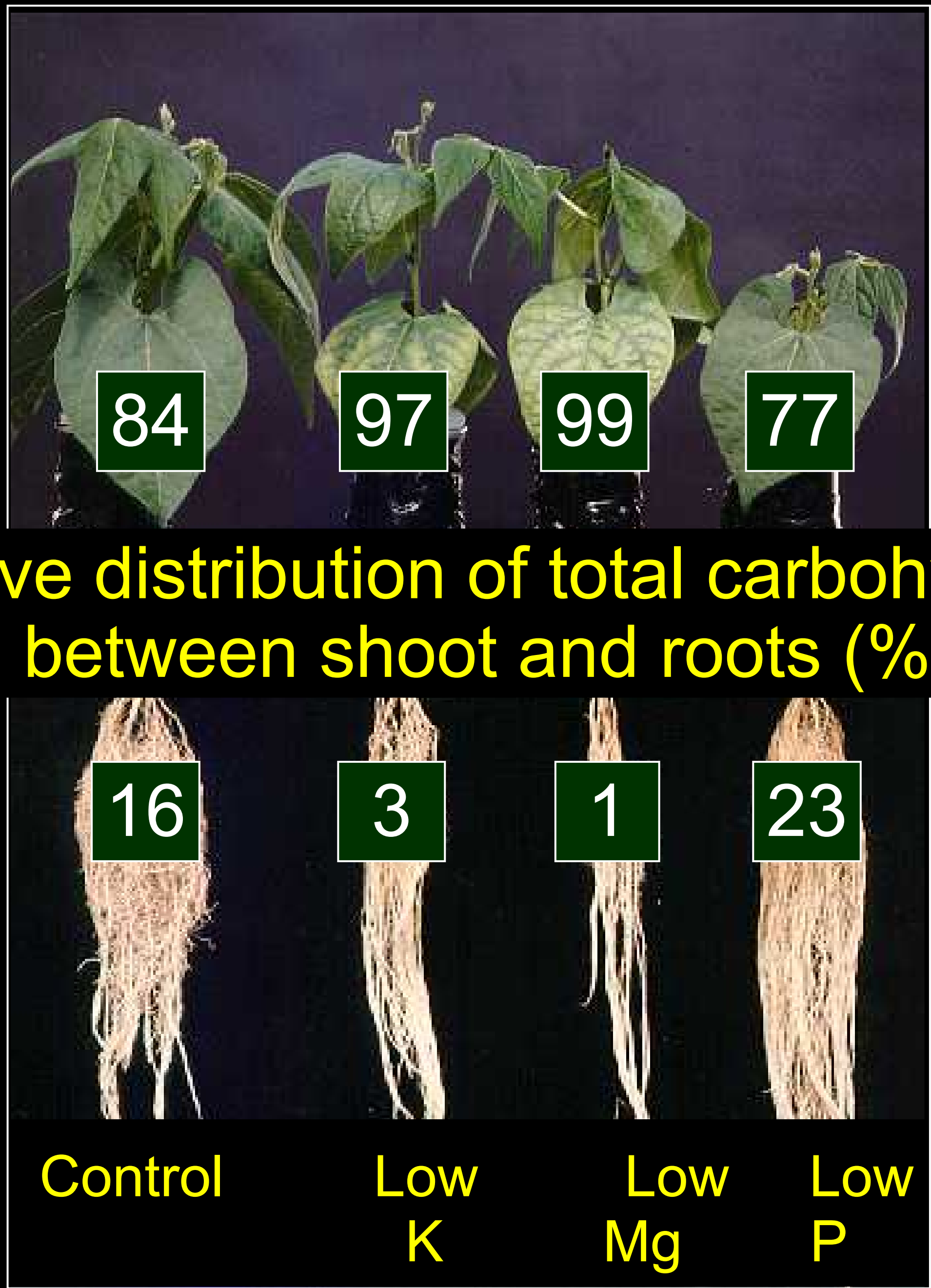
Phloem Export of Sucrose from bean leaves

(mg Glucose equiv · g^{-1} DW · $8h^{-1}$)



Cakmak et al., 1994b, J. Exp. Bot.

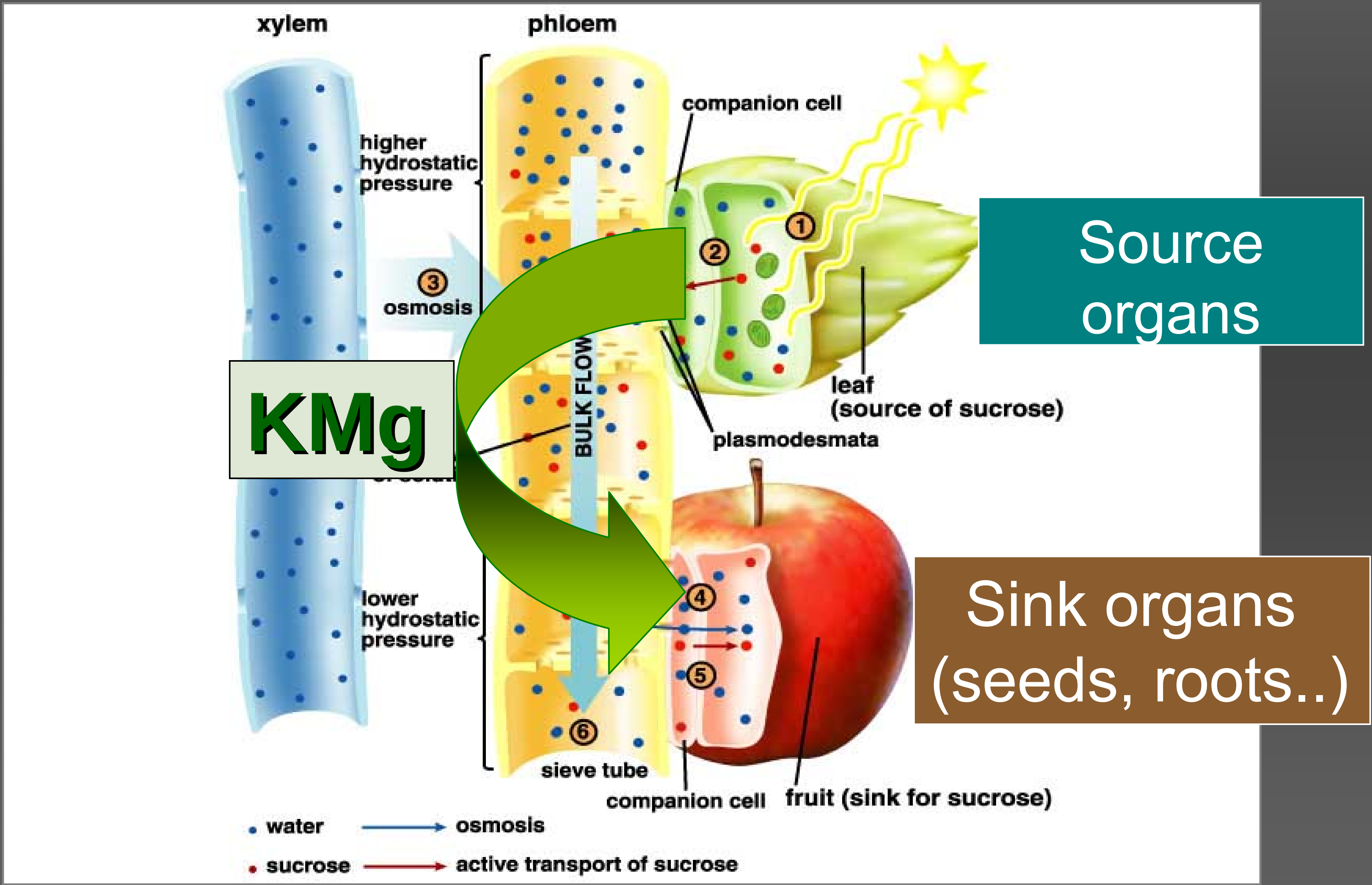
Relative distribution of total carbohydrates between shoot and roots (%)



Cakmak et al., 1994a

PHLOEM TRANSPORT

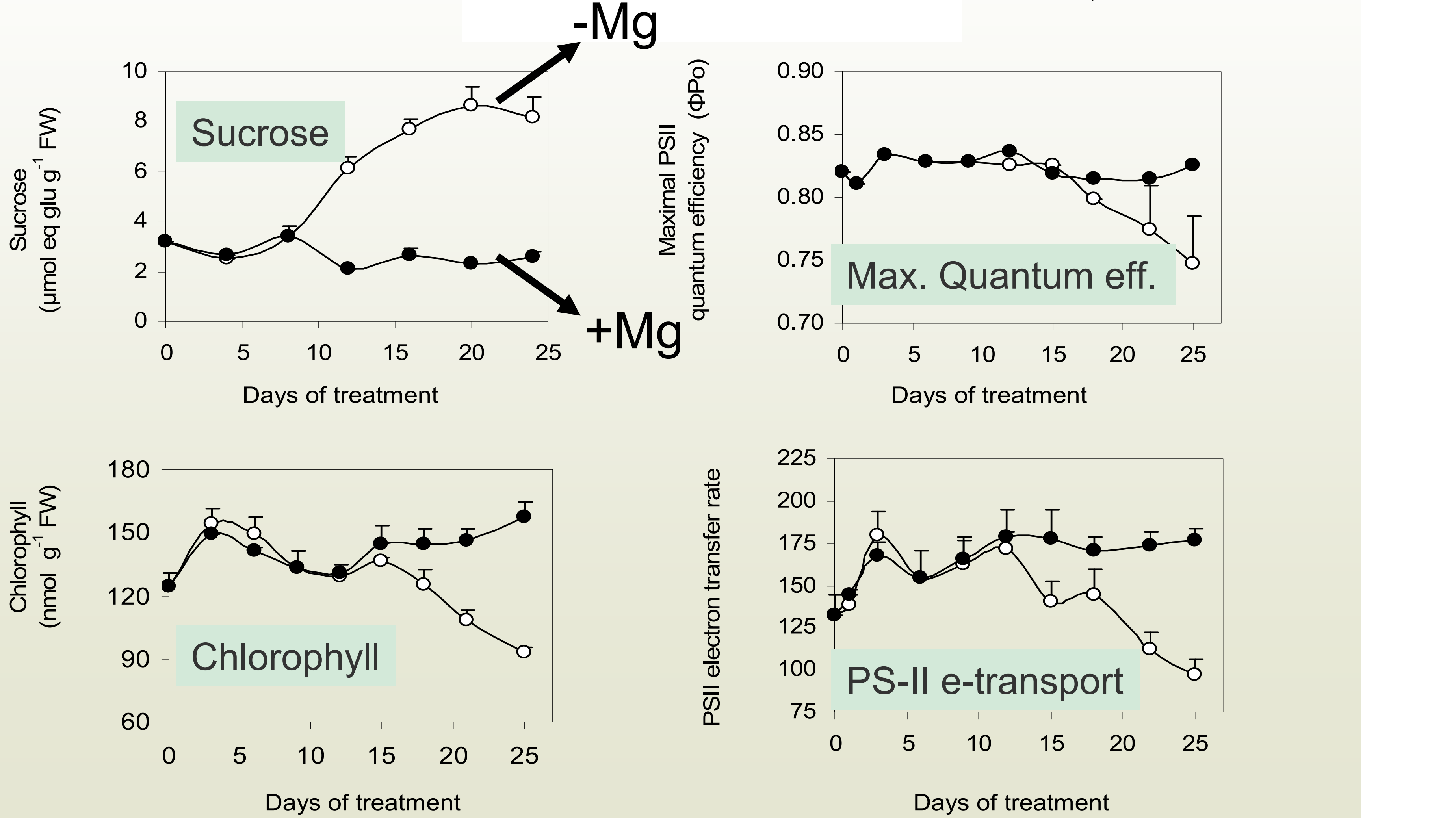
Mg and K play critical role in phloem transport



