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# Editorial

Dear readers,

Is the agricultural sector fully benefiting from the digital revolution? You may not be surprised to know that some say agriculture is the least digitized business sector. There are many reasons for this, including that: agriculture is practiced in the field which poses some unique technical challenges for implementing technology; the farming community, in general, is pretty conservative and risk averse; and there are higher perceptions of non-repayment to investors due to sector-specific risks, such as production, price and markets. Still, it can be expected that in spite of all these challenges, the digital era will find roots in agriculture. Indeed, some are already there…

What benefits can AgTech bring? Of course, it can serve farmers by managing activities more efficiently and help to increase yields as a result of better crop management. It will also serve agricultural input providers, as more efficient use and better targeting of inputs will increase farmers' expendable incomes, enabling them to put more money back into the farm and the input sector.

For those of us in the fertilizer sector, we expect and wish to be able to better diagnose nutrient availability through using plant and/or soil sensors. We should also be able to make use of historical data; this is a treasure we must learn how to tap.

In the meantime, until the revolution arrives, I wish you an enjoyable read.

**Hillel Magen**
**Director**



**Photo cover page:**
Harvesting sugarcane in Vietnam. Photo by Nguyen Duy Phuong.

# Research Findings

Photo by IPI.

## Conclusions from the Permanent Plot Experiment at Gilat, Israel: Long-Term (35-Year) Effects of Manure and Fertilizer on Crop Yield, Soil Fertility, N Uptake, and Solutes Leaching in Soil*

Bar-Yosef, B.[(1), (2)]

### Abstract

Long-term application of fertilizer and manure may change soil fertility, crop yield, N uptake efficiency and nitrate and chloride leaching to underground water. The objectives were to quantify those aspects in a long-term (35-year) permanent plots field experiment in a typical arid zone (~250 mm rain) soil, and suggest fertilization and manuring regimes leading to reduced aquifer pollution by nitrate and chloride without compromising crop yield and soil sustainability. Results proved that mineral-N application exceeding plant demand leached, subject to recommended irrigation plus rainfall, below 4 m thus becoming a potential underground water pollution hazard. Leaching was significantly reduced by partially replacing fertilizer-N by manure-N, with negligible adverse effect on crop yield. Under ample manure (M2) and mineral N (N3) supply (treatment M2N3),

[(1)]Institute of Soil, Water and Environmental Sciences, ARO, Volcani Center, Israel
[(2)]Agri-Ecology, Katif Labs & Research Center, Sedot Negev, Israel
vwbysf@agri.gov.il

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the estimated cumulative (35-year) $NO_3^-$ leaching was 557 g N $m^{-2}$ and the corresponding $Cl^-$ leaching 4,097 g $Cl^-$ $m^{-2}$. In treatment M2N0 the corresponding leaching was 0 and 4,135 g $m^{-2}$. The cumulative solute leaching depth was estimated to be 66 m in treatment M2N3 (that gave maximum fruit and dry matter yield) and 125 m in treatment M0N0 (minimum fruit and dry matter yield). Soil cultivation and cropping for 35 years had negligible effect on the plants response to fertilizer level and on the soil mineralogical composition.

*Keywords*: Loess soil; manure; soil organic nitrogen; P K availability in soil; N uptake; leaching; dry matter production; transpiration; irrigation.

## Introduction

The Gilat long-term fertilization experiments (LTFE) was established in Israel in 1961 by the Volcani Institute of Agricultural Research, to provide a scientific basis to the transition from rain-fed to irrigation-fed agriculture in the southern, arid part of the country. This area is characterized by 200-300 mm rain (all in winter), a loessial soil and good quality water (EC < 1.2 dS $m^{-1}$) imported from the north. The objectives of the LTFE were to develop and test new fertilization regimes under conditions of controlled irrigation in arid climate; adopt new cash crops grown under irrigation; study the plants short and long-term response to fertilizer and manure N; and to improve and calibrate soil tests to evaluate nutrients availability in soil. The experiment prevailed until 1994 and involved 35 growing seasons of the major crops grown in the area. The historic season-by-season crop and soil data of all the 16 N x Manure treatments was compiled recently and stored on the web (Bar-Yosef and Kafkafi, 2016). This report focuses on the long-term fertilizer and manure effects on crop fresh and dry yield, mineral and organic N balance in soil, N uptake efficiency, and nitrate and chloride leaching to underground water. Results concerning the annual crop response to N and the interrelationships with other nutrients in soil are outside the scope of this article.

## Materials and methods

### Soil and manure properties

The experimental site was Gilat Experiment Station (35°E, 30°N). The soil is loessial (Typic Haplargid, Calcic Haploxeralf) and its chemical properties are summarized in Table 1. The soil volumetric water content at air dryness and field capacity are 3.5% and 23%, respectively.

The mean dry matter of the dairy manure contained 40% organic matter (dry digest), 1.8% N, 0.6% P and 2.5% K. The mean contents of the dry matter city refuse compost were 45% organic matter, 1.5% N, 0.35% P and 0.5% K.

### Growth conditions, treatments and agro-technique

The time-averaged monthly mean air temperatures in January to December were 11, 13, 16, 21, 24, 29, 32, 32, 29, 25, 18 and 13°C, respectively. The cumulative (35-year) irrigation, rainfall, and seasonal evaporation from class A pan were 16,000, 6,676, and 22,900 mm, respectively. The experimental design was four mineral-N x four manure levels, replicated six times in random blocks. The N was applied until 1985 as ammonium sulfate and later (as drip replaced sprinkle irrigation) as ammonium nitrate supplied via the water (average Na and Cl concentrations 7.0 and 7.5 mM, respectively). The manure treatments were control, two levels of commercial dairy manure, and one level of city refuse compost. All treatments received identical superphosphate and KCl doses before seeding and same irrigation rate. More details can be found in Bar-Yosef and Kafkafi (2016). The irrigation was applied to replenish class A pan evaporation ($EV_a$) multiplied by a time dependent crop coefficient. The major crops, grown in rotation were corn, cotton, onion, carrot, potatoes, processing tomatoes, pepper, lettuce, broccoli, celery, Chinese cabbage and muskmelon. The yield of 15 m row length of two centered rows was cut and measured for fresh and dry weight. Plant tissue was analyzed by digesting dry (60°C) ground tissue sample with $H_2SO_4 + H_2O_2$ for N, P, K, Na determination and with $HNO_3 + HClO_4$ for S analysis. N, P and S were determined by auto-analyzer, K and Na by flame

**Table 1.** Some soil properties of the Gilat soil.[1]

| Layer | Horizon | pH | EC 1:1 | $CaCO_3$ | Clay | Silt | Sand | | Org C | Org N |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Fine | Coarse | | |
| *cm* | | | *dsm$^{-1}$* | ---% | | | | | | |
| 0-25 | Ap | 8.2 | 1.2 | 18.6 | 16.5 | 33.2 | 46.3 | 4.0 | 0.70 | 0.075 |
| 25-40 | B1 | 8.2 | 0.9 | 28.0 | 22.0 | 39.9 | 35.4 | 2.7 | 0.77 | 0.078 |
| 40-80 | B2 | 8.3 | 0.7 | 28.9 | 23.0 | 43.2 | 30.4 | 3.4 | 0.73 | 0.075 |
| 80-120 | B3 | 8.3 | 0.6 | 21.1 | 25.9 | 38.9 | 30.6 | 4.6 | 0.67 | 0.084 |

*Note:* [1]The data was derived from Feigin and Hidesh (1969). The untreated soil mineralization potential at field capacity conditions is 1.5% of the soil organic N per year (0-20 cm soil layer), which is equivalent to ~30 kg N $ha^{-1}Y^{-1}$ (Feigin and Sagiv, 1988). The soil volumetric water content at air dryness and field capacity are 3.5% and 23%, respectively. The mineral composition of the soil is quartz (45-60%), clay minerals + micas (10-20%), plagioclase (10%), K-feldspare (10%) and calcite (10%). The major clay mineral is illite-smectite (montmorillonite). The soil chemical composition is 61% $SiO_2$, 7% $Al_2O_3$, 3% $Fe_2O_3$, 11% CaO, 1.7% MgO and 1.2% $K_2O$. All the above mentioned results were very similar (within the range of analytical error) in the 0-20 and 20-40 cm soil layers. The cation exchange capacity (CEC) of the soil is 9.7 - 10.9 $mmol_c$ 100 $g^{-1}$, the range covering the time and treatments span of the experiment. Calcium (Ca) and potassium (K) constitute ~50% and ~15% of the CEC, respectively. The source of all these results is Sandler *et al.* (2009).

photometer and Cl by chloridometer. Soil samples were dried at 40°C and ground to pass through a 2 mm sieve. Soil tests included 1:1 soil: water extracts (unless otherwise stated), soil extracts by $CaCl_2$ and $NaHCO_3$, and total N (Kjeldahl-N), all performed by standard methods (Sparks, 1996).

### Computations

Dry matter (DM) was used to estimate transpiration (T) in treatment i (Hanks and Ashcroft, 1980):

$$T_i = T_{max} DM_i / DM_{max} \quad [1]$$

$T_{max}$ was evaluated as 0.5 $EV_a$ (transpiration during daylight hours only) and $DM_{max}$ is DM in the treatment that gave maximum yield in a specific year. The annual mineralization ($N_{min}$, g $m^{-2}$) was calculated from two organic-N pools: the soil indigenous organic-N (SON) and manure organic-N (MON).

$$N_{min} = 0.02\ SON + 0.15\ MON \quad [2]$$

It was assumed that the MON pool that was not mineralized in one year became SON (Bar-Yosef, 1999), and 5% of the N consumed by plants returned to the soil as SON.

The water head available for solute leaching (L) was calculated according to [3]:

$$L = I + R - T - E \quad [3]$$

Here I and R are annual irrigation and rainfall rates, and T and E cumulative transpiration and annual evaporation from the soil, respectively. The E was estimated as 120 mm $y^{-1}$, which is ~50% of the mean annual precipitation at the experiment site.

Ions and water mass balance in soil is described in Equation [4]. The IL is the ion quantity leached below 420 cm (g $m^{-2}$); IA is the cumulative (35 year) ion quantity added to the soil. In the case of nitrogen, it is fertilizer-N + mineralized-N, assuming that all the ammonium in the soil solution is nitrified and that denitrification is negligible. IU is the cumulative uptake by plants, and IS the quantity accumulated in the 0-420 cm soil profile ($IS_{end}$ - $IS_{initial}$).

$$IL = IA - IU - IS \quad [4]$$

Mineralized-N was estimated from the organic-N mineralization rate, computed from the mineralization model, Equation [2].

The water head available for solute leaching (L) was calculated according to Equation [3] above. The total DM production in a certain treatment (used to estimate T, Equation [1]) is the sum of annual DM yields over the experiment (Table 2).

The solutes leaching depth (h, cm) was estimated from L by assuming Equation [5], and that salts displacement is instantaneous and driven by piston flow.

$$h = L / (\theta_{fc} - \theta_i) \quad [5]$$

The initial water content ($\theta_i$,) was assigned a value of 0.12 v/v, which is ~50% of the soil's field capacity ($\theta_{fc}$, 0.23 v/v). The $\theta$ values must be uniform along the entire soil profile.

### Statistics

The compiled data set (Bar-Yosef and Kafkafi, 2016) contains only treatment means; the historic per replicate results were unfortunately lost and consequently ANOVA and least significant difference (LSD) tests could not be performed on presented data. Exceptions were the 1993 and 1994 carrot experiments where all replicate results were available. The statistical analysis of the fresh and dry carrot yields revealed that the ratio [LSD] / [treatments mean] was 0.10±0.02 and 0.15±0.01, respectively. Since experimental conditions have not changed along the experiment, the above ratios may also represent the ratio in previous experiments and if the treatments mean is known, the LSD can be approximated.

## Results and discussion

The experimental results are confined to 6 (out of the 16) treatments: M0N0 (no manure, no N-fertilizer), M0N3 (no manure, 789 g fertilizer-N $m^{-2}$ in 35 years), M2N0 (984 g organic-N $m^{-2}$ in 35 years, no mineral N), M1N3 (328 g organic-N $m^{-2}$, 789 g fertilizer-N $m^{-2}$), M2N3 (984 g organic-N $m^{-2}$, 789 g fertilizer-N $m^{-2}$) and RN3 (296 g organic-N $m^{-2}$, 789 g fertilizer-N $m^{-2}$).

### Crop yield and dry matter production

Yields varied in the annual experiments from high to low depending on treatment (for some examples see Table 2). Usually a direct relationship existed between annual fresh fruit yield and plant dry matter production (not presented). The manured, unfertilized plots (M2N0) gave a yield that was somewhat lower than the manured, fertilized plots (M2N3), but close to the

**Table 2.** Fresh yield of representative treatments and total (35-years) dry matter production.

| Year | Crop | Treatment | | | | | |
|---|---|---|---|---|---|---|---|
| | | M0N0 | M0N3 | M2N0 | M2N3 | M1N3 | RN3 |
| | | *Fresh crop yield (kg $m^{-2}$)* | | | | | |
| 1963 | Potato | 2.55 | 3.80 | 3.00 | 3.90 | 3.90 | 3.85 |
| 1978 | Sweet corn | 0.27 | 2.06 | 2.38 | 2.80 | 2.53 | 2.27 |
| 1981 | Processing tomato | 6.16 | 4.90 | 7.95 | 7.58 | 7.34 | 7.58 |
| 1987 | Muskmelon | 1.44 | 2.58 | 2.92 | 2.92 | 2.76 | 3.65 |
| 1994 | Carrot | 5.86 | 8.42 | 7.93 | 9.00 | 8.66 | 9.29 |
| | | *Total dry matter (kg $m^{-2}$)* | | | | | |
| 1961-1994 | All crops | 9.6 | 21.5 | 19.4 | 25.2 | 23.0 | 23.7 |

un-manured, fertilized plots (M0N3). Plots fertilized at the N3 level responded positively in fresh yield when the manure level increased from M0 to M1 and M2, but the enhanced yield was crop specific: negligible in potato and muskmelon, moderate in carrot (8.4, 8.7 and 9.0 kg $m^{-2}$) and considerable in sweet corn (2.1, 2.5 and 2.8 kg $m^{-2}$) and processing tomatoes (4.9, 7.3 and 7.6 kg $m^{-2}$). The response in cumulative dry matter production (all crops, 35-years) was 21.5, 23.0, 25.2 kg $m^{-2}$, all respectively. City refuse compost (R) affected yield similarly to manure level M2. The mechanisms by which manure increased yield at the N3 level could not be explicitly determined in this experiment.

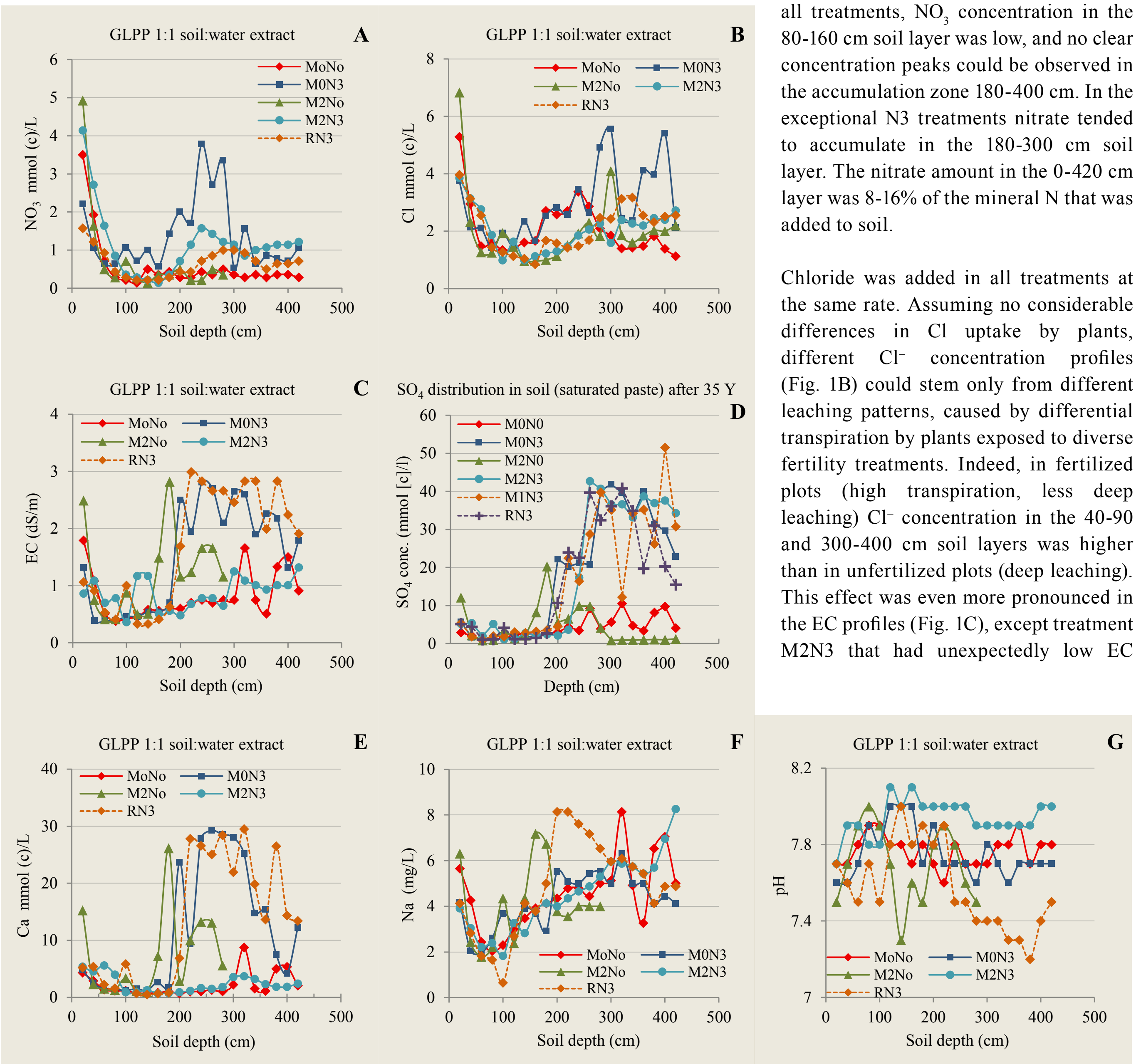



**Fig. 1.** Distribution of the main ions in the soil profile (0-420 cm) at the end of the experiment (35 years) in representative treatments. 1:1 soil: water extract (except saturated paste in $SO_4$). $NO_3$ (A), Cl (B), EC (C), $SO_4$ (D), Ca (E), Na (F), pH (G).

### Ion distribution in soil (0-420 cm) at the end of the experiment

After last harvest (September 1994), the soil was sampled to depth of 420 cm, and major ions were determined in 1:1 soil: water extract. The results are depicted in Fig. 1. The nitrate ($NO_3$) profile (Fig. 1A) was similar in all treatments, but concentration at each depth increased with increasing N application rate. In all treatments, $NO_3$ concentration in the 80-160 cm soil layer was low, and no clear concentration peaks could be observed in the accumulation zone 180-400 cm. In the exceptional N3 treatments nitrate tended to accumulate in the 180-300 cm soil layer. The nitrate amount in the 0-420 cm layer was 8-16% of the mineral N that was added to soil.

Chloride was added in all treatments at the same rate. Assuming no considerable differences in Cl uptake by plants, different $Cl^-$ concentration profiles (Fig. 1B) could stem only from different leaching patterns, caused by differential transpiration by plants exposed to diverse fertility treatments. Indeed, in fertilized plots (high transpiration, less deep leaching) $Cl^-$ concentration in the 40-90 and 300-400 cm soil layers was higher than in unfertilized plots (deep leaching). This effect was even more pronounced in the EC profiles (Fig. 1C), except treatment M2N3 that had unexpectedly low EC values. As in the case of nitrate, no clear peaks were found in the Cl and EC profiles, but unlike nitrate the $Cl^-$ accumulated in the 200-400 cm soil layer.

Sulfate was applied equally to all treatments through the supply water and in superphosphate, and differentially (until 1986) as ammonium sulfate (AS). In plots that were fertilized with AS, the sulfate accumulated in the 200-400 cm soil layer, while in treatment N0 the concentration of $SO_4$ in the entire soil profile was low (Fig. 1D). Below a depth of 200 cm the water soluble $SO_4$ concentration was tenfold greater than Cl concentration. The similarity between the soil $SO_4$ and Ca profiles (Fig. 1E) indicates that the sulfate concentration in treatments receiving high N (N3) were controlled by gypsum solubility. Since the $CaSO_4$ solubility product ($K_{sp}$) is $10^{-4.64}$ (Lindsay, 1979), the $SO_4^{2-}$ solution concentration is expected to be between 9.6 and 25 mmol $L^{-1}$. The higher value is expected if $Ca^{2+}$ concentration is governed by soil $CaCO_3$ (pH 8) and $PCO_2$ of $3 \times 10^{-4}$ atm. The low concentration is expected in a saturated $CaSO_4$ solution. The experimental $SO_4^{2-}$ concentrations in the 0-200 cm soil layer were lower (except one point) than the concentration predicted in saturated $CaSO_4$ solution (Fig. 1D). The concentrations in the 200-250 cm soil layer in high yield (N3) treatments were governed by $CaSO_4$ solubility in the presence of calcite. In low-yield treatments, the large L leached the sulfate below a depth of 250 cm. In the 250-450 cm soil layer, the $SO_4^{-2}$ concentration in N3 treatments was supersaturated with respect to gypsum solubility in the presence of calcite (Fig. 1D), probably due to slow crystallization kinetics in these treatments. Sodium (Na) application in water and fertilizers was identical in all treatments, while M and R added Na to the soil. Overall, the water soluble Na profile (Fig. 1F) was quite similar in all the reported treatments, with largest peaks occurring in treatments RN3 and M2N0. Except at soil depth >300 cm, the experimental sodium adsorption ratio [SAR, $C_{Na}/(C_{Ca}+C_{Mg})^{1/2}$, C in mM] fluctuated around the SAR of the irrigation water (3.1 $mM^{1/2}$) (data not presented). The soil pH profiles (Fig. 1G) were quite uniform with depth with small differences among treatments. Exceptions were treatments RN3 and M2N0 that had lower pH below 100 cm (~7.3 vs. all treatments mean of 7.8) and treatment M2N3 that had pH ~8 below 100 cm. The high pH in treatment M2N3 is compatible with the much lower Ca concentration in the soil water extract along the entire soil profile than in treatments M0N3 and RN3 (Fig. 1E). As a result of the lower Ca concentration in treatment M2N3, its $SO_4$ concentration was much higher than in the other two treatments (Fig. 1D).

### Estimated water head available for leaching and leaching depth

The cumulative and year-specific water head available for solute leaching (L) were calculated according to Equation [3]. Representative annual results and the cumulative (35-year) L are summarized in Table 3. In the low-yield treatment M0N0 the cumulative L (1,368 cm) was ~60% higher than in treatment M2N3 that gave the maximum yield, compatible with the empirical $Cl^-$ profiles in soil in these treatments (Fig. 2). Differences in L among other treatments were also clear, but they were smaller than in the above mentioned treatments.

The solutes leaching depth (h, cm) was estimated from the cumulative L by Equation [5] above, assuming that salts displacement is instantaneous and driven by piston flow. The obtained leaching depth varied between 66 m in treatment M2N3 and 125 m in M0N0.

Under conditions of solute transport by mass flow only, $\theta = \theta_{fc}$, and soil hydraulic conductivity $K_{fc}$ = 0.003 cm $h^{-1}$, the solute velocity v ($K_{fc} / \theta_{fc}$) is 110 cm $y^{-1}$. Movement by diffusion at $\theta_{fc}$ is estimated to be ~10 cm $y^{-1}$ which gives a total v of 120 cm $y^{-1}$. For $\theta_{fc}$ = 0.26, the calculated v is ~200 cm $y^{-1}$.

### Total (Kjeldhal) N concentration in soil (0-20 cm) as function of time

The amount of organic N added to soil in the manure treatments, and total (Kjeldhal) N found in the top 0-20 cm soil layer, both as function of time (1963-1994), are presented for four representative treatments in Fig. 2. During the first 14 years, between 1963 and 1976, the total (Kjeldhal) N concentration in soil increased in all treatments, including M0N0 and M0N3 that did not receive manure. The average accumulation rate (0-20 cm soil layer) in treatments M2N3, M1N1 and M0N0 during this period was 26.1, 16.1 and 3.1 mg N $kg^{-1}$ soil $y^{-1}$, respectively. The average organic N supply rate in treatments M2N3 and M1N1 was 130 and 50 mg N $kg^{-1}$ soil $y^{-1}$.

**Table 3.** The water head available for solute leaching (L) in representative crops and the cumulative L over the entire (35-years) experiment.

| Year | Crop | Treatment | | | | | |
|---|---|---|---|---|---|---|---|
| | | M0N0 | M0N3 | M2N0 | M2N3 | M1N3 | RN3 |
| | | *L (mm)*[1] | | | | | |
| 1974 | Potato | 364 | 225 | 320 | 300 | 308 | 292 |
| 1978 | Sweet corn | 702 | 494 | 492 | 457 | 497 | 489 |
| 1981 | Processing tomato | 687 | 711 | 526 | 526 | 606 | 606 |
| 1987 | Muskmelon | 464 | 304 | 298 | 194 | 233 | 103 |
| 1994 | Carrot | 469 | 415 | 418 | 388 | 444 | 379 |
| | | *Cumulative L (m)* | | | | | |
| 1961-1994 | All crops | 13.68 | 8.47 | 9.60 | 7.28 | 8.31 | 7.88 |

*Note:* [1] L was calculated according to Equation [3].

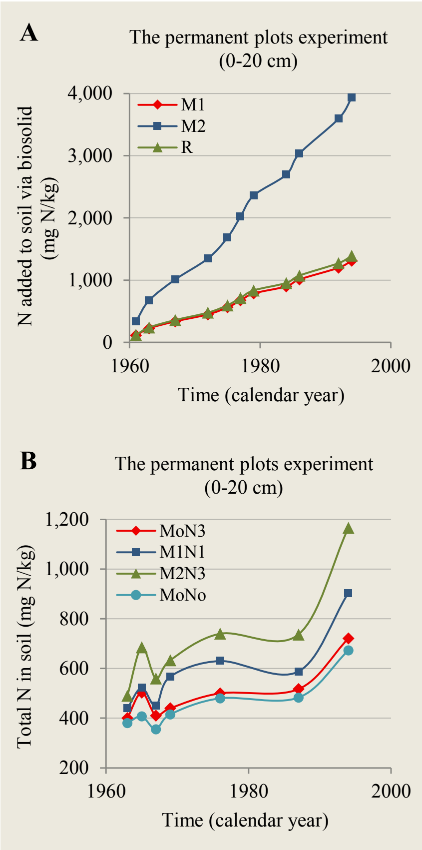



**Fig. 2.** Added organic N in applied manure (A) and organic (Kjeldhal) N (B) found in soil (0-20 cm) as a function of time in selected treatments.

The fraction of the added organic-N in treatment M2N3 that was recovered in the 0-20 cm soil test at the end of the experiment is calculated as [(soil organic N)$_{M2N3}$ - (soil organic N)$_{M0N0}$] / (organic N applied)$_{M2N3}$, all in units of [mg N kg$^{-1}$ soil]. The recovered manure-N for treatment M2N3 over the period 1963-1976 is 18%, meaning that ~82% of the added manure-N was mineralized or moved by tilling to deeper soil layers. The recovered organic-N in treatment M1N1 was found to be 26%. Between 1976 and 1987, total N in soil in all treatments was steady (Fig. 2B) even though the supply of organic-N continued. In 1994, the concentration of total N in soil was much higher than in 1987 in all treatments. Repeating the recovered organic-N calculation for the 1987-1994 time interval gives % recovery of 28% and 30% for treatments M2N3 and M1N1, respectively.

### Nitrogen supply vs. uptake

The difference between the quantity of mineral-N added to soil (fertilization + mineralization (NAD)) and N uptake (NUP) by plants (NAD-NUP) is part of the mass balance (Equation [4]), but it is worthwhile discussing it separately because it yields the treatments effect on crop N uptake efficiency. In treatment M0N3, the 35-year cumulative NAD-NUP was 542 g N m$^{-2}$ (Table 4). When the N3 level was supplemented by manure at level M1 (M1N3), or by city refuse compost (RN3) the cumulative NAD-NUP increased to 600 g N m$^{-2}$. Treatment M2N0 gave interesting results: its 35-years cumulative dry matter was 19.4 kg m$^{-2}$, which is close to the 25.2 kg m$^{-2}$ obtained in treatment M2N3 (Table 2); the difference in fresh edible yield between those treatments was even smaller (Table 2). Despite the small difference in yield, the cumulative NAD-NUP in treatment M2N0 was 65 g N m$^{-2}$ and in treatment M2N3 665 g N m$^{-2}$ (Table 4). In treatment M0N0, the cumulative NAD-NUP was ~0, indicating that the original assumption of 1.5% soil organic-N mineralization per year (footnote Table 1) is reasonable.

The NUP:NAD ratio is the crop N uptake efficiency. In treatment M0N0 the cumulative uptake was 140 g N m$^{-2}$ (see later in Table 6) and since no N was added, it indicates the long-term soil mineralization power (~4 g N m$^{-2}$ y$^{-1}$). In treatment M0N3 the cumulative NUP was 406 g m$^{-2}$ and NUP:NAD = 0.51. This ratio is the N uptake efficiency when N was supplied solely as fertilizer. In treatment M2N0 (all N supplied as manure) the NUP was 343 g N m$^{-2}$ and NUP:NAD 0.45. Combining M2 and N3 (treatment M2N3) gave cumulative NU of 523 g N m$^{-2}$ but reduced the N uptake efficiency to 0.34.

In a few cases in Table 4 negative values were obtained, meaning greater mineral-N supply by the soil than predicted. This could stem from the fact that mineralization took place below the 0-40 cm soil layer as well. It is noted that the experimental NUP values (see later in Table 6) in treatments with high yield were in line with data on optimal nutrient uptake by field crops in Israel published by Bar-Yosef (1999).

**Table 4.** The difference between mineral-N added+ to soil (NAD) and N uptake (NUP) by representative crops and years, and cumulative differences over the entire (35-years) experiment period.

| Year | Crop | Treatment | | | | | |
|---|---|---|---|---|---|---|---|
| | | M0N0 | M0N3 | M2N0 | M2N3 | M1N3 | RN3 |
| | | ---------------------*NAD-NUP (g N m$^{-2}$)*--------------------------- | | | | | |
| 1974 | Potato | 0.2 | 20.6 | 5.6 | 14.4 | 11.4 | 9.6 |
| 1978 | Sweet corn | 1.8 | 27.0 | 7.8 | 36.9 | 29.2 | 30.9 |
| 1981 | Processing tomato | -6.2 | 9.3 | -9.4 | 5.1 | 8.0 | 8.2 |
| 1987 | Muskmelon | 0.0 | 22.5 | 3.9 | 25.4 | 23.9 | 21.4 |
| 1994 | Carrot | -8.0 | 14.3 | -7.3 | 19.5 | 16.4 | 12.6 |
| 1961-1994 | All crops | 12 | 542 | 65 | 665 | 605 | 599 |

*Note:* +NAD = Fertilizer N + Manure mineralized N + Soil organic matter mineralized N. Mineralization was calculated according to Equation [2].

### Mineral and organic-N in the root zone along the experiment

Mineral N in soil was determined to a depth of 120 cm four times during the experiment (Table 5). The quantity found was proportional to fertilizer and manure application rates. The mineral N did not accumulate in soil because, in all cases, the water head available for leaching (L) was sufficiently large to leach nitrate beyond the depth of 120 cm. The 35-year average mineral-N quantities in soil in

**Table 5.** Seasonal variations in N quantities (mineral and organic) in soil. Values in parenthesis were predicted according to Equation [2][1].

| Year[2] | Crop | Treatment | | | | | |
|---|---|---|---|---|---|---|---|
| | | M0N0 | M0N3 | M2N0 | M2N3 | M1N3 | RN3 |
| | | *Mineral-N (g m$^{-2}$, 0-120 cm)*[3] | | | | | |
| 1969 | Processing tomato | 12 | 22 | 26 | 28 | 25 | 22 |
| 1974 | Potato | 16 | 18 | 24 | 42 | 36 | 38 |
| 1978 | Sweet corn | 17 | 39 | 31 | 51 | 46 | 55 |
| 1994 | Carrot | 12 | 13 | 35 | 42 | 40 | 35 |
| 1961-1994 | Mean | 14±3 | 22±7 | 26±7 | 36±8 | 33±9 | 31±10 |
| | | *Organic-N (g N m$^{-2}$, 0-40 cm)*[4] | | | | | |
| 1963 | Potato | 230 (280) | 250 (274) | 300 (330) | 300 (321) | 240 (358) | 300 (334) |
| 1967 | Cotton | 215 (248) | 245 (250) | 300 (348) | 335 (341) | 280 (338) | 310 (338) |
| 1969 | Processing tomato | 240 | 250 | 335 | 360 | 340 | 340 |
| 1976 | Pepper | 270 (205) | 280 (222) | 340 (350) | 445 (318) | 385 (337) | 310 (340) |
| 1987 | Muskmelon | 290 (166) | 310 (180) | 470 (485) | 442 (462) | 400 (328) | 400 (361) |

*Note:* [1]The reference year for predicting organic-N in soil was 1969. [2]Since 1986, the plots were irrigated by trickle irrigation and N was applied as $NH_4NO_3$ via the water. [3]Mineral-N = $NH_4$ + $NO_3$; $NH_4$-N comprised ~10% of mineral-N. [4]Organic-N concentration in soil (0-40 cm) at the beginning of the experiment was 200 g N m$^{-2}$.

treatments M0N0 and M2N0 were 14 and 26 g N m$^{-2}$, while in treatments M0N3 and M2N3 the quantities were 22 and 36 g N m$^{-2}$, respectively (Table 5).

Organic-N was measured in the 0-40 cm soil layer five times (Table 5), showing increase in quantity between 1963 and 1987: in manured plots, it increased from ~300 to ~430 g organic-N m$^{-2}$, while in M0 treatments it was only ~250 to ~300 g m$^{-2}$. The fluctuations with time are explained by the fact that manure was applied every 3-to-5 years, and soil samples were taken regardless of the time after manure application. The experimental organic-N results in Table 5 were accompanied by the mineralization model predicted values (Equation [2]). The model predicted a decrease in soil organic-N (SON+MON) with time in treatment M0, negligible variation with time in treatments M1 and R, and increase with time in treatment M2 (Table 5). The experimental soil organic-N, however, increased in all treatments, including M0. The main reason for discrepancies between experimental and predicted results was the larger quantity of plant residue incorporated into the soil than assumed in the model. In treatment M2, the contribution of incorporated plant residue was small relative to manure application therefore the agreement between experimental and predicted data was better than in other treatments.

### Ions mass balance in soil

The inorganic ions mass balance in soil after 35-year of experiment is presented in Table 6. The only term in the mass balance Equation [4] that was not determined experimentally is the N leaching below 420 cm (IL). The IS data at the end of the experiment is known from the soil sampling to the depth of 420 cm (Fig. 1) coupled with the assumption that the initial amount in soil ($IS_{initial}$) is negligible relative to added quantities. The calculated IL in treatment M2N3 was 557 g N m$^{-2}$. In treatments RN3 and M1N3, leaching was 430-to-557 g N m$^{-2}$ as compared with only 85-to-176 g N m$^{-2}$ found in the soil at the end of the experiment. In treatments M2N3 and RN3 N leaching was greater than in treatments M0N3 and M1N3 (535 vs. 430 g N m$^{-2}$) due to the greater mineralization. In treatment M0N0 and M2N0, no nitrate was leached below 420 cm and the balance was negative, indicating that in these treatments neglecting $IS_{initial}$ was unjustified.

The $Cl^-$ leaching beyond 420 cm in the various treatments ranged between 4,135 g m$^{-2}$ (M2N0) and 3,410 g m$^{-2}$ (M0N3) (Table 6). The leaching increased with added manure due to $Cl^-$ presence. The expected impact of transpiration on $Cl^-$ leaching was probably expressed below a depth of 420 cm, as was found in deep soil sampling in the Permanent Plots Experiment at Bet Dagan (Feigin and Halevy, 1995).

Sulfate did not leach beyond 420 cm and the added amounts (as superphosphate and ammonium sulfate, and in manure) accumulated in the 0-420 cm soil layer (Table 6), which is compatible with the sulfate concentration profiles in soil shown in Fig. 1D. The quantity of sulfate in the 0-420 cm soil layer exceeded the difference between application and uptake (Table 6), thus indicating that the assumption of negligible sulfate $IS_{initial}$ was incorrect.

### Potassium, sodium and phosphate status in soil

Potassium uptake by plants in treatments M0, M1 and R exceeded its addition to the soil (Table 6). Exchangeable and fixed K contributed to the unaccounted-for K. In treatments M2N0 and M2N3, surplus K (355 and 74 g K m$^{-2}$, respectively) should be found in the soil as K addition exceeded uptake and K mobility in Gilat soil is limited. The soil-K harvesting observed in treatments M0, M1 and R indicates that in order to sustain the soil fertility, K in fields well fertilized by N and P must be added to replace at least the K consumption by the crop.