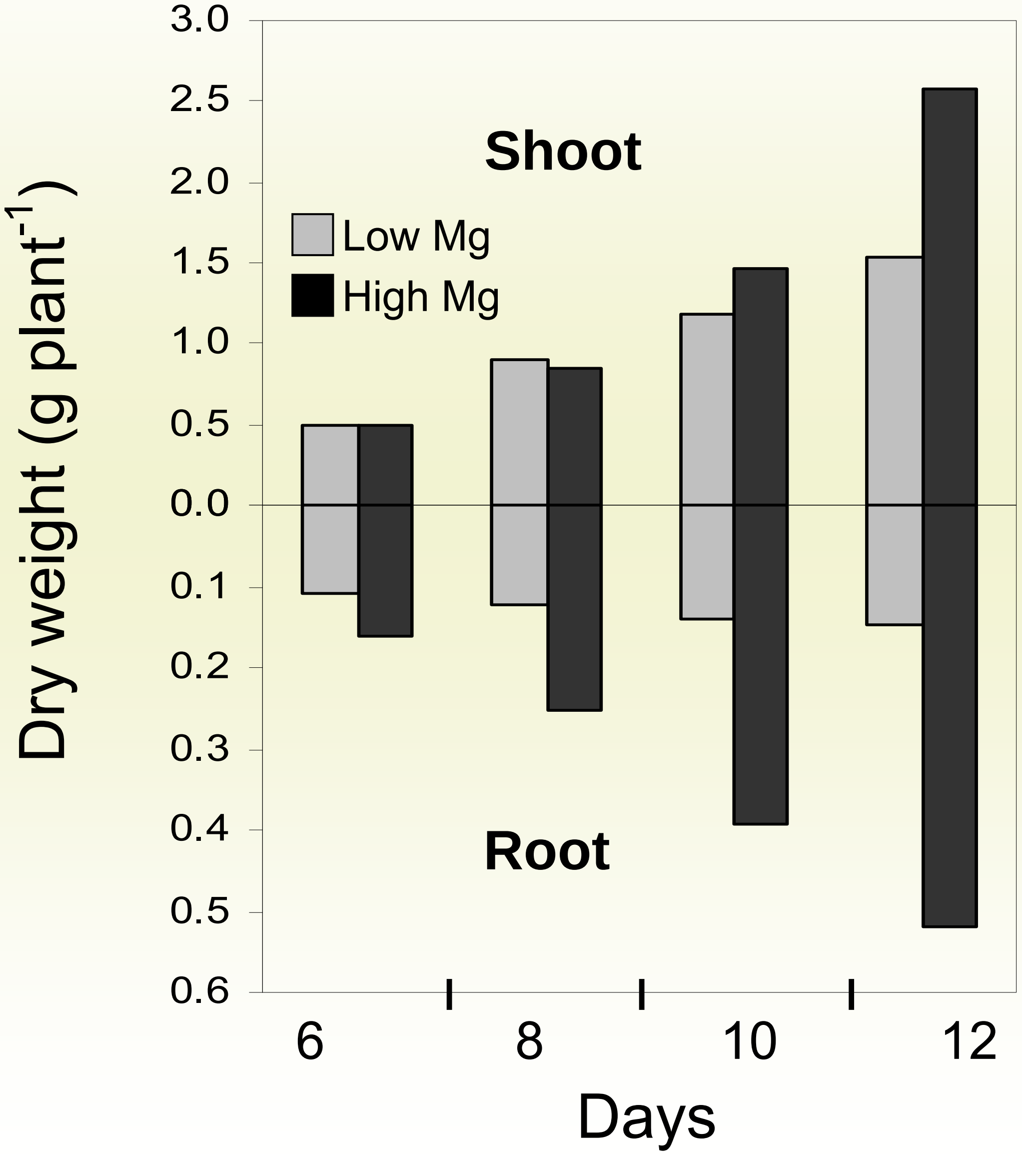
What is the first reaction of plants to Mg or K deficiency ?

Sucrose, chlorophyll and maximal quantum efficiency and electron transport rate of PSII in sugar beet plants with deficient (O) and adequate (•) Mg supply.

Hermans et al., 2004 Planta



Shoot and root dry weight of bean plants with deficient and adequate Mg supply

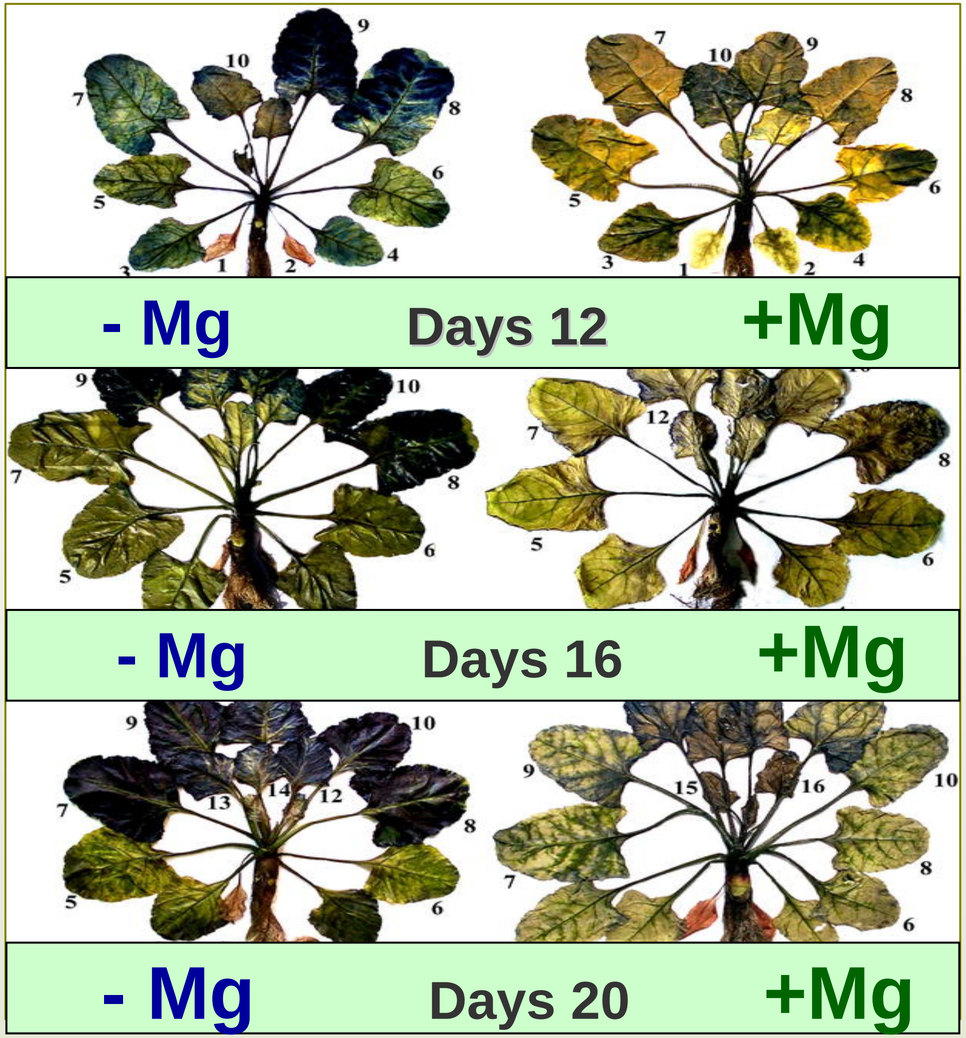


Before any visible change occurs in shoot, root growth is impaired under low Mg supply.

In field, the situation with impaired root growth under low Mg supply is not seen/recognised!!

Cakmak et al., 1994a J. Exp Bot.