Sodium accumulation in soil was unaffected by treatments as it was added

**Table 6.** Inorganic ions balance in soil after thirty-five years of experiment.

| Element | Treatment | | | | | |
|---|---|---|---|---|---|---|
| | M0N0 | M0N3 | M2N0 | M2N3 | M1N3 | RN3 |
| | *Application (g element m$^{-2}$)[1]* | | | | | |
| N | 152 | 948 | 407 | 1,188 | 1,070 | 1,081 |
| K | 237 | 237 | 957 | 957 | 477 | 477 |
| Cl | 4,212 | 4,212 | 4,692 | 4,692 | 4,372 | 4,372 |
| S | 434 | 1,090 | 434 | 1,090 | 1,090 | 1,090 |
| Na | 2,589 | 2,589 | 2,784 | 2,784 | 2,654 | 2,654 |
| | *Uptake (g element m$^{-2}$)[2]* | | | | | |
| N | 140 | 406 | 343 | 523 | 464 | 482 |
| K | 316 | 693 | 602 | 883 | 680 | 790 |
| Cl | 48 | 108 | 97 | 126 | 115 | 118 |
| S | 48 | 108 | 97 | 126 | 115 | 118 |
| Na | 10 | 21 | 19 | 25 | 23 | 24 |
| | *Application minus uptake (g element m$^{-2}$)* | | | | | |
| K | -79 | -456 | 355 | 74 | -203 | -313 |
| Na | 2,579 | 2,567 | 2,765 | 2,759 | 2,631 | 2,630 |
| | *Quantity in soil (0-420 cm) at the end of experiment (g element m$^{-2}$)* | | | | | |
| Min-N | 136 | 105 | 66 | 108 | 176 | 85 |
| Cl | 482 | 694 | 460 | 469 | 590 | 490 |
| S | 456 | 1,995 | 468 | 1,234 | 1,889 | 1,825 |
| | *Quantity leached beyond a depth of 420 cm (g element m$^{-2}$)* | | | | | |
| Min-N | -124 | 437 | -2 | 557 | 430 | 514 |
| Cl | 3,682 | 3,410 | 4,135 | 4,097 | 3,667 | 3,764 |
| S | -70 | -1,013 | -131 | -270 | -914 | -853 |

*Note:* [1]Application includes fertilizer + manure + water. [2]N, P, K uptake according to plant analyses; other elements according to dry matter multiplied by approximate concentrations in plant (Cl, S 0.5%, Na 0.1%).

mainly via the irrigation water with negligible contribution by added manures (Table 6), and its uptake by plants is negligible in comparison with its addition to soil.

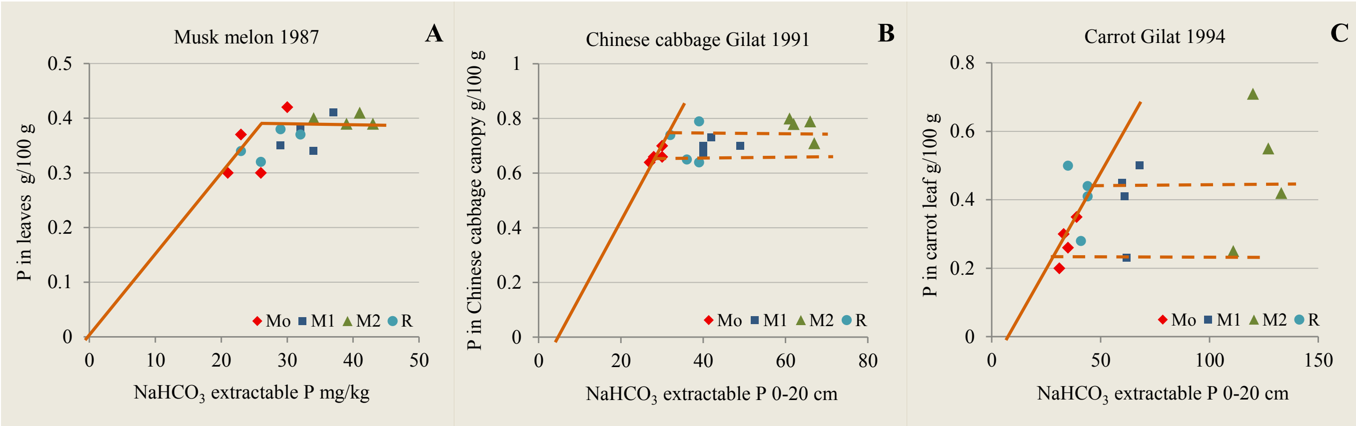
Phosphorus addition to the soil exceeded its consumption by plants over the 35 years by a margin of 80-to-225 g P m$^{-2}$, depending on manure treatment (data not presented). The excess P was retained in soil by adsorption, fixation, precipitation and biological reactions.

Phosphorus and K fertilizers were applied at identical rates to all treatments, but the manure treatments created differential P and K availability levels in soil. The availability of both P and K was evaluated by a single $NaHCO_3$ extract, as suggested by Bar-Yosef and Akiri (1978), except in 1963 when K was evaluated by the $CaCl_2$ 0.01M (1:7) extract (Table 7). The impact of N fertilization level on P and K availability in soil at any manure level was small, with a trend of decrease in available P and K concentration in soil at the N level that resulted in maximum crop yield.

**Table 7.** Available P and K in soil as function of treatment and time.[1]

| Treatment | $NaHCO_3$ extractable P | | | | | | $NaHCO_3$ extractable K | | | $CaCl_2$ |
|---|---|---|---|---|---|---|---|---|---|---|
| | 0-20 cm | | | | | 20-40 cm | 0-20 cm | | 20-40 cm | 0-20 cm |
| | 1963 | 1965 | 1987 | 1991 | 1994 | 1991 | 1991 | 1994 | 1991 | 1963 |
| | *mg P kg soil$^{-1}$* | | | | | | *mg K kg soil$^{-1}$* | | | *mg K L$^{-1}$* |
| M0N0 | - | - | 23 | 28 | 33 | 19 | 255 | 462 | 192 | - |
| M0N3 | - | - | 21 | 27 | 31 | 16 | 275 | 433 | 170 | - |
| M2N0 | - | - | 41 | 67 | 120 | 42 | 405 | 690 | 345 | - |
| M2N3 | - | - | 39 | 62 | 111 | 33 | 424 | 800 | 266 | - |
| M1N3 | - | - | 34 | 42 | 62 | 35 | 386 | 583 | 250 | - |
| RN3 | - | - | 26 | 32 | 41 | 24 | 266 | 540 | 213 | - |
| | Main factor means | | | | | | | | | |
| N0 | 25 | 49 | 31 | 45 | 63 | 30 | 320 | 543 | 176 | 23 |
| N1 | 24 | 44 | 33 | 38 | 69 | 24 | 300 | 621 | 244 | 25 |
| N2 | 24 | 40 | 30 | 42 | 69 | 27 | 300 | 578 | 318 | 27 |
| N3 | 21 | 40 | 30 | 41 | 62 | 27 | 337 | 589 | 204 | 24 |
| M0 | 14 | 20 | 25 | 29 | 35 | 18 | 258 | 458 | 248 | 21 |
| M1 | 25 | 41 | 33 | 42 | 63 | 28 | 333 | 569 | 225 | 27 |
| M2 | 37 | 88 | 39 | 64 | 122 | 37 | 408 | 818 | 232 | 29 |
| R | 18 | 24 | 27 | 37 | 41 | 25 | 263 | 486 | 237 | 22 |

*Note:* [1]In 1963 and 1965 only the mean P and K values were available. Manure doses per application in treatments M0, M1, M2 and R were 0, 30, 90 and 30 t ha$^{-1}$, respectively. The manure was added in the years 1961, 1963, 1967, 1972, 1976, 1978, 1979, 1984, 1986, 1992 and 1994.



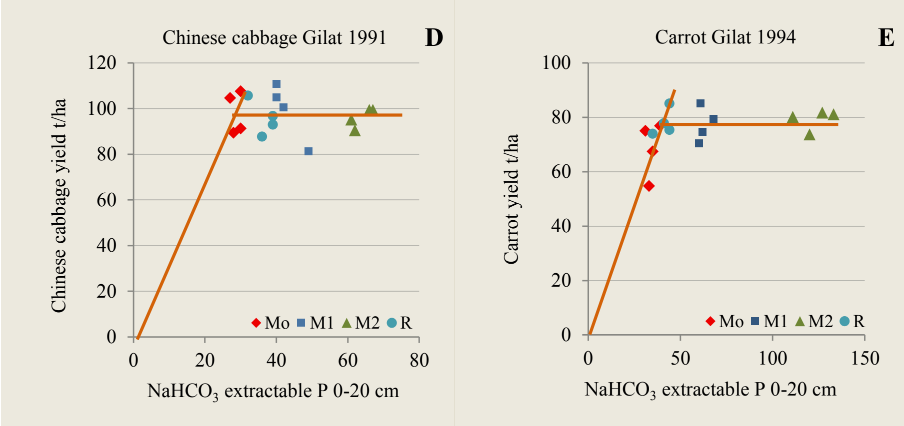




**Fig. 3.** Percentage of P in leaves in muskmelon (A), Chinese cabbage (B) and carrot (C), and yield response to available P in soil of Chinese cabbage (D) and carrot (E).

The time effect on P availability in soil (0-20 cm) can be best evaluated via the manure mean fertilizer treatments (Table 7). Treatment M0 received no manure, but the $NaHCO_3$ extractable P concentration in soil increased from 14 mg P $kg^{-1}$ in 1963 to 35 mg P $kg^{-1}$ in 1994. The source of this P is fixed P and sparingly soluble P compounds that were mobilized by root activity, and by mineralization of soil organic-P.

Treatments M1, M2 and R (Table 7) clearly increased the available P concentration in soil between 1963 and 1965, but in 1987 the concentrations declined and were lower than in 1965 and even closer to the concentrations that prevailed in 1963. This was the result of fewer manure applications between 1979 and 1987 than prior to 1979. In 1991, the available P concentration regained the values that existed in 1965, and in 1994 the concentration steeply increased thanks to manure application in 1992. The results show that there is only a short-term impact of manure on available P in soil, and 3-4 years with no manure supply results in re-equilibration of P in soil depending on soil pH and $Ca^{2+}$ activity.

The available P and K concentrations in soil increased in the order M2 > M1 > R > M0. That was also the order in the case of $CaCl_2$ soluble K (1963). In 1991, available P and K were determined in both the 0-20 and 20-40 cm soil layers. The concentration in the deeper soil layer varied between ~50 and ~75% of that in the top soil layer.

The crop response to available P and K concentration in soil could be evaluated three times along the experiment (in 1987, 1991 and 1994). The response to P is depicted in Fig. 3. In 1987 (Fig. 3A), the range of $NaHCO_3$ extractable P concentration in the 0-20 cm soil layer was ~20-to-~45 mg P $kg^{-1}$ soil, depending on the manure application dose. In 1991 (Fig. 3B), the range was ~30-to-~65 mg P $kg^{-1}$, and in 1994 (Fig. 3C) ~30-to-~130 mg P $kg^{-1}$. For comparison, we can estimate the theoretical maximum increase in soil P concentration due to application of 30 t manure $ha^{-1}$, which is the dose per application in treatment M1. In the dairy manure (~50% water and 0.6% P in dry matter), this dose elevated the P concentration by ~35 mg P $kg^{-1}$ soil (0-20 cm soil layer). Two manure applications between 1991 and 1994 can explain the observed increase in available P concentration in this treatment (from ~38 mg P $kg^{-1}$ in 1991 to ~70 in 1994 and bearing in mind that the $NaHCO_3$ extract does not release the entire adsorbed P in the soil). The effect of N at each manure level on available P concentration was significant in 1987 and negligible later on. Despite the difference in tissue P concentration between the three crops, the threshold $NaHCO_3$-P concentration above which no increase in tissue P was obtained was 25-30 mg P $kg^{-1}$ soil (Figs. 3A, 3B, 3C). This was also the threshold in the relationship between crop edible yield and available P concentration

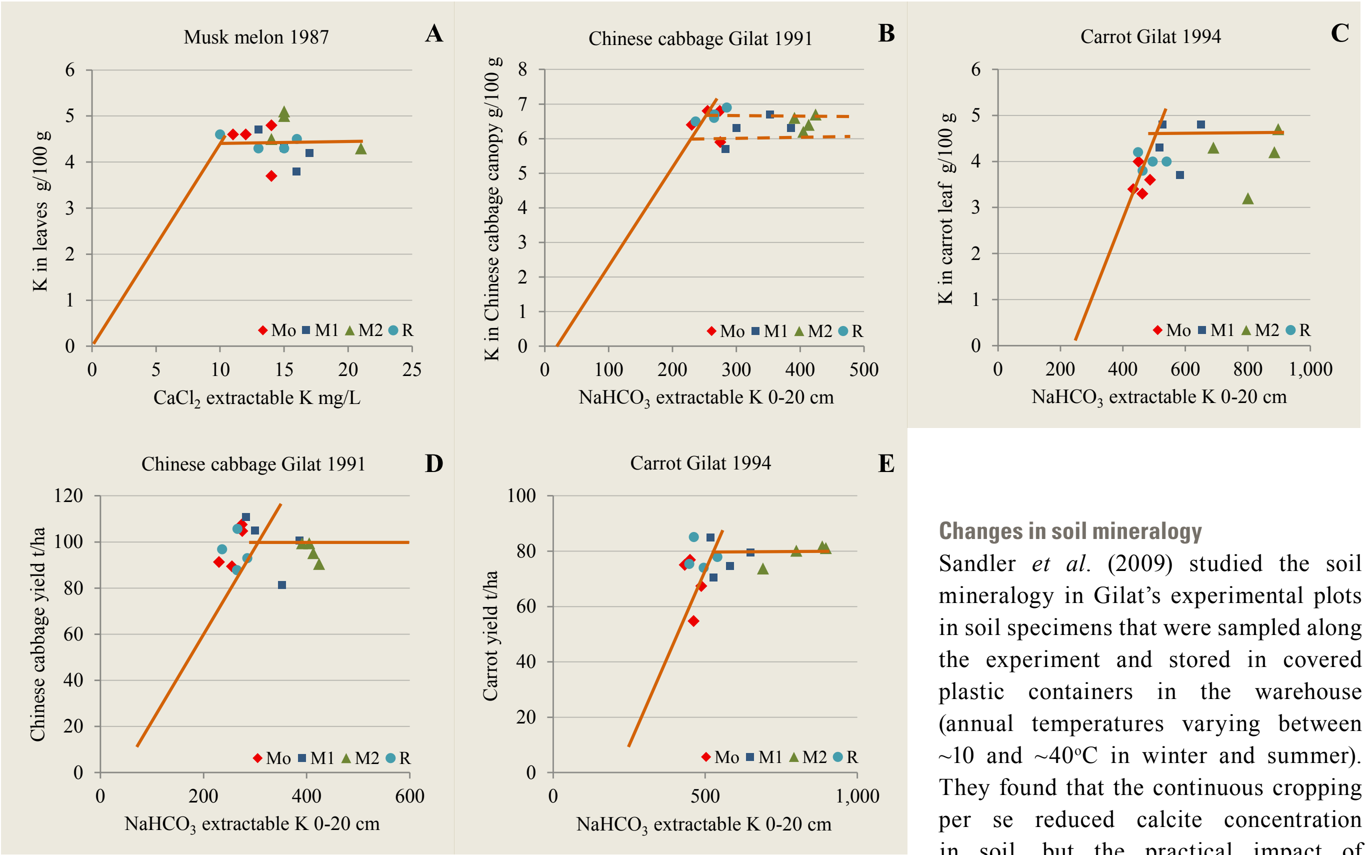



**Fig. 4.** Crop yield, percentage of K in leaves of muskmelon (A), Chinese cabbage (B), and carrot (C), and yield response of to available K in soil of Chinese cabbage (D), and carrot (E). The response in %K in leaves in 1987 is to $CaCl_2$ soluble K.

in the soil (Figs. 3D, 3E). The straight lines to the abscissa show the crop response to soil available P when it is the main growth limiting factor in the system.

The crop response to soil available K is presented in Fig. 4. In 1987 (muskmelon), the threshold concentration of $CaCl_2$ soluble K was 8 mg K $L^{-1}$ (Fig. 4A), and this value was exceeded even in the un-manured treatment M0. The available K concentration in soil in 1991 and 1994 was evaluated by the $NaHCO_3$ 0.5M extract that was used to estimate available P in soil (Bar-Yosef and Akiri, 1978). The obtained concentrations spread in 1991 was between ~220 and ~420 mg K $kg^{-1}$ soil, the values increasing with increasing manure application rates (Fig. 4B). In 1994, the spread was ~410-to-~900 mg K $kg^{-1}$ soil (Fig. 4C). To assess this increase, the K found in 30 tons of dairy manure and mixed in the 0-20 cm soil layer of 1 ha (treatment M1) can increase the soil K concentration by up to 150 mg K $kg^{-1}$. It is interesting to note that in treatment M0, in which K uptake exceeded fertilizer-K application and organic matter has not been added, the soil K concentration still increased with time. A reasonable explanation is that fixed K was released to the soil solution in response to the depletion of K by the plants. In Chinese cabbage (1991), the threshold $NaHCO_3$-K concentration in both yield and % K in leaves was ~200 mg K $kg^{-1}$, while in carrot (1994) it was ~500 mg K $kg^{-1}$ (~1.2 mmol(c) 100 $g^{-1}$ soil) (Figs. 4D, 4E).

## Changes in soil mineralogy

Sandler *et al.* (2009) studied the soil mineralogy in Gilat's experimental plots in soil specimens that were sampled along the experiment and stored in covered plastic containers in the warehouse (annual temperatures varying between ~10 and ~40°C in winter and summer). They found that the continuous cropping per se reduced calcite concentration in soil, but the practical impact of this finding was small. The long-term fertilization had a slight impact on the soil's mineralogical composition: high manure and fertilization rates caused a small decline in soil illite due to K consumption by plants and a subsequent increase in soil smectite.

## Conclusions

The main conclusions from the Gilat LTFE can be summarized as follows:

1. Replacing fertilizer-N by manure-N under controlled irrigation and sufficient N supply had long-term beneficial effect on reducing underground water pollution, and minor adverse effect on crop yield.

2. Enhanced dry matter (DM) production due to fertilization reduced nitrate and chloride leaching depth, thus supporting the theory that transpiration is directly proportional

to DM production. Applying this theory allowed estimating the cumulative (35-year) water head available for leaching (L), which varied between 730 cm in treatment M2N3 and 1370 cm in treatment M0N0. Assuming piston solute flow, these L values could displace soluble salts to depth of 66 m in treatment M2N3 and 125 m in M0N0 at estimated velocity of ~120 cm $y^{-1}$.

3. In the ample N supply treatment (M2N3), which represents conditions of high $NO_3^-$ pollution hazard, the estimated cumulative (35-year) $NO_3^-$ leaching was 557 g N $m^{-2}$ and the corresponding $Cl^-$ leaching was 4,097 g Cl $m^{-2}$. In treatment M2N0 the corresponding leaching values were 0 and 4,135 g $m^{-2}$.

4. The [cumulative irrigation] - [cumulative estimated crop transpiration] varied between 60 cm (treatment M2N3) and 700 cm (M0N0). This indicates that irrigation in high yield treatments was efficient, and deep leaching was done by winter rain.

5. The long-term soil cultivation had a negligible effect on the crops response to N fertilization treatments.

6. The long-term N uptake efficiency was 0.51 in treatments receiving all the N as mineral-N and 0.45 in treatments receiving all the N as organic-N.

7. High manure and fertilizer application rates caused a small decline in soil illite due to K consumption by plants and a subsequent increase in soil smectite.

8. The soil organic-N (SON) increased with time in all treatments depending on the organic-N application level. In treatment M2 the increase in the 0-40 cm soil layer was from 280 (in

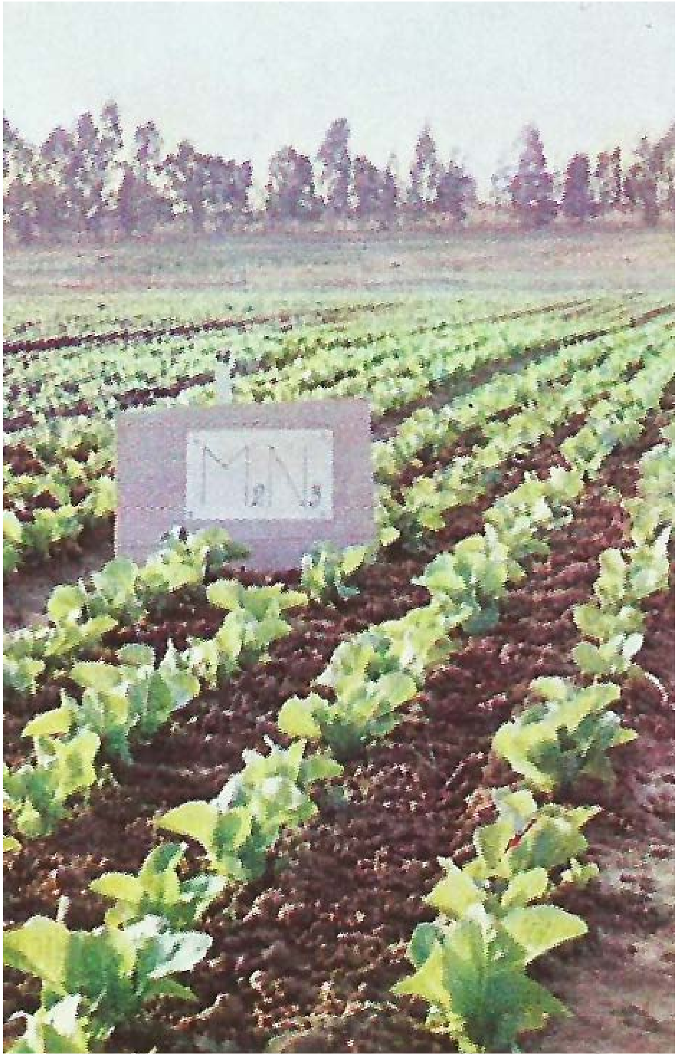


**Photo 1.** Authentic picture of the lettuce crop in the Gilat LTFE, 1970. The plots were 16 m long and 6 m wide (3 beds per plot). Photo by author.

**Photos 2.** Overview of the Gilat LTFE in 1976 (left) and 1981 (right). The soil color is misleading, not reflecting the natural color of the experimental loess soil. Photos by author.

1963) to 470 g N $m^{-2}$ (in 1987), while in M0 the increase was from 280 to 300 g N $m^{-2}$. The mineralization rate of SON was 4 g N $m^{-2}$ $y^{-1}$.

9. Potassium uptake, under recommended K fertilization and low manure application, exceeded the K addition to soil and caused depletion of soil K. The threshold soil $CaCl_2$ soluble K, above which no muskmelon yield increase was obtained, was 8 mg K $L^{-1}$. The corresponding threshold $NaHCO_3$ extractable K in soil was 220 mg K $kg^{-1}$ in Chinese cabbage and 450 mg K $kg^{-1}$ in carrot.

10. An observed beneficial effect of manure addition on available P in soil was short-termed, and 3-4 years without re-supply of manure resulted in re-equilibration of mineral-P in soil depending on soil pH and $Ca^{2+}$ activity. The threshold $NaHCO_3$ extractable P in soil above which no increase in tissue P concentration or crop edible yield were obtained was 25-30 mg P $kg^{-1}$ soil.

11. Available P and K concentration in soil in the 20-40 cm layer varied between ~50 and 75% of that in the 0-20 cm soil layer.

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**The paper "Conclusions from the Permanent Plot Experiment at Gilat, Israel: Long-Term (35-Year) Effects of Manure and Fertilizer on Crop Yield, Soil Fertility, N Uptake, and Solutes Leaching in Soil" also appears on the IPI website at:**

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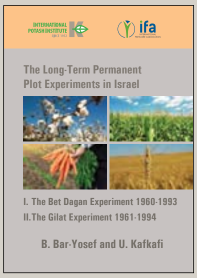


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# Research Findings

Ms. Hillette Hailu with Prof. Tekaling Mamo (center) at field research plot with different levels of K and P in Akaki woreda, Oromia Region, Ethiopia. Photo by E. Sokolowski.

## Response of Wheat (*Triticum aestivum* L.) to Phosphorus and Potassium Fertilization on Vertisols in Ethiopia's Central Highlands

Hailu, H.[(1)*], T. Mamo[(2)], and R. Keskinen[(3)]

### Abstract

Nutrient depletion is one of the major causes that contribute to declining soil productivity in the highlands of Ethiopia. Applications of urea and diammonium phosphate (DAP) were started four decades ago to improve soil fertility for enhanced crop production. However, the average national wheat yield is much lower than Africa's, as well as the world's average. In order to improve wheat yields, field experiments were established in the 2012 and 2013 cropping seasons on two rainfed locations in central highland Vertisols in Ethiopia to determine the response of bread wheat (*Triticum aestivum* L.) to phosphorus (P) and potassium (K) fertilization along with other limiting nutrients. A total of 16 treatments were tested in a 4 x 4 factorial design involving four P (0, 10, 20 and 30 kg ha$^{-1}$) and four K (0, 26, 39 and 52 kg ha$^{-1}$) fertilization levels with three replications.

[(1)]College of Agriculture, Wollo University, Dessie Ethiopia
[(2)]Center for Soil and Fertilizer Research in Africa (CESFRA), Mohammed VI Polytechnic University, Benguerir, Morocco
[(3)]Natural Resources Institute Finland (Luke), Jokioinen, Finland
[*]Corresponding author: hillette16@gmail.com

Analysis of variance revealed a significant difference ($P < 0.01$) between treatments in yield and nitrogen (N), P and K uptake by wheat at both sites over the two cropping seasons. In addition, the study showed that concurrent use of P and K significantly increased yield and the N, P and K uptake of wheat, compared to the levels obtained with either P or K applied alone. The fertilization treatments had no significant effect on grain size. In the Cheffe Donsa site, the highest grain yields, 6.4 and 7.6 t ha$^{-1}$, were exhibited by a combination of 10 kg P ha$^{-1}$ and 26 kg K ha$^{-1}$ in the 2012 and 2013 cropping seasons, respectively. In the Akaki site the highest grain yields, 2.8 t ha$^{-1}$ (2012) and 4.8 t ha$^{-1}$ (2013), were acquired with 30 kg P ha$^{-1}$ and 26 kg K ha$^{-1}$. In conclusion, the concurrent use of P and K fertilizers enhanced the yield and nutrient uptake of wheat in the studied sites.

*Keywords:* Wheat (*Triticum aestivum* L.), phosphorus, potassium, yield, nutrient uptake.

## Introduction

Wheat (*Triticum aestivum* L.) is one of the major global cereal crops, ranking second after paddy rice both in area and production, and provides more nourishment than any other food crop (Curtis, 2002). Ethiopia is one of the largest wheat producers in sub-Saharan Africa (Tanner and Mwangi, 1992; FAOSTAT, 2014) with an estimated area of 1 million ha under wheat production (CSA, 2000). The central highlands of Ethiopia are historically an important wheat-growing region. In this region, wheat ranks second in total area, production and market demand after tef (*Eragrostis tef*) (CSA, 1997a; CSA, 2000), and is produced across a range of soil conditions, particularly on well-drained highly-weathered reddish-brown soils (Nitisols) and poorlydrained heavy dark clay soils (Vertisols) (Woldeab *et al.*, 1991; Asamenew, 1991; Gebremariam, 1991). Despite the significant area of wheat production in Ethiopia, the mean national wheat yield of 1.3 t ha$^{-1}$ is 24% below the mean yield for Africa and 48% below the global mean yield (Gavian and Degefa, 1996). The national average yield of the crop is estimated at 2.11 tonnes ha$^{-1}$ (CSA, 2013), which is very low compared to the world's average yield of 3.09 tonnes ha$^{-1}$ (FAOSTAT, 2012). Low productivity is attributed to the use of old and low-yielding varieties, depletion of soil nutrients, poor weed management practices, low levels of fertilizer application, waterlogging in Vertisol areas, prevalence of aggressive and virulent crop pathogens, and unavailability of modern crop management inputs (Mamo *et al.*, 1988; Gorfu *et al.*, 1991; Woldeab *et al.*, 1991; Asamenew, 1991; Tanner and Mwangi, 1992; Tarekegne *et al.*, 1997a,b; CSA, 1997b; Zegeye *et al.*, 2001).

Vertisols are considered to be suitable for producing cereals like wheat. They cover about 12.61 million ha of land in Ethiopia and the country ranks third in Vertisols abundance in Africa after Sudan and Chad. The majority of Ethiopian Vertisols, about 8 million ha, are located in the highlands (Debele, 1985). As in many other tropical and subtropical regions (Sanchez, 1976), soils in the highlands of Ethiopia, particularly in the central region, exhibit low levels of essential plant nutrients and organic matter content (Woldeab *et al.*, 1991; Mamo *et al.*, 1988). Poor soil fertility (Tarekegne *et al.*, 1997a), especially low availability of nitrogen (N) and phosphorus (P) (Woldeab *et al.*, 1991; Mamo *et al.*, 1988), has been demonstrated to be a major constraint to wheat production in Ethiopia. This is largely a consequence of the cereal-dominated cropping history of most fields and continuous nutrient mining by crop removal (Tarekegne *et al.*, 1997b; Gorfu *et al.*, 1991), which eventually leads to depletion of soil nutrients (Woldeab *et al.*, 1991; Tanner and Mwangi, 1992). Soil nutrient depletion has been exacerbated by low levels of chemical fertilizer usage (Woldeab *et al.*, 1991; CSA, 1997b) due to both high costs, and constraints to timely availability of fertilizers (Ayele and Mamo, 1995). Generally, N and P are the most limiting nutrients in Vertisols (Finck and Venkateswarlu, 1982) and this holds true for Ethiopian soils as well. The lack of response to P fertilizer application on Vertisols could be attributed to various factors including high P sorption capacity of the soil and soil moisture conditions (Sahrawat *et al.*, 1995; Abunyewa *et al.*, 2004), and limitation of nutrients other than P (EthioSIS, 2015; Hailu *et al.*, 2015). The risk of yield decline can be minimized by application of balanced mineral fertilizers in terms of all nutrient elements (Öborn *et al.*, 2005).

In Ethiopia, potassium (K) status of agricultural soils is generally found to be adequate for crop production, though a few studies show acutely deficient soil K levels (Mamo and Haque, 1988; Gebeyehu and Mamo, 1999; Bellete, 2014; Tilahun, 2014; Mekonnen, 2014; EthioSIS, 2015; Laekemariam, 2015). Fixation of K is correlated with the percentage of clay and is highest in Vertisols. Potassium fixation is enhanced by the presence of smectite and amorphous materials. The limited response of crops to applied K and the often high levels of exchangeable K found in most Ethiopian soils have led researchers and development agents to conclude that the K fertilization need in these soils is minimal. However, continuous cropping, in which fertilizer responsive varieties and improved management practices are used, results in K mining from the soil. Wheat crops can remove more than 400 kg $K_2O$ ha$^{-1}$ year$^{-1}$ (IFA, 1986). The total absence or low application level of K fertilization combined with intensive continuous cropping leads to the depletion of soil K reserves. Even soils which are initially well supplied with K will become deficient under such management systems. Total consumption of K from soil by wheat producing yields of 10 t ha$^{-1}$ varies from 160 to 242 kg K ha$^{-1}$ (Kemmler, 1983).

In Ethiopia, reports which indicate crop response to applied K on Vertisols have started to emerge. A study conducted by Abiye *et al.* (2004) found that wheat responded significantly to K application on Vertisols at Cheffe Donsa, in east Shoa. They recommended the need to reassess the traditionally practiced system of not applying K fertilizer to Ethiopian soils. However, there is no information concerning P and K fertilization for wheat grown on highland Vertisols. Thus, this study was conducted to investigate the effect of different levels of P and K additions on yield as well as nutrient uptake of bread wheat (HAR 3116) on two central highland Ethiopian Vertisols.

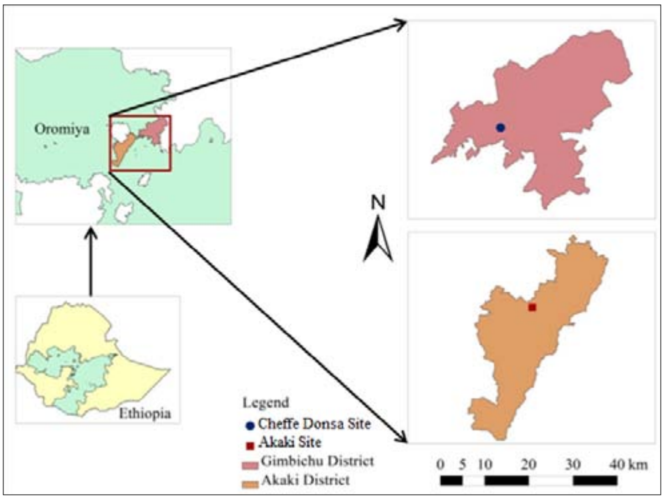


**Fig. 1.** Location map of the experimental sites.

## Materials and methods

### Experimental site description

The experiments were conducted on farmers' fields at two representative central highland locations, Akaki and Cheffe Donsa, during the main cropping seasons in 2012 and 2013. Akaki is located 25 km south east of Addis Ababa (08°49'40.5''N lat. and 38°49'17.9''E long.) at an altitude of 2,400 meters above sea level (m a.s.l.) (Fig. 1). Akaki receives a mean annual rainfall of 930 mm, and a mean annual minimum and maximum temperature of 8 and 27°C, respectively (Table 1). The Cheffe Donsa site is positioned about 80 km east of Addis Ababa (08°57'59.6''N lat. and 039°06'28.4''E long.) at an altitude of 2,444 m a.s.l. (Fig. 1). Cheffe Donsa receives a mean annual rainfall of 1,098 mm, and a mean annual minimum and maximum temperature of 10 and 25°C, respectively (Table 1).

**Table 1.** Climate data of Akaki and Cheffe Donsa area in the 2012 and 2013 cropping season.

| | Akaki | | Cheffe Donsa | |
|---|---|---|---|---|
| | 2012 | 2013 | 2012 | 2013 |
| Total annual rainfall (mm) | 826 | 1,033 | 936 | 1,259 |
| Mean annual maximum temperature (°C) | 27 | 27 | 25 | 24 |
| Mean annual minimum temperature (°C) | 9 | 7 | 11 | 9 |

*Source:* National Meteorological Agency of Ethiopia.

### Experimental design

The experimental design was a randomized complete block design in a factorial combination of P and K. A plot size of 3 m by 3 m was used and adjacent plots and blocks were spaced 1 m apart. Both experiments contained the following treatments; four rates of P as triple super phosphate (0, 10, 20 and 30 kg ha$^{-1}$) and four rates of K as murate of potash (0, 26, 39 and 52 kg ha$^{-1}$) (Table 2). There were three replications. Nitrogen as urea (60 and 92 N kg ha$^{-1}$ in the first and second cropping season, respectively), sulfur (S) as gypsum (20 S kg ha$^{-1}$) and zinc (Zn) as zintrac (700 g Zn ha$^{-1}$) were applied as a basal dose.

**Table 2.** Details of the experimental treatments.

| Treatment | Fertilizer dozes | |
|---|---|---|
| | P | K |
| | -----------------------*kg ha$^{-1}$*----------------------- | |
| $T_1$ (control) | 0 | 0 |
| $T_2$ | 0 | 26 |
| $T_3$ | 0 | 39 |
| $T_4$ | 0 | 52 |
| $T_5$ | 10 | 0 |
| $T_6$ | 10 | 26 |
| $T_7$ | 10 | 39 |
| $T_8$ | 10 | 52 |
| $T_9$ | 20 | 0 |
| $T_{10}$ | 20 | 26 |
| $T_{11}$ | 20 | 39 |
| $T_{12}$ | 20 | 52 |
| $T_{13}$ | 30 | 0 |
| $T_{14}$ | 30 | 26 |
| $T_{15}$ | 30 | 39 |
| $T_{16}$ | 30 | 52 |

### Experimental materials and procedures

The experimental fields were prepared using a local plow (maresha) according to farmers' conventional farming practices. The fields were ploughed two times, after which broad beds and furrows were constructed by a broad bed maker (BBM). The BBM is an oxen-drawn traditional wooden plow, modified for the construction of raised beds and furrows to facilitate surface drainage through the furrows between the beds so that the crops are grown on the beds (Jutzi and Abebe, 1986).

Wheat is grown at an altitude ranging from 1,500 to 3,000 m a.s.l., between 6-160 N latitude and 35-420 E longitude. The most suitable agroecological zones, however, fall between 1,900 and 2,700 m a.s.l (Kotu *et al.*, 2000). The major wheat producing areas in Ethiopia are located in Arsi, Bale, Shewa, Ilubabor, Western Hareghe, Sidamo, Tigray, Northern Gonder and Gojam zones (Kotu *et al.*, 2000). The test variety used in the study areas was an improved bread wheat variety (HAR 3116), which is a high yielding variety widely grown in the wheat belt highlands in the central part of the country. Digalu (HAR 3116) occupied over 0.5 million ha (approx. 31% of production acreage) in Ethiopia and made a major contribution to the record wheat harvest of 3.92 million tons in the 2013/2014 season (CSA, 2014). This variety is semi-dwarf and was released by Kulumsa Agricultural Research Centre in 2005 (Alemayehu *et al.*, 2015). The seed was sown at a rate of 80 kg $ha^{-1}$, which is about half of the recommended rate (150 kg $ha^{-1}$) for broadcast and maresha incorporated seed (Gorfu, 1988), with row spacing of 20 cm.