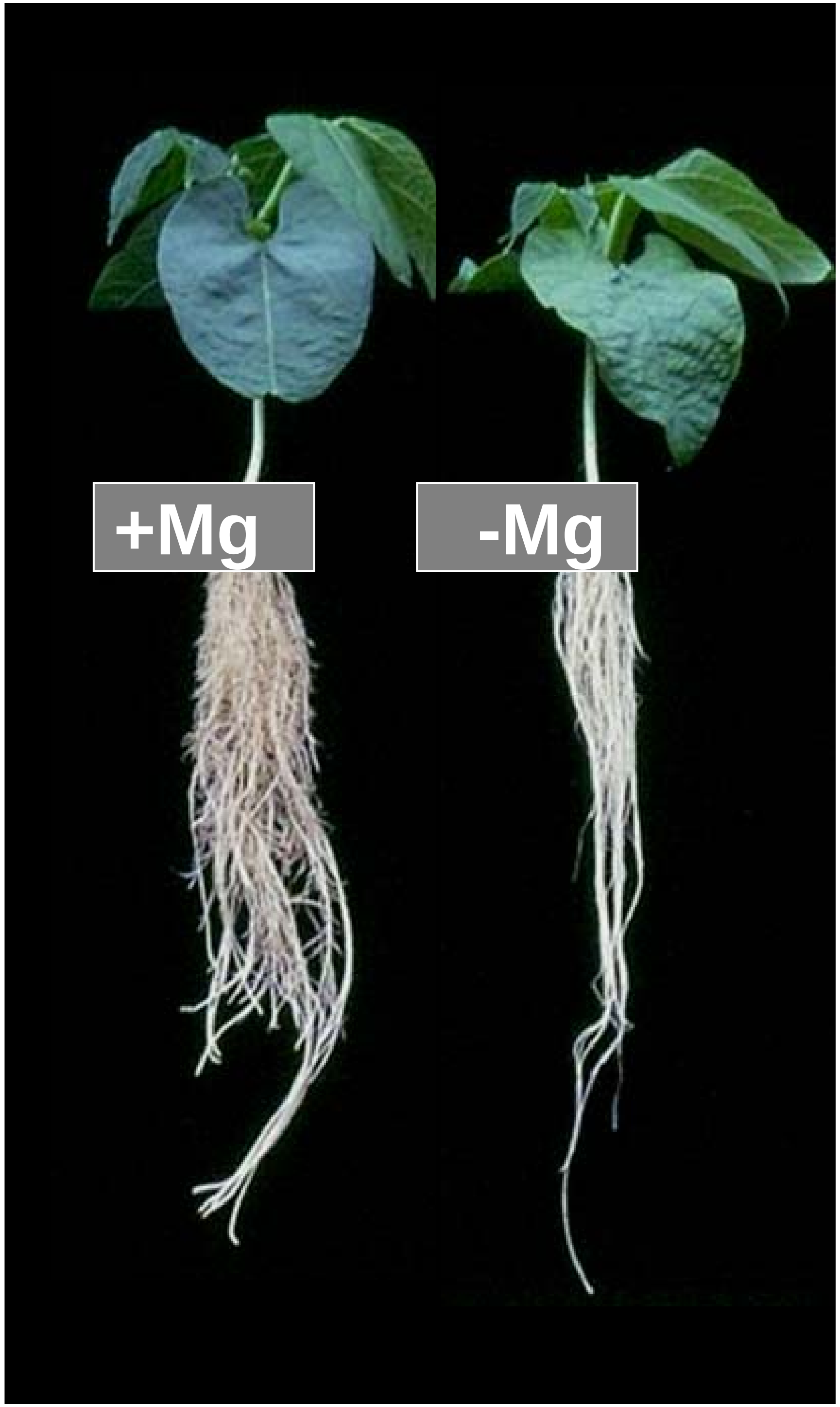
Effect of Mg deficiency on starch accumulation in sugar beet leaves, as detected by lugol staining



Adverse consequences for bioethanol crops

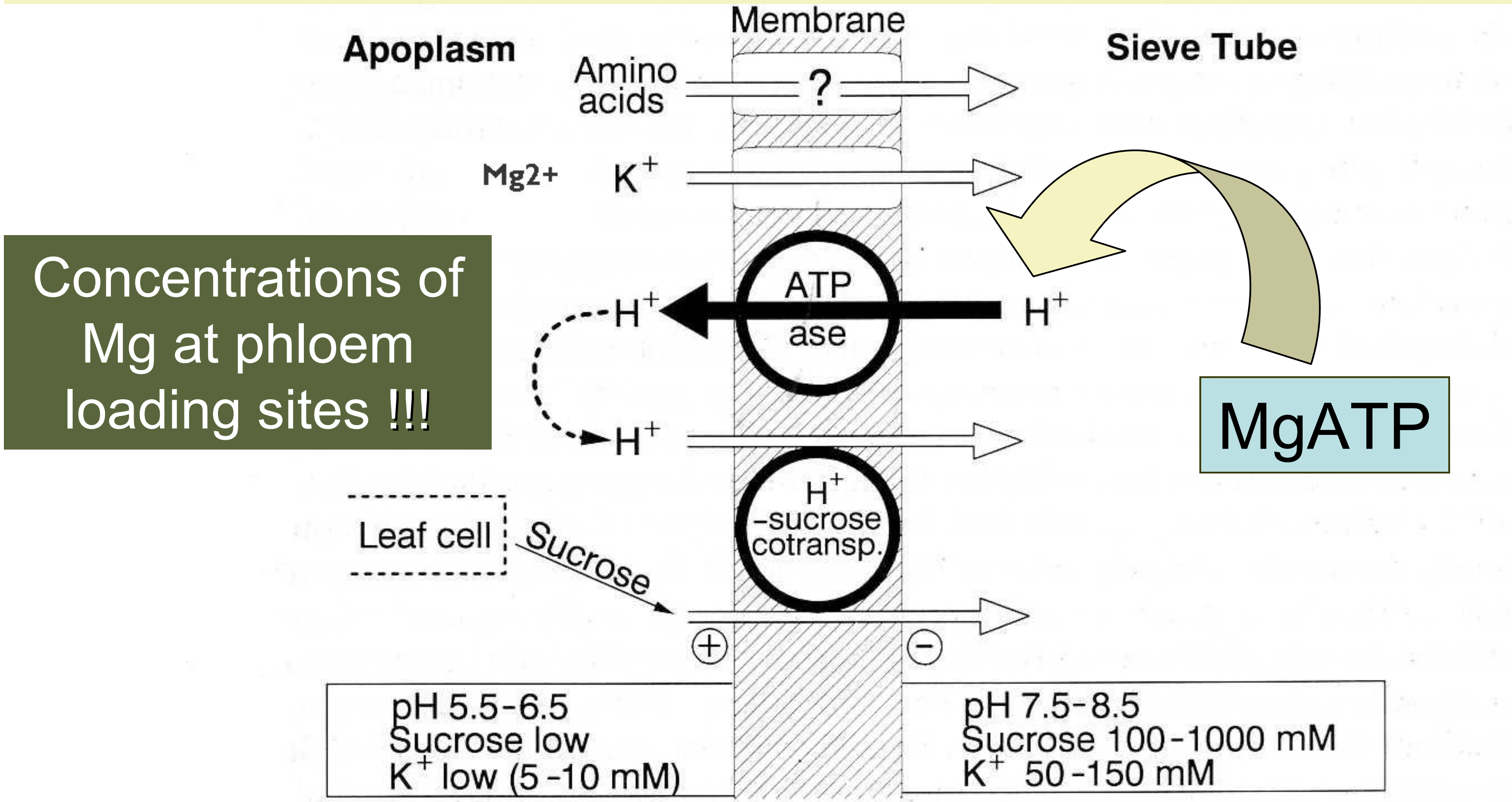
Hermans et al., 2005 Planta 220: 541-549

The most early physiological reaction of plants to low Mg supply is the reduced phloem export of sucrose



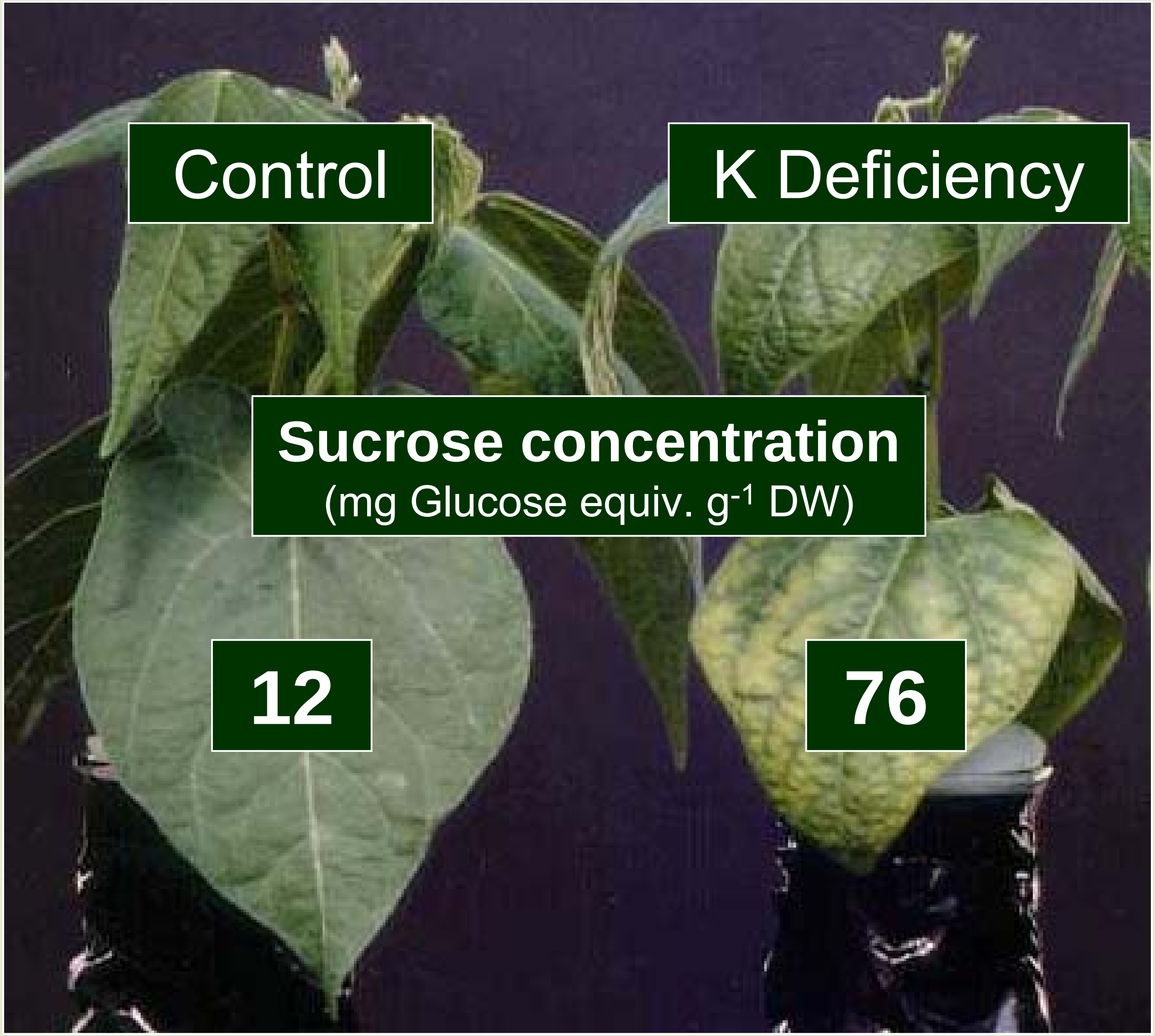
Cakmak et al., 1994a J. Exp Bot.

Mg plays a key role in phloem loading of sucrose



Model of phloem loading of sucrose mediated by proton-sucrose co-transport

Accumulation of Phosynthates in K-Deficient Source Leaves



Cakmak et al., 1994b, J. Experimental Bot.