The entire amount of P and S designed for each treatment was applied once at sowing, whereas N and K fertilization was split into two applications. One third of the N and half of the K were applied at sowing and the remaining was top dressed after 35 and 45 days, respectively. Zn was applied twice, at the tillering stage and again 14 days after that. Weed control was done by hand 20 days after sowing and as needed throughout the growing season in all the treatments. Planting and harvesting were also done by hand. Sowing was done within the range of July 5 to 15 whereas the wheat was harvested between the end of October and early November.

### Soil sampling and analysis

For assessing the fertility of surface soil, 12 composite soil (0–15 cm) samples, four per block, were taken from each experimental site before planting. Each composite soil sample comprised 15 sub samples collected in a zigzag pattern within the replication and mixed thoroughly following a standard procedure for soil sampling and sample preparation (Paetz and Wilke, 2005).

The analyses of soil particle size distribution, pH and electrical conductivity (EC) were conducted at the Debre Ziet Agricultural Research Center (DZARC). All other parameters were analyzed by Natural Resources Institute Finland (former MTT Agrifood Research Finland). Soil particle size distribution was analyzed by hydrometer method (Gee and Bauder, 1986). Soil textural class names were assigned based on the relative contents of the sand, silt and clay separates using the soil textural triangle of the United States Department of Agriculture (USDA, 1951). Soil pH (McLean, 1982) and EC (Rhoades, 1982) were determined from a suspension of 1:2.5 soil:water ratio. Soil organic carbon (OC) and total nitrogen (TN) content were determined by dry combustion methods based on ISO 10694 (1995) and ISO 13878 (1998) protocols, respectively. For available P determination, soil samples were extracted with 0.5M $NaHCO_3$ at a nearly constant pH of 8.5 in 1:20 of soil to solution ratio for half an hour, as described by Olsen *et al.* (1954), and thereafter measured using Perkin Elmer Optima 8300 Inductively Coupled Plasma - Optical Emission Spectrometer (ICP-OES). Available S was determined by the extraction of $SO_4$-S with $CaCl_2 \cdot 2H_2O$. Sulfate - sulfur ($SO_4$-S) concentration in the extracts was measured by a turbidimetric procedure using barium chloride (Williams and Steinbergs, 1959). Exchangeable bases (calcum [Ca], magnesium [Mg], K and sodium [Na]) of the soil samples were extracted with 1M buffered ammonium acetate extractant (Cottenie, 1980) and basic cations were determined by ICP-OES. The cation exchange capacity (CEC) of the soils was determined by 1M buffered ammonium acetate extraction method and distillation of the ammonium saturated soil in a Kjeldahl distillation apparatus while receiving the distillate in boric acid and then titrating with sulfuric acid (Cottenie, 1980). Base saturation percentage (BSP) was calculated by dividing the sum of base-forming cations by CEC (Coyne and Thompson, 2006). Micronutrients (copper [Cu], iron [Fe], manganese [Mn] and zinc [Zn]) were determined from ammonium bicarbonate di-ethylene tri-amine penta-acetic acid (AB-DTPA) extracts (Soltanpour and Schwab, 1977). The micronutrient concentrations were determined by ICP-OES.

### Crop data collection and analysis

The wheat crop was harvested by collecting the above ground plant mass from the central 2 $m^2$ area of each plot when the plants showed clear signs of maturity (complete yellowing of leaves and spikes). The total above ground plant biomass (biological yield) obtained was weighed, after which grains were separated and weighed to record the grain yield. Straw yield was determined by subtracting the grain yield from the biological yield. Thousand grain weight was recorded for each plot in five replicates by weighing 1,000 randomly selected grains.

Grain and straw samples from each treatment were oven dried at 60-70°C to a constant weight and thereafter ground and analyzed for N, P and K contents. Total N concentrations of the samples were determined using the modified Kjeldahl method (Jackson, 1958). For the P and K analyses, the samples were first re-dried at 60°C and then ashed at 550°C for eight hours. Thereafter, the ashes were digested in 20% $HNO_3$ (Zarcinaas *et al.*, 1987). Phosphorus concentration of the digests was measured with a spectrophotometer and the K concentration with a flame photometer.

The uptake of nutrients (N, P and K) into straw and grain was calculated by multiplying the nutrient content (%) with the respective straw and grain yield $ha^{-1}$ on dry weight basis. Total nutrient content in the biological yield was obtained by summing up the nutrient uptakes by grain and straw.

$$\text{Nutrient uptake of the grain} = \frac{\text{nutrient content of the grain (\%)} \times \text{grain yield (kg ha}^{-1})}{100}$$

$$\text{Nutrient uptake of the straw} = \frac{\text{nutrient content of the straw (\%)} \times \text{straw yield (kg ha}^{-1})}{100}$$

Total nutrient uptake = nutrient uptake of the grain + nutrient uptake of the straw.

### Statistical analysis

The data on crop yield and yield related traits were subjected to analysis of variance (ANOVA) using SAS statistical software and the statistical procedures described by Gomez and Gomez (1984). The least significant difference (LSD) was used for comparing the means of wheat yields and nutrient uptake obtained with the different rates of P and K applications.

## Results and discussion

The results of compound analysis on the studied characteristics were significantly different in 2012 compared to 2013. Accordingly, data from each year were analyzed separately for all characteristics.

### Soil characteristics

The results of initial soil properties, as presented in Table 3, reveal that the particle size distribution of the surface soils (0–15 cm) of both experimental fields was dominated by clay fraction (above 53%). Debele (1985) and Tsegaye (1992) also reported that Vertisols in Ethiopia generally contain more than 40% clay in the surface horizons. The surface soil (0–15 cm) analysis showed that prior to sowing, the experimental soils had a pH of 7.2-7.8 (slightly to moderately alkaline), which is typical for Ethiopian Vertisols (Debele, 1985; Kebede and Charles, 2009). This pH range is favorable for most crops (Tadesse, 1991; FAO, 2000). The soil organic matter (Tadesse, 1991; Debele, 1980) and available S (Lewis, 1999) contents, however, were in low ranges. According to the ratings of Cottenie (1980), the available P (Olsen extractable) was low and moderate at Akaki and Cheffe Donsa sites, respectively.

Exchangeable Ca and Mg were the dominant cations in the surface soils of both experimental fields (Table 3). Calcium comprised 77 and 78% of the soil cation exchange sites of Akaki and Cheffe Donsa, respectively. Similarly, Mg occupied 19 and 12.3% of the soil cation exchange sites in Akaki and Cheffe Donsa. The exchangeable K was in the high range (0.7 to 2 $cmol_{(+)}$ $kg^{-1}$) (Hazelton and Murphy, 2007; Peverill *et al.* 1999). Sodium had the lowest concentration (0.16-0.27 $cmol_{(+)}$ $kg^{-1}$ of soil) among the base forming cations found in the top soil cation exchange complex in both experimental fields. The K:Mg ratio of the soil in the experimental sites varied from 0.17:1 to 0.35:1, which indicates Mg induced K deficiency using the rating of Loide (2004). The CEC of the surface soils of Akaki and Cheffe Donsa were 49.4 and 42.1 cmol $kg^{-1}$, respectively. The CEC of the study area can be termed as very high according to the ratings given by Hazelton and Murphy (2007). The surface horizons of Ethiopian Vertisols have generally been found to have very high CEC (Debele, 1985; Tsegaye, 1992). These high CEC values might result from the dominant smectite clay mineral constituents of the Vertisols in the study area (Debele, 1985). The base saturation of the surface soil of the study area was in the very high range based on the ratings given by Hazelton and Murphy (2007). The high base saturation is explained by the very low rate of leaching due to the very low hydraulic conductivity and low infiltration rates of Vertisols (Pimentel, 2006). According to Soltanpour (1985) and Jones (2003), the AB-DTPA-extractable Cu, Mn and Fe contents of the surface soil of the experimental sites were rated as adequate, while Zn content was deficient and hence inadequate for plant growth (Table 3).

### Biological yield

The above ground biomass of cereal crops (straw and grain) is an important agronomic parameter that is sensitive to soil and applied nutrients (Mirutse *et al.*, 2009). Application of P and K significantly ($P \leq 0.01$) improved the aboveground biomass yield (Tables 4 and 5).

At Akaki, the highest biological yields of 7,662 kg $ha^{-1}$ (first growing season) and 10,739 kg $ha^{-1}$ (second growing season) were recorded from $T_{14}$ (30-26 P-K kg $ha^{-1}$) and $T_{11}$ (20-39 P-K kg $ha^{-1}$), respectively. These were statistically higher over P alone, K alone and the control (without P and K) treatments. In the 2012 cropping season, the second highest biological yield of

**Table 3.** Physical and chemical properties of surface soil (0-15 cm) of the experimental sites.

| Soil property | Experimental sites: Akaki (Akaki) | Experimental sites: Cheffe Donsa (Gimbichu) |
|---|---|---|
| Particle size distribution | | |
| Sand (%) | 15 | 21 |
| Silt (%) | 18 | 25 |
| Clay (%) | 67 | 54 |
| Textural class | Heavy clay | Clay |
| pH (1:2.5 suspension) | 7.4 | 7.8 |
| EC (1:2.5 suspension) (dS $m^{-1}$) | 0.15 | 0.2 |
| Total nitrogen (%) | 0.1 | 1.1 |
| Organic carbon (%) | 1.2 | 1.1 |
| Soil organic matter (%) | 1.9 | 1.9 |
| Olsen's P (mg $kg^{-1}$) | 5.9 | 7.5 |
| Sulfate-S (mg $kg^{-1}$) | 1.8 | 1.2 |
| Ammonium acetate extractable | | |
| Ca ($cmol_{(+)}$ $kg^{-1}$) | 38 | 32.8 |
| Mg ($cmol_{(+)}$ $kg^{-1}$) | 9.4 | 5.2 |
| K ($cmol_{(+)}$ $kg^{-1}$) | 1.6 | 1.8 |
| K:Mg | 0.17 | 0.35 |
| Na ($cmol_{(+)}$ $kg^{-1}$) | 0.16 | 0.27 |
| CEC ($cmol_{(+)}$ $kg^{-1}$) | 49.4 | 42.1 |
| PBS (%) | 99 | 95 |
| AB-DTPA extractable | | |
| Cu (mg $kg^{-1}$) | 3.86 | 3.5 |
| Fe (mg $kg^{-1}$) | 40.8 | 33.6 |
| Mn (mg $kg^{-1}$) | 34.8 | 46 |
| Zn (mg $kg^{-1}$) | 1.14 | 1.1 |

**Table 4.** Wheat yield as affected by different P and K application rates at Akaki in the 2012 (S1) and 2013 (S2) cropping season.

| Treatment | Biological yield | | Grain yield | | Straw yield | | Thousand grain weight | |
|---|---|---|---|---|---|---|---|---|
| P + K | S1 | S2 | S1 | S2 | S1 | S2 | S1 | S2 |
| | -----------------------------------------*kg ha$^{-1}$*----------------------------------------- | | | | | | ----------*g*--------- | |
| $T_1$ (0+0) control | 5,185 | 8,926 | 1,947 | 3,011 | 3,238 | 5,915 | 29 | 38 |
| $T_2$ (0+26) | 5,585 | 8,691 | 2,098 | 3,812 | 3,487 | 4,879 | 34 | 36 |
| $T_3$ (0+39) | 4,970 | 8,652 | 1,852 | 3,948 | 3,118 | 4,703 | 31 | 38 |
| $T_4$ (0+52) | 5,807 | 9,237 | 2,150 | 3,913 | 3,657 | 5,324 | 31 | 38 |
| $T_5$ (10+0) | 3,648 | 8,324 | 1,372 | 3,698 | 2,277 | 4,627 | 29 | 36 |
| $T_6$ (10+26) | 5,148 | 9,921 | 1,820 | 4,208 | 3,228 | 5,713 | 31 | 35 |
| $T_7$ (10+39) | 4,382 | 9,126 | 1,615 | 3,988 | 2,767 | 5,138 | 30 | 39 |
| $T_8$ (10+52) | 5,650 | 10,325 | 2,393 | 4,426 | 3,257 | 5,900 | 32 | 38 |
| $T_9$ (20+0) | 4,098 | 8,716 | 1,282 | 3,693 | 2,817 | 5,023 | 32 | 37 |
| $T_{10}$ (20+26) | 5,013 | 9,340 | 1,973 | 4,061 | 3,040 | 5,279 | 34 | 39 |
| $T_{11}$ (20+39) | 6,478 | 10,739 | 2,682 | 4,476 | 3,797 | 6,263 | 31 | 37 |
| $T_{12}$ (20+52) | 5,308 | 8,821 | 2,232 | 3,997 | 3,077 | 4,824 | 32 | 39 |
| $T_{13}$ (30+0) | 5,842 | 8,574 | 2,055 | 3,804 | 3,787 | 4,770 | 29 | 38 |
| $T_{14}$ (30+26) | 7,662 | 10,497 | 2,815 | 4,797 | 4,847 | 5,700 | 32 | 39 |
| $T_{15}$ (30+39) | 6,490 | 10,078 | 2,688 | 4,651 | 3,802 | 5,427 | 30 | 37 |
| $T_{16}$ (30+52) | 5,423 | 9,878 | 1,992 | 4,339 | 3,432 | 5,539 | 31 | 38 |
| LSD | 1,224 | 600 | 857 | 1,123 | 1,335 | 653 | 4.2 | 2.3 |
| SE | 243 | 192 | 110 | 109 | 144 | 124 | 1.5 | 1.2 |
| *P* value | ** | ** | ** | ** | ** | ns | ns | ns |

*Note:* ** and 'ns' indicate significance at $P \leq 0.01\%$ and non significant difference, respectively. LSD: Least significant difference; SE: Standard error.

**Table 5.** Wheat yield as affected by different P and K application rates at Cheffe Donsa in the 2012 (S1) and 2013 (S2) cropping season.

| Treatment | Biological yield | | Grain yield | | Straw yield | | Thousand grain weight | |
|---|---|---|---|---|---|---|---|---|
| P + K | S1 | S2 | S1 | S2 | S1 | S2 | S1 | S2 |
| | -----------------------------------------*kg ha$^{-1}$*----------------------------------------- | | | | | | ----------*g*--------- | |
| $T_1$ (0+0) control | 11,450 | 7,910 | 4,370 | 5,520 | 7,080 | 2,390 | 39 | 41 |
| $T_2$ (0+26) | 14,695 | 10,120 | 5,545 | 6,197 | 9,150 | 3,924 | 39 | 46 |
| $T_3$ (0+39) | 13,383 | 9,283 | 5,183 | 6,328 | 8,200 | 2,955 | 38 | 42 |
| $T_4$ (0+52) | 14,998 | 10,362 | 5,725 | 6,395 | 9,273 | 3,967 | 38 | 44 |
| $T_5$ (10+0) | 13,283 | 8,834 | 4,385 | 5,962 | 8,898 | 2,873 | 38 | 41 |
| $T_6$ (10+26) | 16,955 | 11,668 | 6,380 | 7,568 | 10,403 | 4,100 | 39 | 44 |
| $T_7$ (10+39) | 14,525 | 9,951 | 5,378 | 6,164 | 9,147 | 3,788 | 38 | 43 |
| $T_8$ (10+52) | 15,173 | 10,518 | 5,862 | 7,069 | 9,312 | 3,449 | 39 | 44a |
| $T_9$ (20+0) | 13,842 | 9,473 | 5,105 | 7,024 | 8,737 | 2,450 | 39 | 43 |
| $T_{10}$ (20+26) | 16,152 | 11,118 | 6,085 | 7,223 | 10,067 | 3,896 | 37 | 45 |
| $T_{11}$ (20+39) | 15,260 | 10,369 | 5,478 | 6,608 | 9,782 | 3,761 | 38 | 44 |
| $T_{12}$ (20+52) | 15,995 | 10,938 | 5,880 | 6,701 | 10,115 | 4,236 | 40 | 44 |
| $T_{13}$ (30+0) | 14,760 | 10,118 | 5,475 | 6,539 | 9,285 | 3,579 | 39 | 48 |
| $T_{14}$ (30+26) | 15,965 | 10,981 | 5,997 | 7,217 | 9,968 | 3,765 | 38 | 44 |
| $T_{15}$ (30+39) | 17,190 | 11,706 | 6,222 | 7,235 | 10,968 | 4,471 | 39 | 44 |
| $T_{16}$ (30+52) | 16,553 | 11,352 | 6,150 | 6,935 | 10,403 | 4,417 | 39 | 46 |
| LSD | 1,907 | 836 | 1,315 | 1,403 | 1,317 | 886 | 2.4 | 4.4 |
| SE | 378 | 261 | 149 | 138 | 238 | 161 | 0.18 | 0.47 |
| *P* value | ** | ** | ** | ** | ** | ns | ns | ns |

*Note:* ** and 'ns' indicate significance at $P \leq 0.01\%$ and non significant difference, respectively. LSD: Least significant difference; SE: Standard error.

6,490 kg ha$^{-1}$ was recorded from 39-30 P-K kg K ha$^{-1}$ application. Results in 2013, however, indicated that a combined application of 26 kg K ha$^{-1}$ with the highest P rate of 30 kg P ha$^{-1}$, exhibited the second highest biological yield of 10,497 kg ha$^{-1}$ (Table 4).

In Cheffe Donsa the $T_{15}$ (30-39 P-K kg ha$^{-1}$) treatment resulted in the highest biological yields of 17,190 kg ha$^{-1}$ and 11,706 kg ha$^{-1}$ in the 2012 and 2013 growing seasons, respectively (Table 5). In a similar manner, these were statistically higher than the control and treatments of P and K alone. In both cropping seasons, the second highest biological yields of 16,955 and 11,668 kg ha$^{-1}$ were recorded from 26 kg K ha$^{-1}$ when applied with the lowest P rate, 10 kg P ha$^{-1}$. The biological yields were gradually decreased by increasing the rate of P from 10 to 20 and 20 to 30 kg ha$^{-1}$ when applied in combination with the low rate of 26 kg K ha$^{-1}$ over the two cropping seasons. However, a gradual biological yield increment was recorded by increasing the rate of P from 10 to 20 and 20 to 30 kg ha$^{-1}$ when applied in combination with the highest K rate of 52 kg ha$^{-1}$.

Generally, the highest biological yields obtained from P by K combinations were 48 and 50% higher than the control at Akaki in the first and second cropping seasons, respectively. Similarly, the highest values of biological yield recorded from P by K combination at Cheffe Donsa were 20 and 48% higher over the control in the first and second cropping seasons, respectively. Greater yields were recorded in the second cropping season at both sites. This is attributed to the relatively higher amount of N fertilizer (92 kg N ha$^{-1}$) applied in the second cropping season as well as higher rainfall recorded in the second cropping season. Other authors (Haile *et al.*, 2012; Cui *et al.*, 2005; Ricardo *et al.*, 2010) also reported an increase in grain yield with an increase in N rate. The highest biological yield was recorded at Cheffe Donsa site which could be due to the medium available P content prior to planting. Generally, the highest biological yield was obtained from plots treated with P and K at both sites over the two cropping seasons. This is expected because soils of the experimental sites were deficient in both P and K. The potential benefits of providing sufficient P and K for wheat, as well as other plants, often include promoting early plant maturity, resistance to diseases and other pests, reduced lodging, tillering, vigorous growth, and improved yield (Liakas *et al.*, 2001; Ma *et al.*, 2006; Slaton *et al.*, 2007).