Net carbon increment in castor bean as affected by P deficiency and salinity

Plant part	Control	Low-P	Salt-treated
		(mmol C $plant^{-1}$ $9d^{-1}$)	
Leaf laminae	240 ± 30	35 ± 8	67
Petioles	67 ± 11	10 ± 2	9
Stem + apex	97 ± 16	18 ± 4	31
Root	160 ± 30	51 ± 9	28

Jeschke et al., 1996, J. Exp. Botany

Net carbon increment in castor bean as affected by P deficiency and salinity

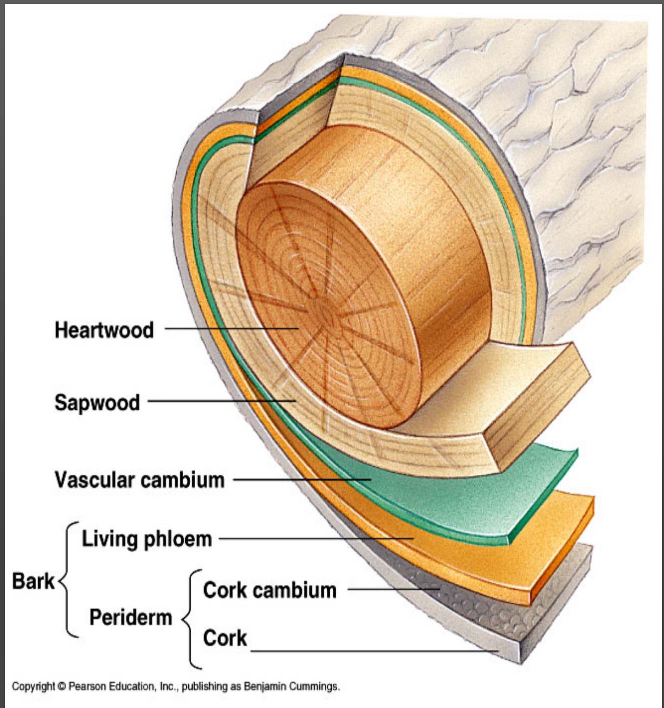
Plant part	Control	Low-P	Salt-treated
		(mmol C $plant^{-1}$ $9d^{-1}$)	
Leaf laminae	240 ± 30	35 ± 8	67
Petioles	67 ± 11	10 ± 2	9
Stem + apex	97 ± 16	18 ± 4	31
Root	160 ± 30	51 ± 9	28

Jeschke et al., 1996, J. Exp. Botany

Salt Stress-Induced K or Mg Deficiency????

Expansion of biofuel crop production:
impacts on the amount of land available to produce food
(use of degraded and marginal areas)

Role of K and Mg in phloem export has consequences for the size and quality of the plant organs which used for biofuel production



Potassium is involved in wood formation **(lignocellulose production)**

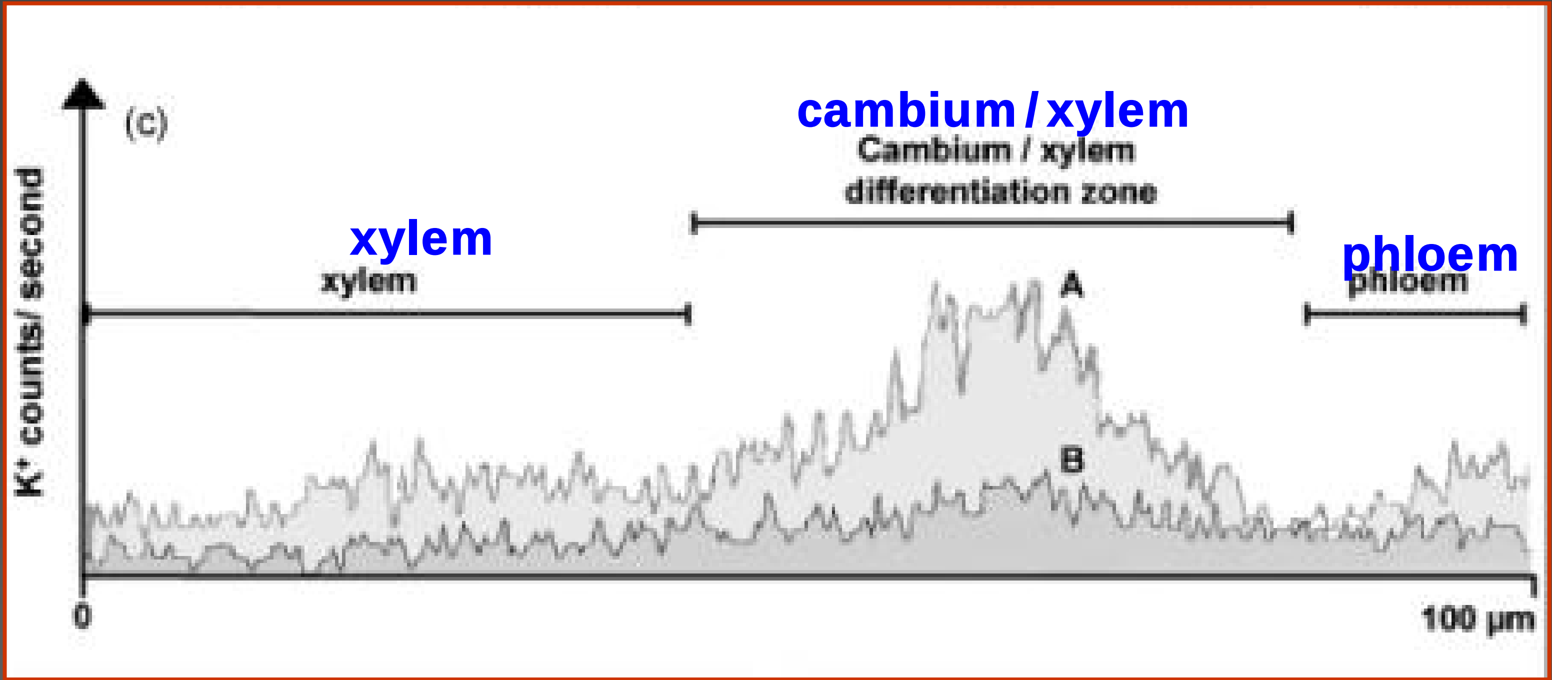
In cambial region and xylem differention zone a strong potassium demand has been shown.

Differentiating xylem cells involved in wood formation represent a strong sink for potassium that provides the driving force for cell expansion (reduced assimilate transport)

Langer et al., 2002; Plant Journal, 32: 997-1009

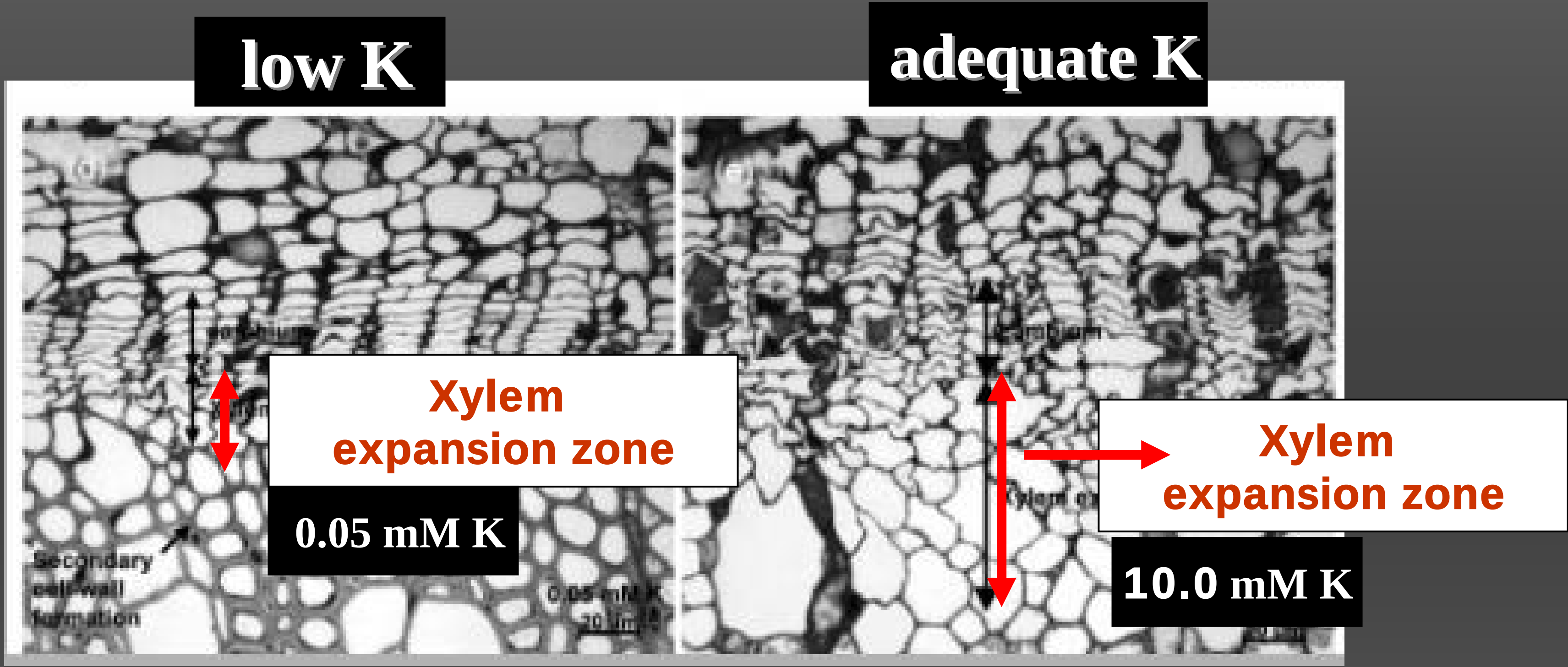
K nutritional status strongly affects development of wood producing cells

Potassium concentration in xylem tissue, cambium / xylem differention zone and phloem tissue



Langer et al., 2002; Plant Journal, 32: 997-1009

Under K deficiency cambial and cell-expansion zones lack 2-3 cell layers each



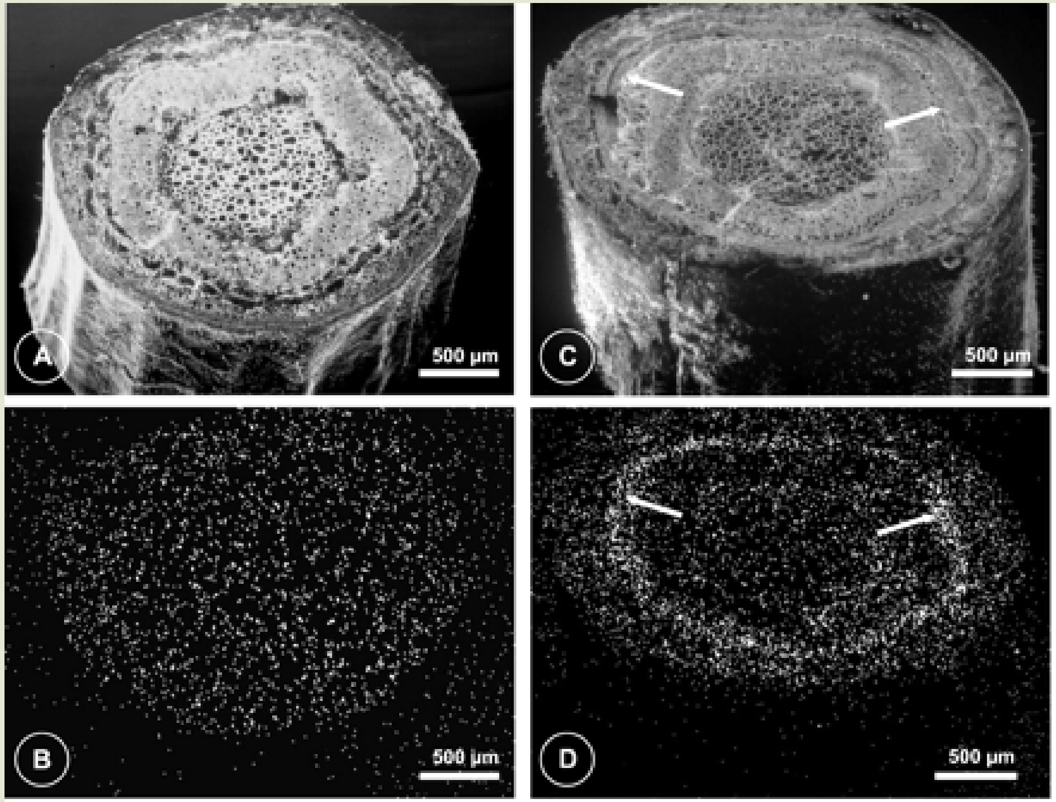
Langer et al., 2002; Plant Journal, 32: 997-1009

Lack of cell divisions in the vessel development region results in reduced wood production

Potassium distribution in twigs of poplar plants

Low K+ supply during cambial growth markedly reduced.

Cambial zone represents the major sink for K in the stem



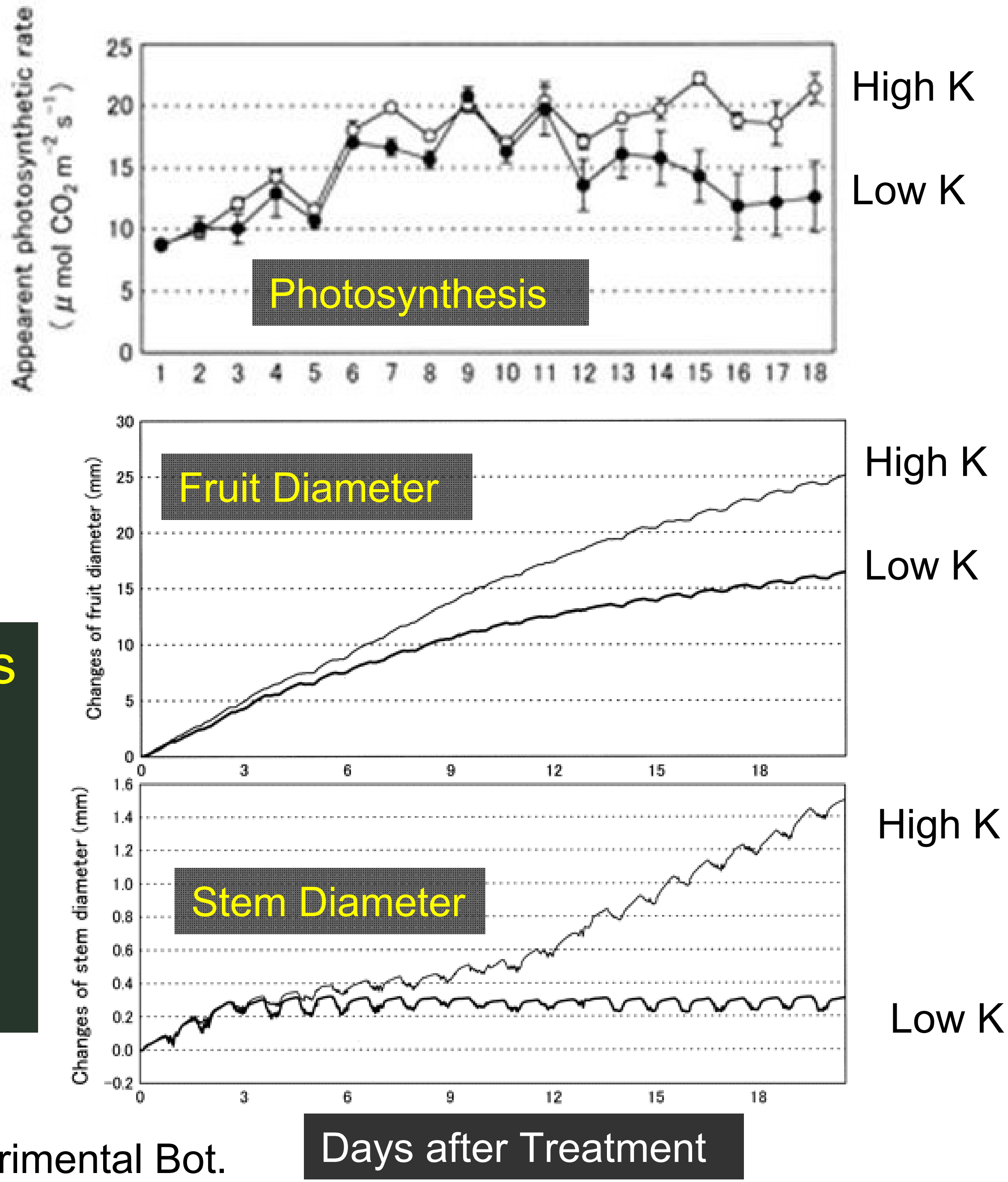
B: Mapping of potassium-specific x-ray signals indicating a strong accumulation of potassium in the activated cambial zone

Arend et al., 2002, Plant Physiol, 2002, 129: 1651-1663

Stem growth is highly sensitive to K deficiency (less production of **lignocellulose** material for biofuell production)

The effect of K deficiency on changes in in stem diameter of tomato plants

Stem development is highly sensitive to K deficiency and related to reduced 14C partitioning in the stem



Kanai et al., 2007, J. Experimental Bot.

Reduced 14C partitioning in the stem under K deficiency

The effect of K deficiency on 13C atom percentage excess in various parts of tomato plants

Plant part	7 days after treatment		14 days after treatment	
	Control	**K deficiency**	**Control**	**K deficiency**
Fed leaf	0.629±0.048	0.880±0.056	1.250±0.089	1.327±0.096
Other leaves	0.005±0.000	0.004±0.000	0.003±0.000	0.002±0.000
Fruits	0.248±0.016	0.155±0.009	0.080±0.022	0.060±0.013
Stem	0.032±0.002	0.018±0.002	0.035±0.005	0.023±0.002
Root	0.029±0.002	0.026±0.007	0.068±0.017	0.015±0.007

Kanai et al., 2007, J. Experimental Bot.

In K-deficient tomato plants, growth inhibition in stem and fruit occurred prior to depression of photosynthetic activity

Stem and fruits are the strongest sink for both carbon assimilates and K.

Demand for K during rapid fruit growth might be above the root uptake capacity or the capacity of leaves to rremobilize adequate K..**Needs for foliar K application.**

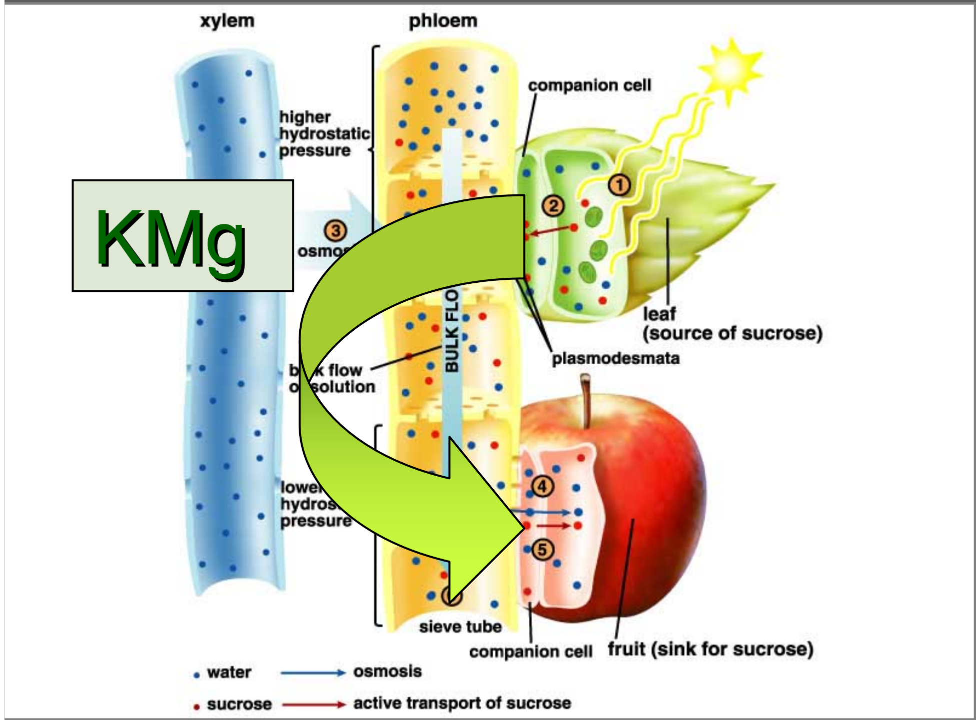
These effects are important for plant materials harvested for lignocellulose production.