### Grain yield

Application of P and K significantly ($P \leq 0.01$) increased grain yield of wheat at both sites over the two cropping seasons (Tables 4 and 5). At Akaki, there were no significant grain yield differences in applying $T_8$, $T_{11}$, $T_{12}$ $T_{14}$ and $T_{15}$, but $T_{14}$ (30-26 P-K kg ha$^{-1}$) resulted in the highest grain yield of 2,815 kg ha$^{-1}$, significantly higher than P alone and the control in the first growing season. In the same growing season, the addition of P with K at the rates of 39 kg K ha$^{-1}$ with 20 and 30 kg P ha$^{-1}$, didn't significantly increase grain yield over treatments with K alone with the possible exception of K applied at the rate of 39 kg K ha$^{-1}$. In the 2013 cropping season, grain yield was significantly increased over the control (without P and K) in all treatments but the magnitudes of responses were highest in three P and K rate combinations ($T_{11}$, $T_{14}$ and $T_{15}$). Among these treatments the highest grain yield (4,797 kg ha$^{-1}$) was recorded from $T_{11}$ (30-26 P-K kg ha$^{-1}$).

The trend of response was different at Cheffe Donsa where the highest grain yields of 6,380 and 7,568 kg ha$^{-1}$ were obtained from a P and K rate combination (20 kg P ha$^{-1}$, 26 kg K ha$^{-1}$) in 2012 and 2013 cropping seasons, respectively (Table 4). When the highest rate of both P and K (30 kg P ha$^{-1}$ and 52 kg K ha$^{-1}$) were applied together, the resultant yield was apparently lower than the yields from P and K combinations ($T_6$ and $T_{15}$) though not significantly lower. A tendency to achieve significantly higher grain yields over the control was observed by two K only treatments (26 kg ha$^{-1}$ and 52 kg ha$^{-1}$) in the first growing season. In contrast, the apparent yield increments by all treatments of K only over the control (without P and K) were not significant in the 2013 growing season.

The combined analysis of variance in each location on grain yield is presented in Table 6. The significant difference in grain yield between the locations was caused by the difference between the sites. Even though the interaction of P and K rates did not show a significant difference in grain yield at Cheffe Donsa (both seasons) and the second season in Akaki, their combination gave the highest grain yield and showed a significant ($P \leq 0.01$) difference in grain yield as compared to P alone, K alone and the control (without P and K). The highest grain yields (2,815, 4,797 kg ha$^{-1}$ and 6,380, 7,568 kg ha$^{-1}$) were obtained on the interaction of 30-26 and 10-26 P-K kg ha$^{-1}$ in the first and second cropping season at Akaki and Cheffe Donsa, respectively. Soils of the experimental sites were deficient in both P and K, so P and K fertilization induced grain yields of 45%, 59% and 46%, 37% over the control plots at Akaki and Cheffe Donsa in the first and second cropping seasons, respectively. The potential benefits of providing sufficient P and K for wheat, as well as other plants, often include promoting early plant maturity, resistance to diseases and other pests, reduced lodging, tillering, vigorous growth, and improved yield (Liakas *et al.*, 2001; Ma *et al.*, 2006; Slaton *et al.*, 2007). Snyder and Mascagni (1998), Sharshar *et al.* (2000); Liakas *et al.* (2001); Akhtar *et al.* (2002); Ghulam *et al.* (2010) reported similar benefits of P and K fertilization on wheat grain yield.

### Thousand grain weight

The fertilization treatments had no effect on ($P \leq 0.05$) the thousand grain weights in either of the seasons or sites. Heavier seeds were observed in the second season compared to the first season at both sites. The interaction of P and K ($T_{12}$, $T_{13}$, $T_7$ and $T_{10}$) showed a trend towards heavier seeds compared to P alone, K alone and the control (without P and K). Zero fertilization and applying $T_5$ (P-K 10-0 kg ha$^{-1}$) had lighter seed weight (Table 4 and Table 5) compared to P and K interaction at both sites over the two cropping seasons. Although the mean thousand grain weight appeared to be relatively similar under the various treatments at Akaki in the 2012 growing season, few differences (non-significant) were observed in the 2013 growing season (Table 4). In 2013, a heavier thousand grain weight of 39 g was resulted from two P and K combinations (10, 39 and 20, 26) though were statistically similar with the control (without P and K) and most other treatments.

At Cheffe Donsa, the trend was different, thousand grain weight appeared to be similar in 2012 but few differences were

**Table 6.** Analysis of variance on grain yield of wheat for Akaki and Cheffe Donsa in the 2012 (S1) and 2013 (S2) cropping season.

| Source of variance | Akaki | | Cheffe Donsa | |
|---|---|---|---|---|
| | S1 | S2 | S1 | S2 |
| | -----------------------------*kg ha$^{-1}$*----------------------------- | | | |
| P | ns | ** | * | * |
| K | ns | ns | ns | ns |
| P x K | ** | ns | ns | ns |
| Mean yield of 0-0 P-K | 1,947 | 3,011 | 4,370 | 5,520 |
| Highest mean yield | 2,815 | 4,797 | 6,380 | 7,568 |
| P-K combination for highest yield | 30-26 | 30-26 | 10-26 | 10-26 |

*Note:* *, ** and 'ns' indicate significance at P <0.05, 0.01 probability levels.

observed in the 2013 cropping season (Table 5). Increasing the rate of P from 10 to 20 and 20 to 30 kg ha$^{-1}$ when applied with the various rates of K over the two cropping seasons didn't affect the thousand grain weights significantly. These results agree with the finding of Cruz *et al.* (2013) who reported that thousand grain weight was not significantly affected by P and K application.

### Nutrient uptake

The data shown in Tables 7 and 8 revealed that there were significant ($P \leq 0.001$) differences among treatments in total N, P and K uptake by wheat (kg ha$^{-1}$) during the first and second cropping seasons. At Akaki in 2012, the total N uptake was significantly increased over the control and P and K only treatments on plots treated with combined application of P and K, with the possible exception of various K rates combined with a low rate of P. The highest total P uptake of 12.3 kg ha$^{-1}$ was found on plots treated with 26 kg ha$^{-1}$ of K and 10 kg ha$^{-1}$ of P. The lowest total P uptake was obtained from the control plot (without P and K). The total uptake of K under the various P and K combinations was either significantly higher or comparable to P and K only treatments. In 2013, the pattern of total nutrient uptake and significance was similar. In addition the magnitude of total nutrient uptake was more noticeable in this growing season. This could be due to the relatively high amount of N fertilizer applied.

Among the various treatments, $T_{10}$ (20-26 P-K kg ha$^{-1}$) resulted in the highest total N uptake of 92 kg ha$^{-1}$ at Cheffe Donsa in the 2012 cropping season by some margin. Likewise, the highest total P uptake of 21.6 kg ha$^{-1}$ was exhibited by $T_{11}$ (20-39 P-K kg ha$^{-1}$). The total uptake of K was generally increased on plots treated with P and K combinations compared to the control and K only treated plots, but the differences were not significant in some of the cases. In 2013, increased uptake of N and K was noticed but total P uptake did not show a

**Table 7.** Total N, P and K uptake (kg ha$^{-1}$) of wheat as affected by application of P and K at Akaki during 2012 (S1) and 2013 (S2).

| Treatment | Akaki | | | | | |
|---|---|---|---|---|---|---|
| | S1 | | | S2 | | |
| P + K | Total N | Total P | Total K | Total N | Total P | Total K |
| | | | *kg ha$^{-1}$* | | | |
| $T_1$ (0+0) control | 20 | 3 | 13 | 46 | 10 | 30 |
| $T_2$ (0+26) | 24 | 5 | 23 | 55 | 12 | 46 |
| $T_3$ (0+39) | 25 | 5 | 18 | 71 | 14 | 51 |
| $T_4$ (0+52) | 29 | 8 | 28 | 90 | 15 | 58 |
| $T_5$ (10+0) | 22 | 7 | 16 | 74 | 13 | 62 |
| $T_6$ (10+26) | 37 | 12 | 28 | 93 | 20 | 71 |
| $T_7$ (10+39) | 29 | 12 | 29 | 104 | 17 | 66 |
| $T_8$ (10+52) | 39 | 14 | 29 | 102 | 23 | 81 |
| $T_9$ (20+0) | 19 | 7 | 26 | 76 | 14 | 54 |
| $T_{10}$ (20+26) | 46 | 11 | 29 | 88 | 20 | 70 |
| $T_{11}$ (20+39) | 49 | 11 | 32 | 95 | 20 | 79 |
| $T_{12}$ (20+52) | 41 | 11 | 32 | 93 | 21 | 64 |
| $T_{13}$ (30+0) | 27 | 6 | 27 | 75 | 15 | 61 |
| $T_{14}$ (30+26) | 68 | 12 | 34 | 107 | 15 | 79 |
| $T_{15}$ (30+39) | 62 | 9 | 40 | 106 | 20 | 85 |
| $T_{16}$ (30+52) | 40 | 10 | 44 | 93 | 17 | 86 |
| LSD | 10 | 4 | 12 | 15 | 5 | 13 |
| SE | 4 | 0.81 | 2 | 4.5 | 0.93 | 3.8 |
| *P* value | ** | ** | ** | ** | ** | ** |

*Note*: ** indicate significant difference at $P \leq 0.01$. LSD: Least significant difference; SE: Standard error.

**Table 8.** Total N, P and K uptake (kg ha$^{-1}$) of wheat as affected by application of P and K at Cheffe Donsa during the 2012 (S1) and 2013 (S2) cropping season.

| Treatment | Cheffe Donsa | | | | | |
|---|---|---|---|---|---|---|
| | S1 | | | S2 | | |
| P + K | Total N | Total P | Total K | Total N | Total P | Total K |
| | | | *kg ha$^{-1}$* | | | |
| $T_1$ (0+0) control | 48 | 10 | 14 | 69 | 12 | 31 |
| $T_2$ (0+26) | 48 | 10 | 20 | 93 | 15 | 50 |
| $T_3$ (0+39) | 53 | 10 | 27 | 84 | 15 | 61 |
| $T_4$ (0+52) | 74 | 12 | 22 | 90 | 9 | 61 |
| $T_5$ (10+0) | 62 | 14 | 9 | 78 | 16 | 44 |
| $T_6$ (10+26) | 85 | 17 | 61 | 117 | 20 | 8 |
| $T_7$ (10+39) | 80 | 18 | 46 | 95 | 16 | 69 |
| $T_8$ (10+52) | 84 | 15 | 55 | 106 | 18 | 84 |
| $T_9$ (20+0) | 72 | 13 | 21 | 85 | 14 | 58 |
| $T_{10}$ (20+26) | 92 | 16 | 70 | 116 | 17 | 83 |
| $T_{11}$ (20+39) | 76 | 22 | 34 | 101 | 17 | 71 |
| $T_{12}$ (20+52) | 81 | 17 | 54 | 104 | 23 | 64 |
| $T_{13}$ (30+0) | 55 | 10 | 19 | 95 | 9 | 63 |
| $T_{14}$ (30+26) | 92 | 19 | 37 | 112 | 3 | 87 |
| $T_{15}$ (30+39) | 83 | 21 | 62 | 109 | 19 | 73 |
| $T_{16}$ (30+52) | 79 | 21 | 70 | 115 | 20 | 69 |
| LSD | 15 | 4 | 24 | 18 | 6 | 17 |
| SE | 3.7 | 1.1 | 5.2 | 3.6 | 1.2 | 5.1 |
| *P* value | ** | ** | ** | ** | ** | ** |

*Note*: ** indicate significant difference at $P \leq 0.01$. LSD: Least significant difference; SE: Standard error.

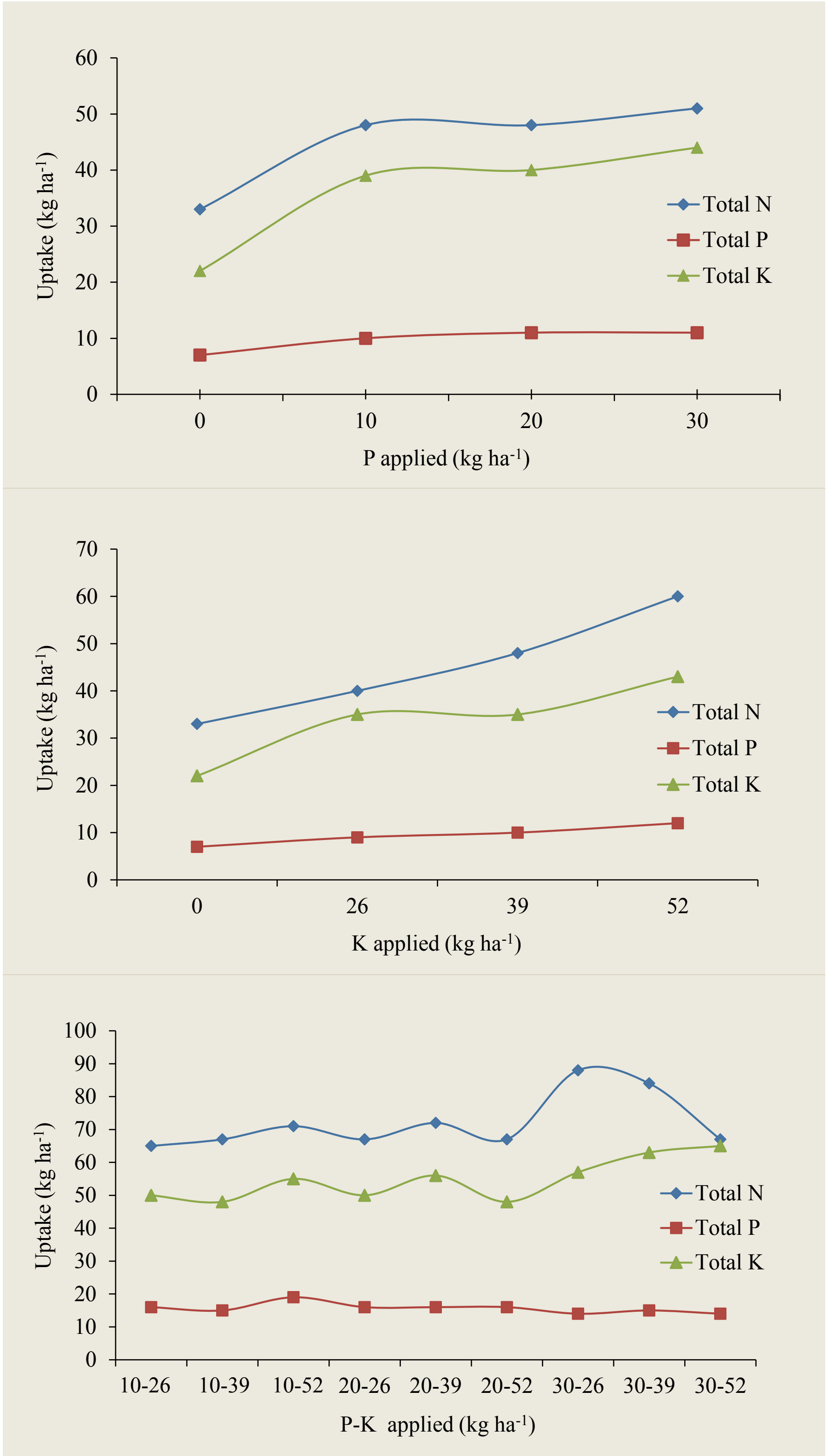


**Fig. 2.** Total N, P and K uptake as influenced by P alone, K alone and P and K fertilization at Akaki, respectively (means of 2012 and 2013 cropping seasons).

marked increase (Figs. 2 and 3). As can be seen from Figs. 2 and 3, P uptake was lower than N and K uptake under all the treatments. This is attributed to the lower P efficiency than N and K. Only about 15-20% of the applied P is used by the first crop. Most of the P applied to soils to meet P demand of plants is converted into unavailable forms of P (fixing by soil) that cannot be easily taken up by plant roots (Malavolta, 1979; Munson, 1982; Baligar *et al.*, 2001; Fageria *et al.*, 2010).

Generally, total N uptake was improved with P and K application and their combined use surpassed their application alone. This showed that the availability of extra K in these soils improved the extraction of N by the wheat crop. Sharma and Ramna (1993) indicated that the application of K released the fixed $NH_4^+$ ion from the soil and helped the crop improve its uptake of N. Total P uptake was highest with P+K, followed by P alone, and both showed significantly higher P uptake compared with K alone and the control. Total K uptake was highest with P+K, followed by K alone, and both showed significantly higher K uptake as compared with P only and the control (without P and K) (Figs. 2 and 3). These results agree with the findings of Slaton *et al.* (2007) and Sharshar *et al.* (2000) who reported that N, P and K uptake of wheat were significantly improved by integrated application of P and K.

Total nutrient uptake and yields varied significantly between the experimental years. In fact, higher yields and total uptake were recorded in the 2013 cropping season at both study sites. This may be attributed to the relatively high amount of N fertilizer (92 kg N ha$^{-1}$) applied in this growing season as well as high levels of rainfall compared to the 2012 growing season. Results obtained during long-term experiments revealed a direct relationship between yield and the amount of rainfall during the vegetative period of wheat (López-Bellido *et al.*, 1996).