Conclusions

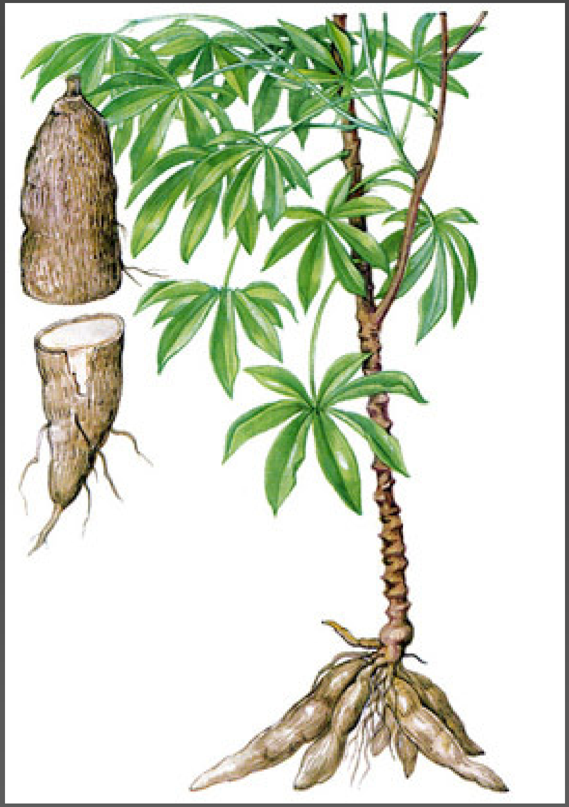
Impairments in maintenance of phloem transport of sugars into the sink organs (e.g., roots and seed) by Mg or K deficiency may affect the size and number of sink organs and consequently yield.

Mg deficiency-induced decreases in single grain weight and number of grains per ear are well-known (Beringer et al..)

Very early impairments in root growth and related decline in root surface by Mg and K deficiencies may have serious impacts on the acquisition of mineral nutrients and uptake of water by roots, **especially under water-limited and nutrient-deficient soil conditions.**



Due to their fundamental roles in phloem export of carbohydrates, nutritional status of plants with Mg or K is important during the reproductive growth stage of biofuel plants, especially under stress conditions which restrict root uptake of Mg and K such as drought stress, low pH, excess N….



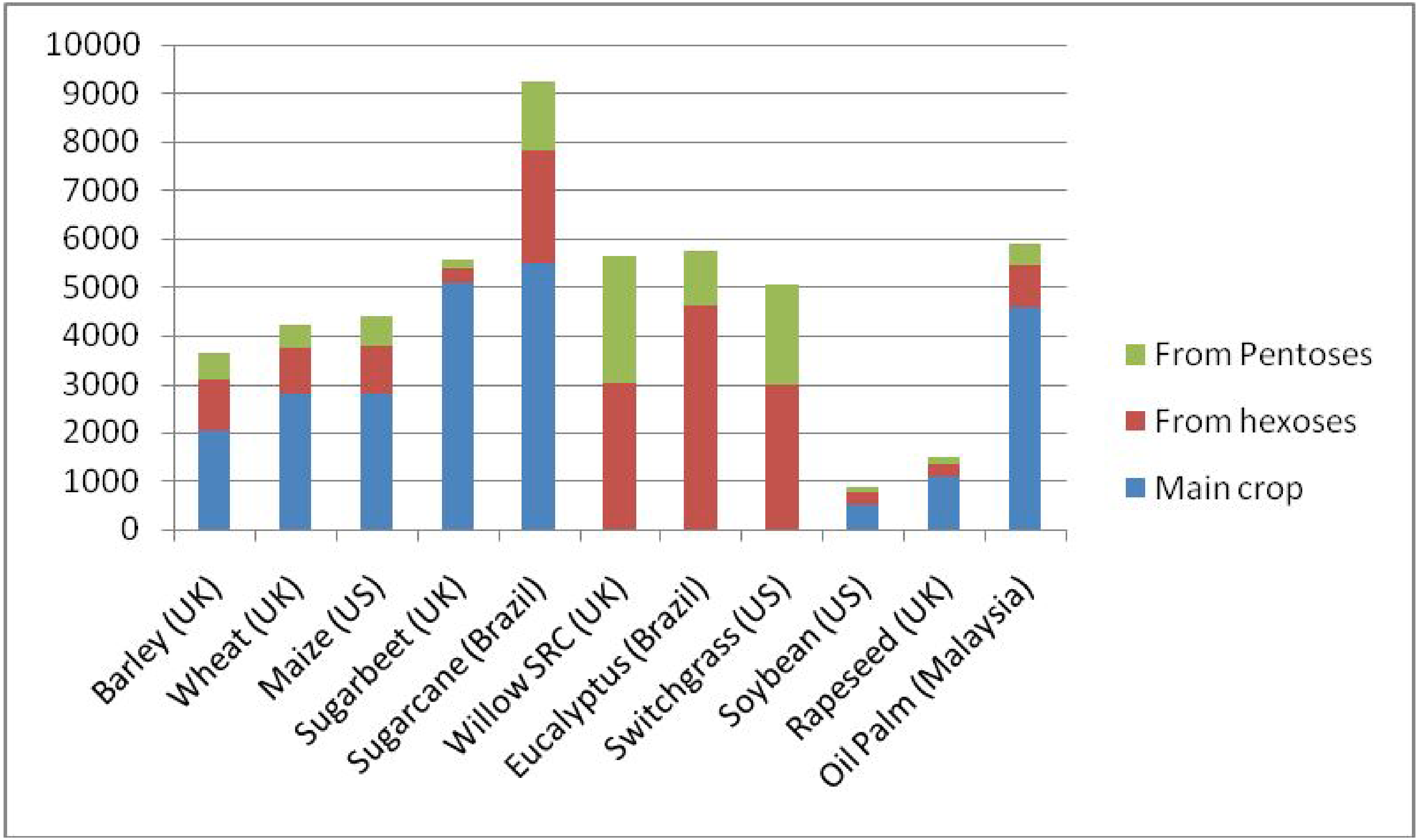
To maximize biomass/starch production

Topdressing or late foliar application of Mg and K (just before or after flowering) to guarantee efficient retranslocation of photo-assimilates/sucrose into harvest products (e.g. grains, stems, tubers),


Thank you...
Sabanci University


SABANCI ÜNİVERSİTESİ

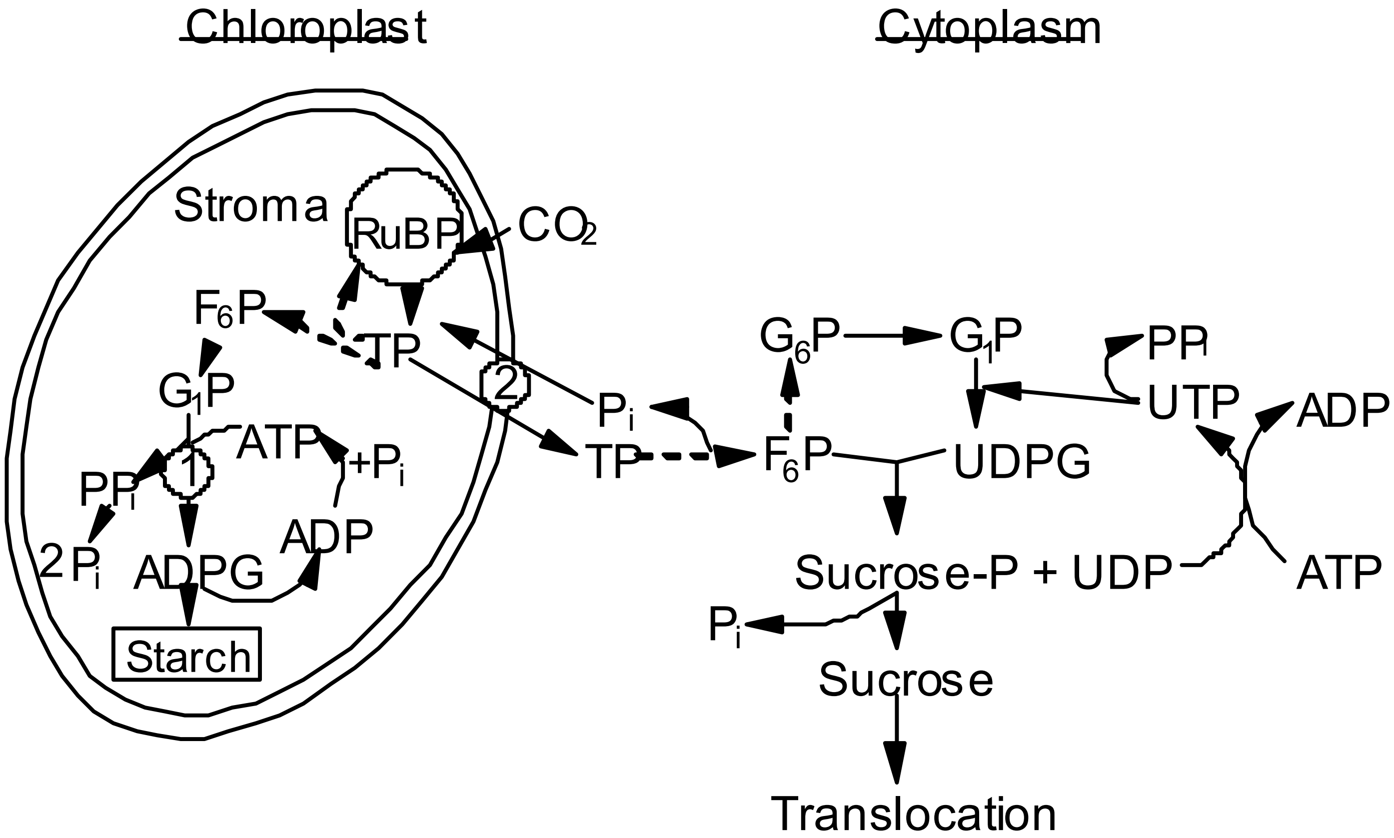
Biofuel yields from a range of crops and locations (litres per hectare)



Woods et al., 2009 http://cip.cornell.edu/biofuels/files/SCOPE13.pdf

Maize Growth at Low Mg or Low K

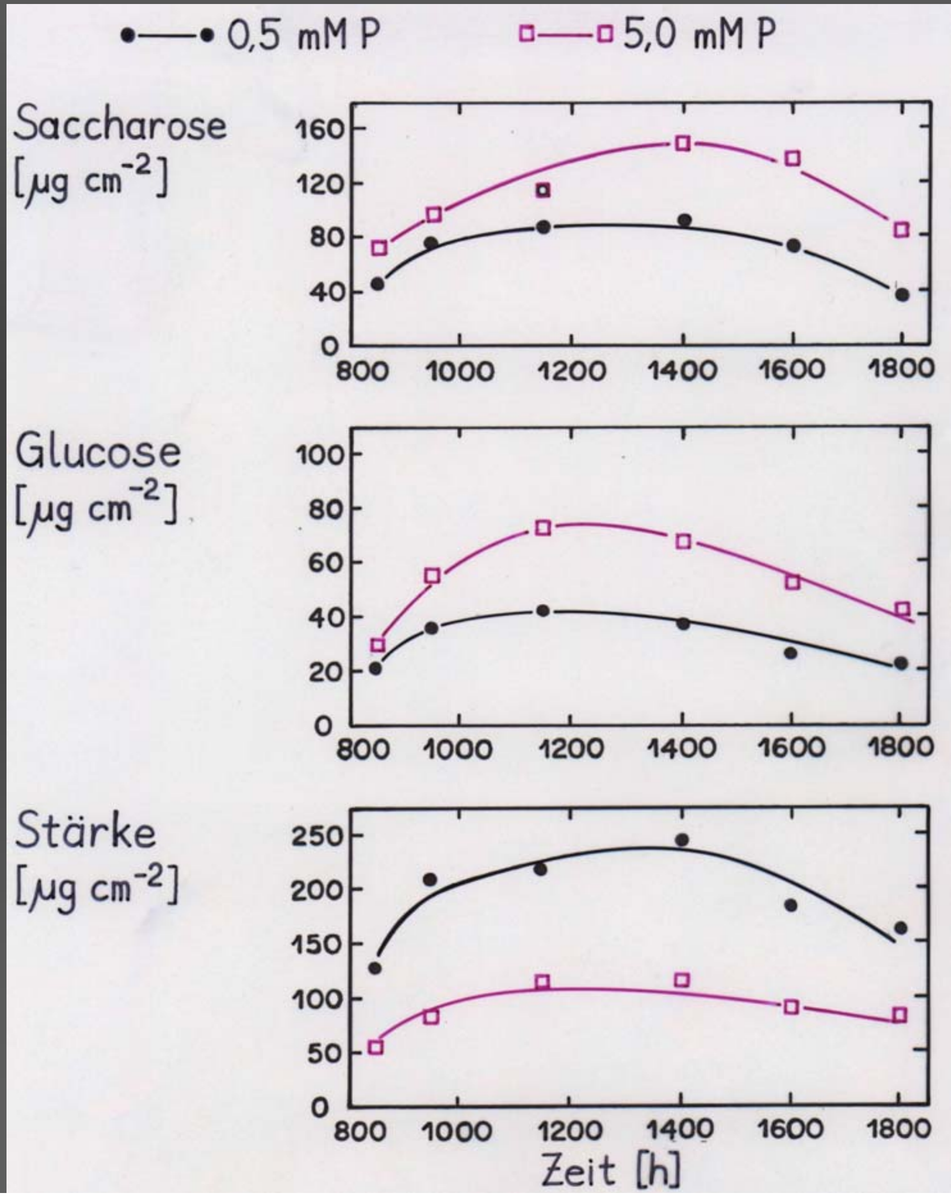
High Inorganic P-Induced Inhibition of Starch Synthesis



ADP-glucose pyrophosphorylase is sensitive to Pi

High amount of Pi induced translocation of Triose P into cytoplasm

Effect of P-Supply on concentrations of starch, glucose and sucrose in cotton leaves



High P
Low P

ACKERSON, Plant Physiol. 1985, 309-312

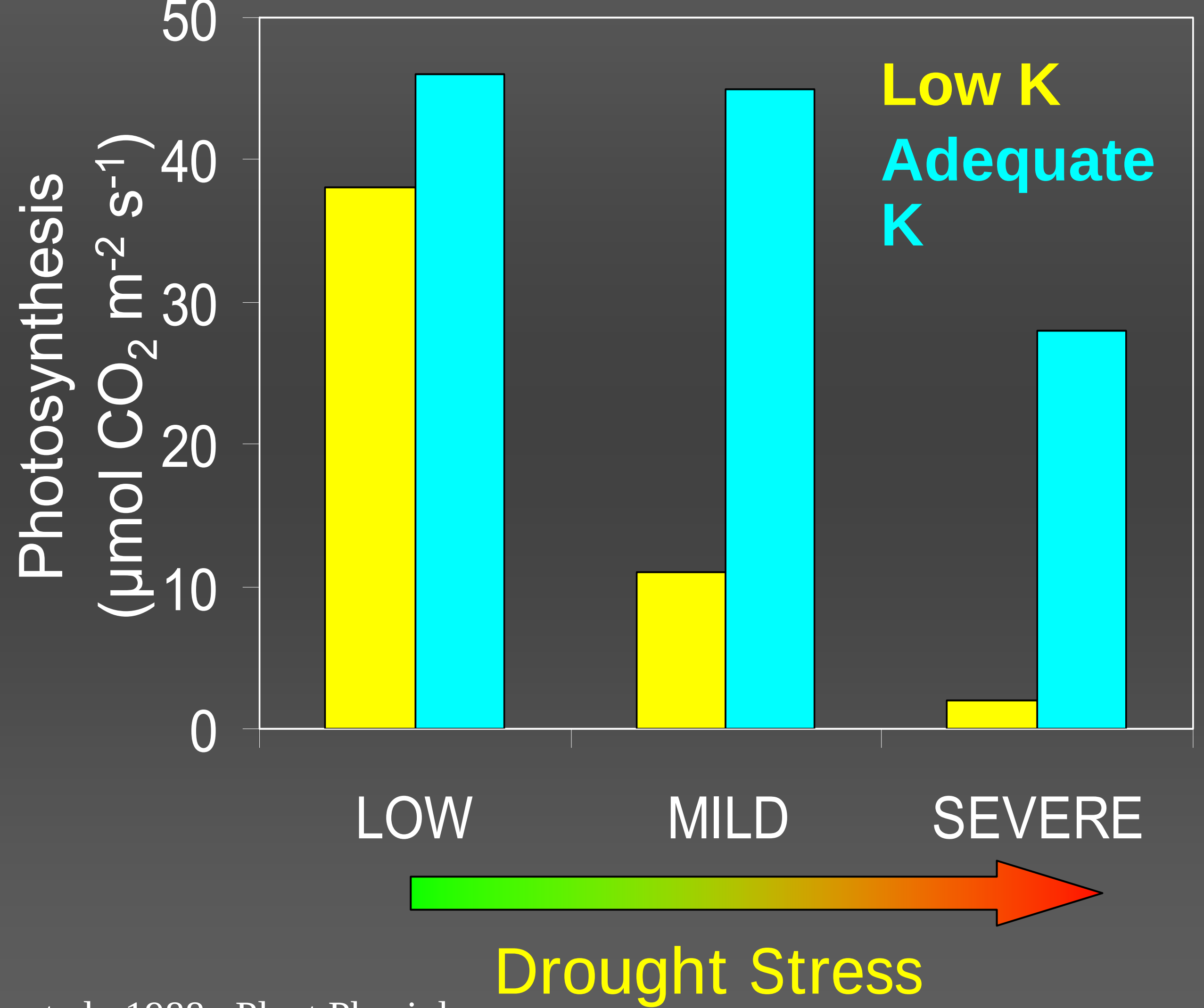
Effect of N fertilization on biomass yield, 5C, 6C and lignin production in *Populus*

Trait	Low N	High N
Leaf biomass (g)	4.86 ± 0.09	6.73 ± 0.12
Stem biomass (g)	3.81 ± 0.08	4.47 ± 0.10
Above-ground biomass (g)	9.06 ± 0.19	12.46 ± 0.24
Root biomass (g)	2.20 ± 0.06	1.27 ± 0.03
Shoot/root wt	5.07 ± 0.08	11.90 ± 0.14
5C hemicellulose sugar	25.68 ± 0.04	27.02 ± 0.08
6C cellulose sugar	32.89 ± 0.07	35.54 ± 0.14
Total lignin	21.69 ± 0.06	17.38 ± 0.06

Novaes et al., 2009

A proper management of mineral nutrition is also very important issue in alleviation of yield decreases caused by various stress factors. This effect of mineral nutrients should be taken in production of bioenergy crops, especially under marginal conditions, e.g., drought stress…

Improved Potassium Nutrition Enhances Photosynthesis Under Drought Stress



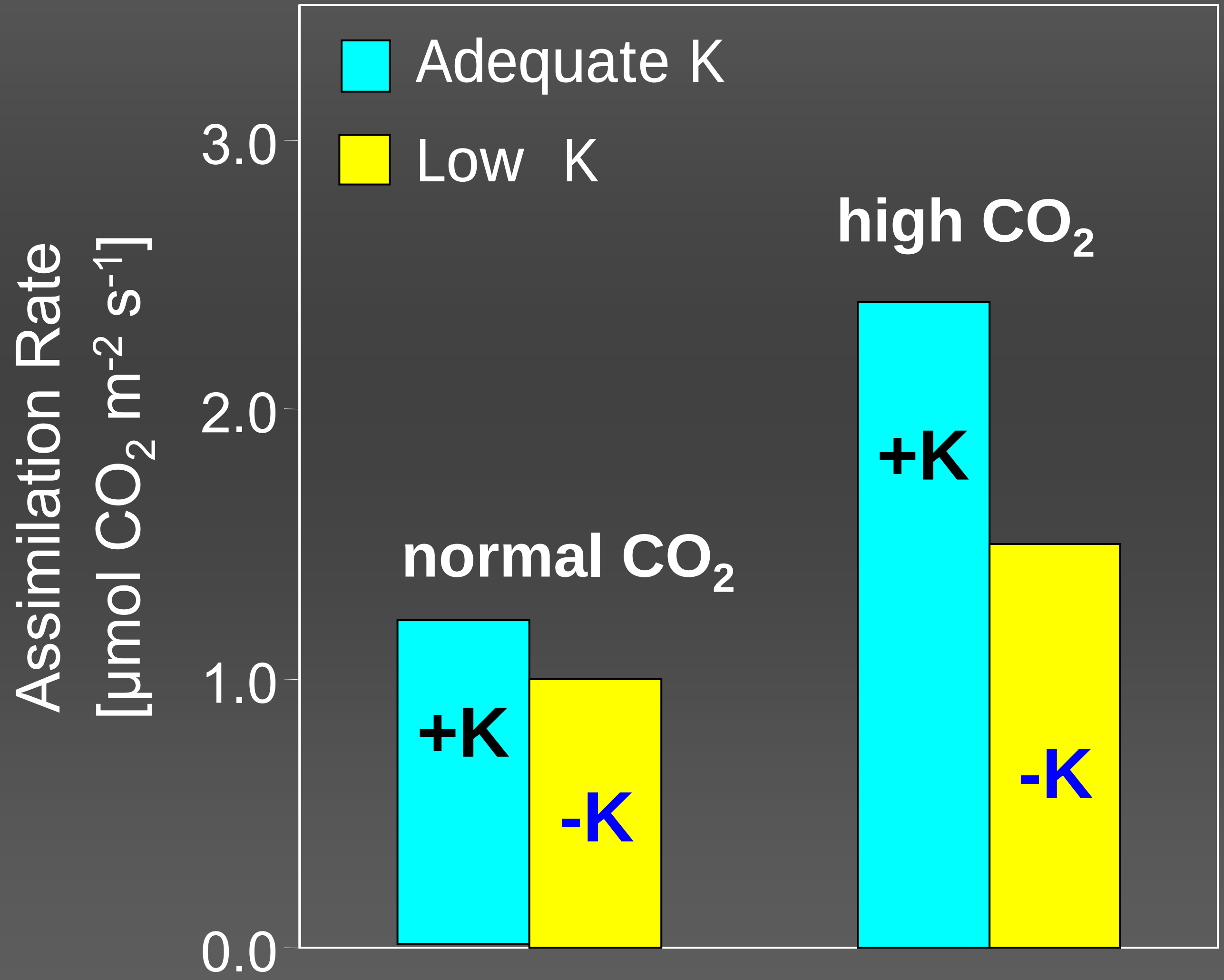
Sen Gupta et al., 1988, Plant Physiol.