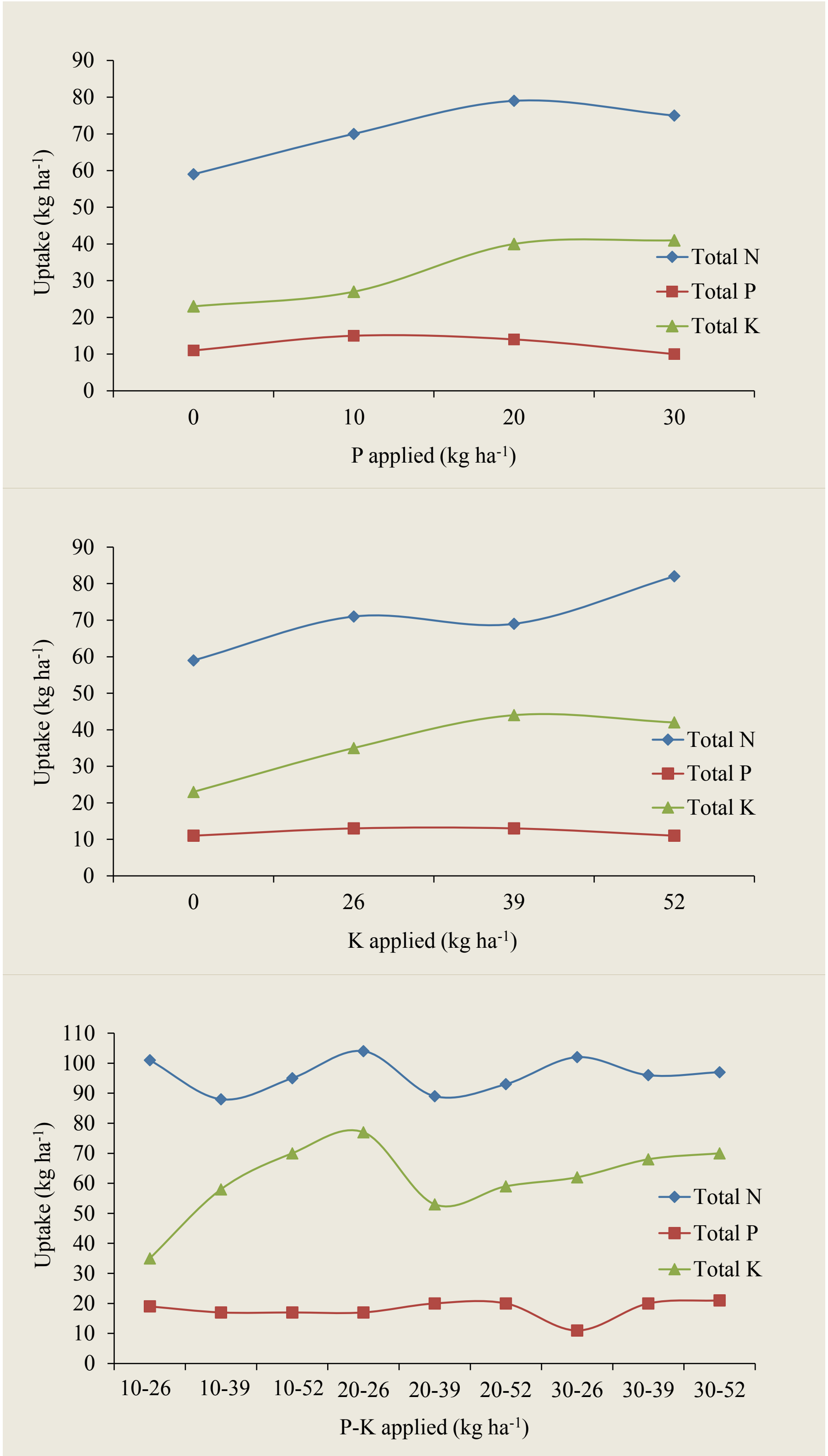


**Fig. 3.** Total N, P and K uptake as influenced by P alone, K alone and P and K fertilization at Cheffe Donsa, respectively (means of 2012 and 2013 cropping seasons).

In Ethiopia, farmers do not apply K fertilizers because researchers and development agents believe that the soil can supply the required K. This practice might hold true with low yield levels of traditional cultivars. However, the introduction of modern high yielding varieties has increased both cropping intensity and yields, which results in larger removal of K and other nutrients from soil. Data presented in this paper do not fully support the perception that the soil of the central highlands in Ethiopia can supply adequate K for achieving high yields of modern varieties. The results of this investigation indicated that integrated application of P and K fertilizers enhanced yields and nutrient uptake of wheat at both sites over the two cropping seasons. These results are supported by the findings of Abiye *et al.* (2004) who stated that there was appreciable yield response upon K fertilization at Cheffe Donsa. They further verified that K application enhanced N uptake of wheat. Overall, the benefits of K fertilization should be evaluated after long-term experimentation on Vertisols of Ethiopian highlands.

## Conclusion

Wheat yield showed significant response to P and K application. Yield increase was observed at both locations over the two cropping seasons with the combined use of P with K. Thus, it can be concluded that the combined use of P with K could be beneficial to enhance productivity and nutrient uptake of wheat in central highland Vertisols of Ethiopia.

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Prof. Tekaling Mamo (center) with Ms. Hillette Hailu (right) at field research plot with different levels of K and P in Akaki woreda, Oromia Region, Ethiopia. Photo by E. Sokolowski.

Ms. Hillette Hailu (right) at field research plot with different levels of K and P in Akaki woreda, Oromia Region, Ethiopia. Photo by E. Sokolowski.

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**The paper "Response of Wheat (*Triticum aestivum* L.) to Phosphorus and Potassium Fertilization on Vertisols in Ethiopia's Central Highlands" also appears on the IPI website at:**

**Regional activities/sub-Saharan Africa/Ethiopia**

# Research Findings


Long-term Rice-Rice field demonstration of target-yield approach. Photo by R. Santhi.

## Soil Nutrients and Crop Response-Curve Types in Farmers' Fields: Key to Balanced Fertilizer Use and Sustainable Soil Fertility Management

Velayutham, M.[1]

### Abstract

Significant efforts have been made during the last 50 years to make traditional Indian agriculture more productive but sustainable, using scientific approaches. In this mini-review, aspects of soil fertility are examined, with an emphasis on the relationships between changes in soil nutrient status and various types of crop response to those changes. In addition, the target-yield approach is re-examined with the aim of maintaining and enhancing long-term soil fertility. An important emerging conclusion is that in order to preserve and improve farmers' benefit from fertilizer inputs, and ensure soil health and fertility, a consistent multi-directional flow of information between farmers, extension officers, soil laboratories, and scientists is essential.

*Keywords:* Integrated plant nutrition; potassium; soil test.

*Abbreviations:* STCR - soil test crop response; IPNS - integrated plant nutrition system.

[1]Former Project Coordinator, All India Coordinated Soil Test-Crop Response Project (ICAR), and Former Executive Director, M.S. Swaminathan Reserch Foundation, Chennai, India. velayutham42@yahoo.co.in

## Introduction

Significant efforts have been made during the last 50 years to make traditional Indian agriculture more productive but sustainable, using scientific approaches. In this mini-review, aspects of soil fertility are examined, with an emphasis on the relationships between changes in soil nutrient status and various types of crop response to those changes. In addition, the target-yield approach is re-examined with the aim of maintaining and enhancing soil fertility. An important emerging conclusion is that in order to preserve and improve farmers' benefit from fertilizer inputs, a consistent multi-directional flow of information between farmers, extension officers, soil laboratories, and scientists is essential.

## Soil fertility

Soil nutrients naturally originate from three sources: local bed-rock weathering, sediments imported by water or wind, and biogenic minerals. The different forms of soil nutrients retain a dynamic equilibrium with their soluble forms (ions) in the soil solution; those that are available and taken up by the root system of the plant. This dynamic equilibrium is constantly changing due to interactions of soil composition and texture with temperature, soil water status, and plant demands for nutrients. Bray (1945) and Black (1973) elaborated this dynamic equilibrium through a nutrient mobility concept of soil-plant relationships.

Truog (1953) put the different forms of soil nutrients into three categories: a) readily available; b) moderately available; and c) slowly available nutrients. Readily available nutrients include soluble nutrients or ions in an exchangeable condition, as either anions or cations, associated with the extensive surface of soil colloids. Nutrients associated with recently formed, less stable chemical precipitates, or those that are fixed in between the lattices of clay minerals are moderately available. Nutrients associated with chemically stable precipitates or those forming the soil lattice or clay minerals are slowly available nutrients. The organic forms fall into the different categories depending on the ease with which they are mineralized in the soil. Usually, there are many members in each category.

Water is the major factor affecting soil nutrient dynamics. Chemical processes that slow down or pause when soil is dry are reactivated and intensified when water returns. Precipitation frequency, quantity, and intensity have significant chemical and physical influences on soil texture, structure, and nutrient readiness or loss. Thus, dry climates produce poor soils, while well distributed and adequate rainfall enhance soil fertility. However, extreme rain intensities usually cause soil erosion and nutrient loss.

In agricultural ecosystems, significant efforts are made to control the edaphic environment. Soil is tilled and prepared in order to maximize water absorbance. Where possible, water is supplied through irrigation. Nutrients are applied through chemical fertilizer or manure. However, soil nutrient dynamics in agricultural ecosystems are also under significant pressure; crops (monoculture in most cases), tend to accelerate soil nutrient depletion, compared to the natural ecosystem. Also, nutrient depletion might be selective, according to the preference of each crop species.

Ramamoorthy (1965) discussed the physical chemistry behind this complex interaction on the availability of plant nutrients in soil, in terms of the potential of nutrient ions such as phosphorus (P) and potassium (K) in the soil solution and in plant roots. He showed that there is need for P and K fertilizers as long as the equilibrium phosphate potential (EPP) and the equilibrium potassium activity ratio (EKAR) of the soil is less than that of the plant.

## Soil and fertilizer nutrients

The role of fertilizers as a prerequisite for food security, particularly in the production of food grains, cannot be overstated (Raju, 2008). The consumption of fertilizer nutrients increased significantly from 9.4 kg $ha^{-1}$ in 1967-68 to 117 kg $ha^{-1}$ in 2007-08, and further to 141 kg $ha^{-1}$ in 2013-14, respectively. In the 1980's, out of a net cropped area of 143 million ha, soils in 95% of the districts were reported to be either low or medium in available P (Tandon, 1987). Fertilizer trials conducted in farmers' fields under irrigated conditions indicated a significant countrywide (in 49 districts of India) response to K application (Sekhon, 1985). Yield response to K was particularly significant in soils from the alluvial plains of India that had long been regarded as K sufficient. In fact, concerning K, nutrient availability, rather than soil nutrient content, is the critical determinant of soil fertility. Pratt (1951) defined three categories of soil K fractions (water soluble, exchangeable, and non-exchangeable) that largely differ in their availability coefficient for plants, with the ratio of 1:0.28:0.003, respectively. The potential K availability is largely dependent on pedogenesis - location-specific soil parent material and forming processes (Reddy *et al.*, 1987).

## Crop nutrient requirements

Plant biomass production requires adequate supplies of mineral nutrients. With carbon (C) assimilated through photosynthesis, nitrogen (N) is needed for protein and nucleus assemblies that govern and enable all growth and developmental processes. Phosphorus is a crucial component of the energy coin, ATP, which enables energy flow and management in plant cells. Potassium is involved in the maintenance of plant water status, photosynthesis, and carbon allocation, storage, and remobilization (other macro- and microelements are important as well but are not discussed here). Plant nutrient demands over time are proportional to the biomass growth rate, nevertheless, nutrient deficiency might limit that rate. Furthermore, nutrient demands may vary among plant development phases. While N is required mostly during the earlier vegetative growth stage, K demands upsurge during the reproductive stage, when C storage or remobilization take place. Therefore, soil nutrient availability is often more about the timing than the demanded quantity.

## Crop response to soil nutrient status

The relationships between plant nutrition, chemical composition of the plant and shape of yield curves have been extensively studied (Steenbjerg, 1951; 1954; Steenbjerg and Jakobsen, 1959; 1963). These authors found that the shape and the position of yield curves were influenced by several factors: the affinity between the specific nutrient and the soil particles; level and method of other nutrients applied; water availability; time; and the crop species. They showed that the yield curve on P deficient soils is sigmoidal and that P adsorption to the soil increased when the P rations applied were too small. Consequently, the nutrient proportion absorbed by the crop was depressed. Thus, only large nutrient rations, above the nutrient fixing capacity of the soils, would result in an increase in the crop nutrient uptake and the subsequent rise in yield. This type of plant response, termed as the 'Steenbjerg effect', was reviewed by Velayutham (1980) with a special focus on the problem of P fixation by minerals and soil colloids.

Monitoring soil nutrient status is essential, preferably prior to planting of each crop. The practical value and benefit of soil test based fertilizer use for achieving targeted crop yields - getting higher profitability from fertilizer use, and long-term soil fertility maintenance for sustainable agriculture - was established and disseminated through the All India Coordinated Soil Test Crop Response Project (AICRP-STCR), (Ramamoorthy *et al.*, 1967; Ramamoorthy and Velayutham, 1971; 1974; Velayutham, 1979).

## Soil testing and crop response to fertilizers

Eight possible types of crop response to fertilizer application emerged from AICRP-STCR (Ramamoorthy, 1974). These types can be classified based on the significant sign of the regression coefficients for the linear, quadratic, and interaction terms of the fertilizer in the multiple regression equation connecting yield with soil test, fertilizer nutrient and their interaction (quadratic curve) for N, P and K nutrients (Fig. 1).

An example of the multiple regression equation as derived from a field experiment on finger millet (*Eleusine coracana*), in a red calcareous soil (Udic Haplustalf), Somayanur soil series, Coimbatore, Tamil Nadu, is given below:

$$Y = -3152.84+20.24\cdot N_S+19.22\cdot P_S+4.78\cdot K_S+47.94\cdot N_F-0.1057\cdot N_F^2+29.03\cdot P_F -0.20\cdot P_F^2+78.535\cdot K_F-0.5659\cdot K_F^2-0.1856\cdot N_S\cdot N_F-1.289\cdot P_S\cdot P_F-0.211\cdot K_S\cdot K_F$$

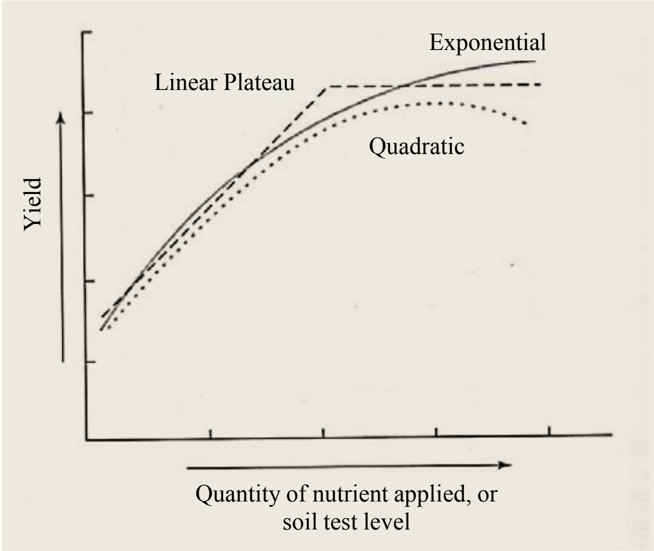


**Fig. 1.** Soil test - crop response calibrations curves - conventional linear, exponential, and quadratic models. Adopted from Havlin *et al.*, 2013.

Where Y = predicted yield; $N_S$, $P_S$ and $K_S$ are soil test values of available N, P and K respectively; $N_F$, $P_F$ and $K_F$ are fertilizer N, $P_2O_5$ and $K_2O$, respectively; $N_F$, $P_F$ and $K_F$ are linear terms, while $N_F^2$, $P_F^2$ and $K_F^2$ are quadratic terms. All units are in kg $ha^{-1}$.

The eight response types are as detailed below (Fig. 2 and Table 1):

**Type I (- - +):** soil test values are lower than the critical level required for a specific nutrient (N, P, or K) to be available for the crop. At nutrient application doses that fail to meet that level, crop depression is often noticed. However, when the critical is reached, optimal fertilizer doses above soil test values are expected to improve crop performance and increase profitability of fertilizer use. This situation is quite rare for N, but more frequent for P and K (Table 1).

**Type II (- - -):** for any level of soil test values within the range studied, the applied nutrient has a depressing effect on crop performance. In such cases, the nutrient is immediately fixed to the soil particles, leaving no residues for uptake by plants. This is a theoretical situation which has very rarely been observed in farmers' fields (Table 1).

**Type III (+ + +):** at any level of soil test values, crop response rises with the increasing fertilizer dose. In these soils, the equilibrium between the soluble and adsorbed phases of the

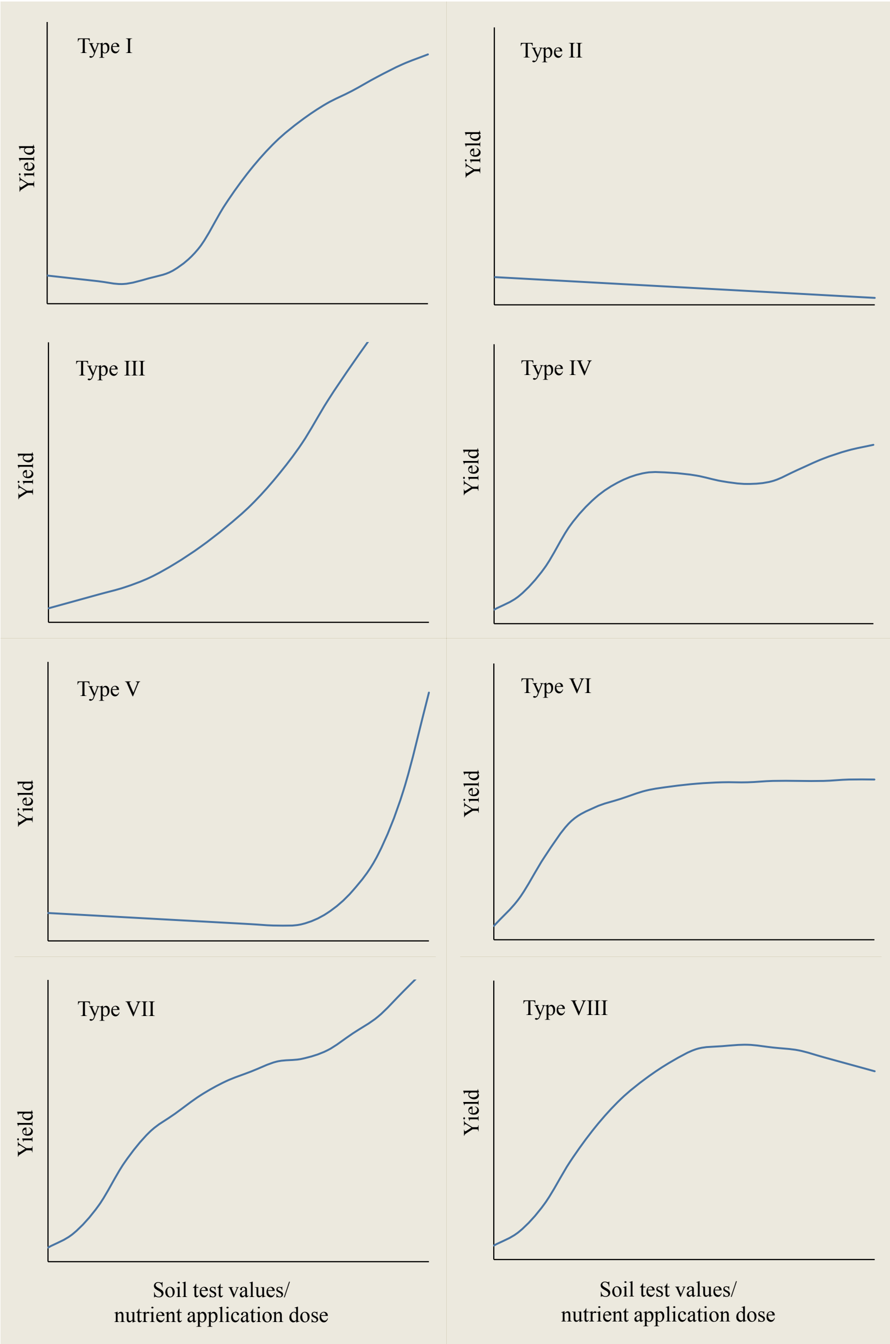


**Fig. 2.** Eight types of crop response to soil nutrient (N, P, or K) status, identified in 31 field experiments (Ramamoorthy *et al.,* 1974).

nutrient is extremely dynamic, allowing increasing nutrient availability with no losses to the environment. This situation was also very rare (Table 1).