Plants grown under elevated CO_2 conditions required greater amounts of K, and were more sensitive to K deficiency compared to plants grown under ambient [CO_2].

Plants grown under elevated [CO_2] required a higher leaf critical K concentration to maintain optimum canopy photosynthesis and biomass production.

Reddy and Zhao, 2005; Field Crops Res. 94: 201-213

Effect of Elevated CO_2 on Photosynthesis at Varied K Supply



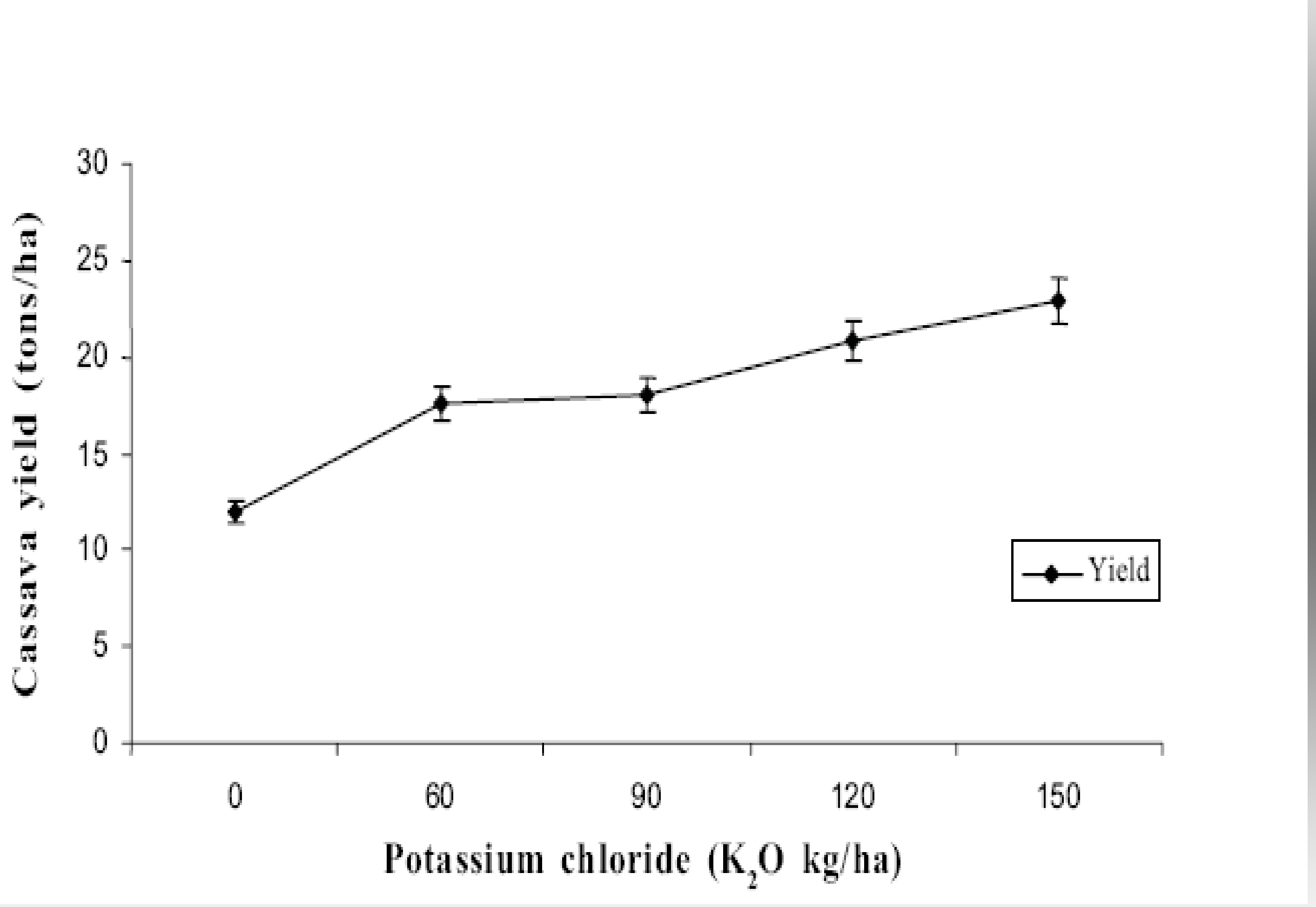
Barnes et al., 1995, Plant Cell Environ.

Ethanol Production per kg fertilizer:

- Sugarcane: 5-7 liter
- Cassava: 0.9-1.7 liter
- Corn: 0.7-1.4 liter
- Sweet Sorghum: 0.5 liter

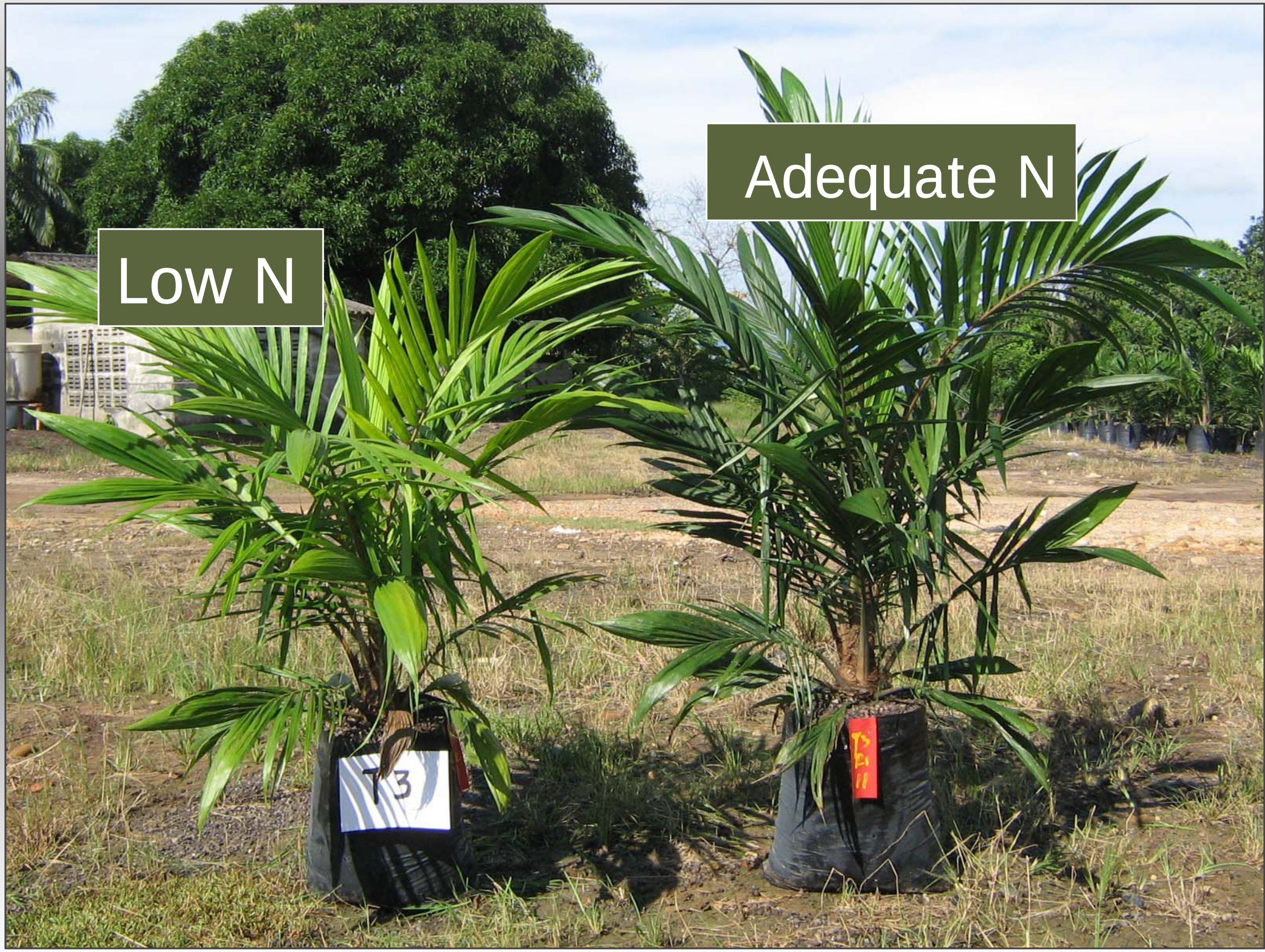
Mendoza, 2008, Philip. J. Crop Sci. 33:21-36

Cassava Production in Nigeria at Different K Rates



Adekayode and Adeola, 2009, J. Food Agric. Environ. 7: 279-282

N deficient oil palm



www.ipni.net

Shoot and root dry wt. and carbohydrate content in leaves and roots of Mg and P deficient bean plants

Treatment	Dry weight (g per plant)			Chlorophyll (mg g^{-1} dry wt)	Carbohydrate (mg g^{-1} dry wt)**			
					Leaves		Roots	
	Shoot	Roots	S/R		**Starch**	Sugars	**Starch**	Sugars
Control	2.5	0.50	5.0	11	**10**	27	**4**	51
- Mg	**1.5**	**0.15**	**10.0**	**4**	**77**	**166**	**4**	**11**
- P	0.9	0.48	**1.1**	12	**43**	34	**8**	35

**mg Glucose equivalents

Cakmak et al., 1994ab