**Type IV (+ + -):** up to a certain soil test value, crop response and profitability both increase with the rising fertilizer dose. Nevertheless, above this critical point crop performance tends to decline to a minimum point at a particular level of the fertilizer dose, above which the yield increases again. Such soils have limited nutrient adsorption capacity. Fertilizer applied beyond this limit might be concentrated in the soil solution and reach toxic levels. Alternatively, depending on precipitation regime and soil characteristics, the excess nutrient might be lost to the environment. Generally, aiming at high yields beyond that minimum point is subject to economic considerations that depend on cost-benefit calculations.

**Type V (- + +):** at lower range of soil test values, crop response to fertilizer application is slightly negative, until a minimum point at a critical soil test value beyond which crop response becomes exponential, as in Type III. As in Type II, the applied nutrient is immediately fixed to the soil particles up to a saturation point, beyond which additional fertilizer is available to the crop. As in Type IV, employing fertilizer doses above the critical point are subject to cost-benefit considerations. This situation is more frequent with K than with N or P (Table 1).

**Type VI (- + -):** crop response is shaped as a saturation curve, as the quantity of fertilizer required for a minimum response increases with the rising soil test values. Soil capacity to maintain an adequate level of exchangeable nutrient is limited and the fertilizer loss proportion increases. Thus, at the higher range of soil nutrient status, an increased fertilizer dose might appear impractical.

**Type VII (+ - +):** the crop is highly responsive to fertilizer at any soil nutrient status. However, at the higher range of soil nutrient status, crop response and profitability further increase with the rise of fertilizer dose.

**Type VIII (+--):** the positive crop response to fertilizer application decreases with the increasing soil test values up to a limit at which a negative response occurs to any further nutrient application. Being the most common type (Table 1), optimizing the multiple regression equation of this response provides the calibration of the fertilizer dose required to maximize fertilizer use efficiency and consequently, the economic yield (Ramamoorthy *et al.*, 1974).

## Upgrading fertilizer use strategy

Depending on the nature and duration of the crop, the initial level of soil nutrient, and the quantity of fertilizer applied, crop response can fall into any of the eight types. Fertilizer application by this approach, based on soil tests and the shape of yield (response) curves, however, does not take into account the removal of soil nutrients for the level of production obtained. Continuous fertilizer application by this approach might decrease soil fertility level over time.

The approach of fertilizer application based on soil tests for targeted yield of crops underlying the 'Law of Optimum' - as elaborated by Ramamoorthy *et al.* (1967), Velayutham (1979), Ramamoorthy and Velayutham (2011), Velayutham and Santhi (2013) and Velayutham *et al.* (2016) - ensures balanced and profitable fertilizer use for realizing targeted yield goal and maintenance of soil fertility in the long run. In Table 2, the effects of the long-term STCR Rice-Rice targeted yield and soil fertility management are demonstrated: the mean grain yield obtained per season (over 18 years, with two seasonal rice crops a year) matched the targeted yield. Furthermore, fertilizer use efficiency was increased significantly. When the two approaches, STCR and IPNS (Chen, 2006) were combined, yield and fertilizer use efficiency increased further. Additionally, the long-term soil fertility was maintained (Table 3); soil organic C increased, soil N content responded mainly to the organic fertilizer, P content was preserved and even rose, whereas K content decreased, pointing to the need to improve the application practices of this nutrient, the most soluble one. Alternating the two approaches based on 1) yield response curves and 2) targeted yield, to interpret soil tests as fertilizer determinant, will be a prudent long-term strategy for both getting profitability from fertilizer use and maintaining/upgrading soil fertility for sustainable agriculture.

## Climate and fluctuations of soil fertility

Van Der Paauw (1950, 1952, 1956, 1960 and 1962) has analyzed fluctuations of soil fertility, and crop and yield responses to

**Table 1.** The frequency (number of cases) of the eight crop response types to N, P, and K, as occurred in 31 field experiments (Ramamoorthy *et al.*, 1974).

| Crop response type | Sign* | Nutrient N | Nutrient $P_2O_5$ | Nutrient $K_2O$ |
|---|---|---|---|---|
| Type I | - - + | 3 | 3 | 7 |
| Type II | - - - | - | - | - |
| Type III | + + + | 2 | 1 | - |
| Type IV | + + - | 3 | 4 | 4 |
| Type V | - + + | 2 | 3 | 6 |
| Type VI | - + - | 2 | 4 | 1 |
| Type VII | + - + | 7 | 2 | - |
| Type VIII | + - - | 12 | 14 | 13 |
| Total | | 31 | 31 | 31 |

*Note:* *The three signs represent the signs of the partial regression coefficient of the linear, quadratic, and interaction terms, respectively, of the three fertilizer nutrients in the multiple regression equation describing crop response to soil nutrient status and added fertilizer.

**Table 2.** Yield targeting in rice and efficiency of fertilizer use (mean of 18 crops per season) on an Alfisol.

| Treatments | Kharif (1998-2015) Grain yield | Kharif (1998-2015) Fertilizer use efficiency | Rabi (1998-2015) Grain yield | Rabi (1998-2015) Fertilizer use efficiency |
|---|---|---|---|---|
| | ---*Mg ha$^{-1}$*--- | ----*kg kg$^{-1}$*---- | ---*Mg ha$^{-1}$*--- | ----*kg kg$^{-1}$*---- |
| General agronomic recommendation | 5.41 | 12.07 | 4.92 | 11.15 |
| STCR-NPK alone - 6/5 Mg ha$^{-1}$ | 5.73 | 13.85 | 5.06 | 15.31 |
| STCR-NPK alone - 7/6 Mg ha$^{-1}$ | 6.56 | 14.66 | 5.90 | 15.98 |
| STCR-IPNS - 7/6 Mg ha$^{-1}$ | 6.79 | 16.38 | 6.06 | 17.88 |
| Absolute control | 2.77 | - | 2.73 | - |

Fertilizer prescription equations (STCR-IPNS)

| Kharif (summer - rainy season) | Rabi (winter - dry season) |
|---|---|
| $N_F = 4.39\ T - 0.58\ N_S - 0.8\ N_O$ | $N_F = 4.63\ T - 0.56\ N_S - 0.90\ N_O$ |
| $P_F = 2.22\ T - 3.63\ P_S - 0.98\ P_O$ | $P_F = 1.98\ T - 3.18\ P_S - 0.99\ P_O$ |
| $K_F = 2.44\ T - 0.39\ K_S - 0.72\ K_O$ | $K_F = 2.57\ T - 0.42\ K_S - 0.67\ K_O$ |

Where: $N_F$, $P_F$, and $K_F$ represent fertilizer dose in kg ha$^{-1}$ of N, $P_2O_5$, and $K_2O$, respectively; T represents rice yield target in q ha$^{-1}$; $N_S$, $P_S$, and $K_S$ represent soil test NPK results (alkaline $KMnO_4$-N, Olsen-P and $NH_4OAc$-K in kg ha$^{-1}$, respectively); $N_O$, $P_O$, and $K_O$ are the NPK quantities (kg ha$^{-1}$) supplied through farmyard manure. Yield targets (T) - Kharif: 6 and 7 Mg ha$^{-1}$; Rabi: 5 and 6 Mg ha$^{-1}$. Adopted from Maragatham, 2016.

**Table 3.** Yield targeting and maintenance of soil fertility status after 36 rice crops on Alfisol.

| Treatments | Soil organic carbon | Available nutrients N | Available nutrients P | Available nutrients K |
|---|---|---|---|---|
| | -----*g kg$^{-1}$*----- | ----------*kg ha$^{-1}$* | ---------- | ---------- |
| Initial status (1998 Kharif) | 4.6 | 280 | 20.2 | 670 |
| Absolute control | 5.4 | 177 | 16.7 | 412 |
| General agronomic recommendation | 6.3 | 230 | 19.6 | 476 |
| STCR-NPK alone - 6 Mg ha$^{-1}$ | 7.5 | 237 | 21.7 | 493 |
| STCR-NPK alone - 7 Mg ha$^{-1}$ | 7.8 | 250 | 25.0 | 504 |
| STCR-IPNS - 7 Mg ha$^{-1}$ | 8.6 | 266 | 29.3 | 567 |

Adopted from Maragatham, 2016.

fertilization, as affected by alternating periods of low or high rainfall. He reported that in the Netherlands, soil P and K contents gradually rose during relatively dry periods and declined during wet ones. Cropping under the Asian monsoonal climate, characterized by two distinct seasons - Kharif (very wet summer) and Rabi (dry winter) - results in significant changes, particularly concerning nutrient availability. Crop P and K requirements must be adequately met for rain-fed crops, in both seasons. Fluctuations of the content of water soluble P corresponds with the alternating periods of rainfall (data not shown). Therefore, as shown in Table 2, fertilizer application practices should be adjusted to the cropping season in order to optimize nutrient use efficiency, maximize profitability, and maintain soil fertility.

## An information flow among stakeholders is essential

The ultimate goal of the STCR-IPNS approach is to enhance the agricultural production at farm, state, and national levels. The way to achieve this goal is by securing sustainable agriculture and soil quality through the maintenance of soil health and productivity. These, in turn, require one-to-one contact between the farmer, extension, and soil laboratory technicians and scientists, acting together to disseminate consistent soil test programs and best management practices, including realization of the 'target yield' of crops and profitability from fertilizer use.

To achieve this vision, a solid network of multi-direction information flow should be developed and include all stakeholders involved. Soil testing laboratories must be established throughout the country, acquiring and qualifying highly committed staff in order to ensure high quality soil analyses (Bhumbla, 2010). Each farmer will be connected to the local soil testing lab, which will test and certify the farm and provide fertilizer recommendations and consultancy. A linkage will be established between soil testing labs working under various agencies (state government, NGO's, research institutes, fertilizer industry, etc.) to periodically monitor soil fertility trends and to promote balanced fertilizer application on farms and at a regional level. This network will be governed academically and administratively by a national headquarters. Information will be evaluated and processed, and then used to support decisions at the regional and national level. The recently launched nationwide flagship program, 'Land Resource and Soil Health Card', linked to the 'Digital India' paradigm shift augers well for meeting the STCR-IPNS strategy at the national level.

## Epilogue

As observed by Sir Albert Howard (1947), "The real arsenal of democracy is a fertile soil, the fresh produce of which is the birthright of the nations". Mother Earth sustains the existence and prosperity of mankind. Inter-generational equity demands that we adopt good crop and land husbandry practices and hand over the fertility and quality of the land and soil undiminished to posterity.

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**The paper "Soil Nutrients and Crop Response-Curve Types in Farmers' Fields: Key to Balanced Fertilizer Use and Sustainable Soil Fertility Management" also appears on the IPI website at:**

**Regional activities/India**

# Events

### IPI events

### October 2017

**The 1st Polyhalite Symposium: Using a Natural Mineral as a Multi Nutrient Fertilizer and Soil Amendment, 31 October 2017, China**

Reports on the effect of Polyhalite application in Brazil, Europe and Israel; reports from China on tea, rapeseed, maize and various horticulture crops.

Update on the venue and more information coming soon on the IPI website/Events. For details contact Mr. Eldad Sokolowski, IPI Coordinator China.

### International Symposia and Conferences

### August 2017

**18th International Plant Nutrition Colloquium, 21-24 August 2017, Copenhagen, Denmark.**

The venue will be the Tivoli Hotel and Congress Center, situated right in the middle of Copenhagen. The main theme of the 18th International Plant Nutrition Colloquium is: "Plant Nutrition for Global Green Growth". For more information go to the IPNC 2017 website.

# Publications

## Publications by the PDA

POTASH News
June 2017

**AHDB Nutrient Management Guide (RB209)**

AHDB have just launched their new Nutrient Management Guide (RB209). It is a revision of the Defra Fertiliser Manual (RB209) and it can be viewed or downloaded to your computer from their website www.ahdb.org.uk/rb209. Also, there is an App for mobile devices. Hard copies can be requested by e mail to cereals.publications@ahdb.org.uk. It is supplied free of charge to farmers, students and advisers.

AHDB took over responsibility for RB209 (issued in 2010) from Defra and the revising process has been undertaken over the last 2 years. Fresh trials data and a wider range of crops and organic materials have been included in this update. It is planned that updating will happen more frequently in future and it will become more digital and interactive.

The new format comprises 7 separate sections:-

1. Principles of Nutrient Management
2. Organic Materials
3. Grass & Forage Crops
4. Arable Crops
5. Potatoes
6. Veg & Bulbs
7. Fruit Vines & Hops

It is expected that everyone will want to use Section 1 (Principles) and Section 2 (Organic Materials) along with those of the other sections that are relevant to their farm/advisory business.

**MAIN CHANGES HIGHLIGHTED**

NB. Nitrogen recommendations have changed for some arable crops and for grass but they are not covered in this article.

There are 4 main areas of change concerning P, K, S and Mg:-

1. Speed of building up low soil indices
2. Crop Offtake values
3. Nutrient content of Organic Materials
4. Sulphur recommendations

**Speed of building up low soil indices for P and K**

The Principles Section now recognises that the rates of building up low soil indices to reach target index (P2, K2-) may be too slow. Current build values take 10-15 years to build, and this is far too long for the field yields to be hindered by their low indices. It discusses this issue and quotes alternative build values to achieve target index in only 5-10 years, which is very helpful. However,

### AHDB Nutrient Management Guide (RB209)

POTASH News, June 2017.

AHDB have just launched their new Nutrient Management Guide (RB209). It is a revision of the Defra Fertiliser Manual (RB209) and it can be viewed or downloaded to your computer from their website www.ahdb.org.uk/rb209. Also, there is an App for mobile devices. Hardcopies can be requested by e mail to cereals.publications@ahdb.org.uk. It is supplied free of charge to farmers, students and advisers.

*Potash Development Association (PDA) is an independent organisation formed in 1984 to provide technical information and advice in the UK on soil fertility, plant nutrition and fertilizer use with particular emphasis on potash. See also www.pda.org.uk.*

# Scientific Abstracts

## K in the Literature

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### Potato Fertilization on Irrigated Soils

Rosen, C.J., and P.M. Bierman. 2017. University of Minnesota. Extension. Nutrient Management.

Optimum potato growth and profitable production depend on many management factors, one of which is ensuring a sufficient supply of nutrients. There are 14 soil-derived elements or nutrients considered to be essential for growth of plants. When the supply of nutrients from the soil is not adequate to meet the demands for growth, fertilizer application becomes necessary. Potatoes have a shallow root system and a relatively high demand for many nutrients. Therefore, a comprehensive nutrient management program is essential for maintaining a healthy potato crop, optimizing tuber yield and quality, and minimizing undesirable impacts on the environment.

Irrigated potatoes are usually grown on coarse-textured soils low in organic matter. Typically, these soils are sandy loams or loamy sands, low in native fertility, and quite acid. High nutrient demand coupled with low native fertility often results in high fertilizer requirements for irrigated potato production. Over the years, however, continued fertilizer applications can build up the soil test levels of certain nutrients. Environmental concerns, especially for nitrogen leaching, are also an important factor in fertilizer use on irrigated sandy soils. A sound nutrient management program for potatoes to ensure optimum crop nutrition without adverse effects on water quality should be based on soil test recommendations, plant tissue testing, the variety grown and the time of harvest, yield goal, and the previous crop in the rotation.

### Response of Seed Cotton Yield to Potassium Fertilization under Cotton-Wheat Cropping System

Rajesh Kumar, D.S. Jakhar, Dheeraj Panghaal and Devraj. 2017. Int. J. Curr. Microbiol. App. Sci.2017.6(3):1252–1258. DOI: https://doi.org/10.20546/ijcmas.2017.603.144.

**Abstract:** The present study was carried out at the research farm of Krishi Vigyan Kendra, Sirsa during kharif 2014. The climate of this tract was semi-arid, sub-tropical with hot and dry summer and cold winters. The maximum temperature during summer months of May and June reached up to 47.2 °C. The total rainfall obtained during the crop season was about 327.5 mm. The cropping

history of field from 2011 was cluster bean in kharif and in rabi crop wheat was grown. Seed cotton yield increased significantly with the application of K and mean highest yield (2751.98 kg/ha) was observed where K was applied @ 60 kg/ha along with two foliar spray of 1% of $KNO_3$. The seed cotton yield increased significantly in the high K fertility soil up to the treatment $T_4$ ($N_{175}P_{60} + K_{30}$). However, the mean seed cotton yield was higher in high K fertility soil as compared to medium K fertility soil. It indicates that in the high K fertility soils, application of potassium at the rate of 30 kg/ha is sufficient of optimizing the seed cotton yield. The number of bolls per plant and boll weight increased with application of K in all the treatments in both soils where as the GOT and harvest index remained unaffected.

### Physiological Responses and Gene Co-Expression Network of Mycorrhizal Roots under $K^+$ Deprivation

Garcia, K., D. Chasman, S. Roy, and J.M. Ané. 2017. Plant Physiology 173(3):1811-1823. DOI: https://doi.org/10.1104/pp.16.01959.

**Abstract:** Arbuscular mycorrhizal (AM) associations enhance the phosphorous and nitrogen nutrition of host plants, but little is known about their role in potassium ($K^+$) nutrition. Medicago truncatula plants were cocultured with the AM fungus Rhizophagus irregularis under high and low $K^+$ regimes for 6 weeks. We determined how $K^+$ deprivation affects plant development and mineral acquisition and how these negative effects are tempered by the AM colonization. The transcriptional response of AM roots under $K^+$ deficiency was analyzed by whole-genome RNA sequencing. $K^+$ deprivation decreased root biomass and external $K^+$ uptake and modulated oxidative stress gene expression in M. truncatula roots. AM colonization induced specific transcriptional responses to $K^+$ deprivation that seem to temper these negative effects. A gene network analysis revealed putative key regulators of these responses. This study confirmed that AM associations provide some tolerance to $K^+$ deprivation to host plants, revealed that AM symbiosis modulates the expression of specific root genes to cope with this nutrient stress, and identified putative regulators participating in these tolerance mechanisms.

### Potassium Deficiency Affects the Carbon-Nitrogen Balance in Cotton Leaves

Hu, W., T.D. Coomer, D.A. Loka, D.M. Oosterhuis, and Z. Zhou. 2017. Plant Physiology and Biochemistry 115:408-417. DOI: https://doi.org/10.1016/j.plaphy.2017.04.005.

**Abstract:** Potassium (K) plays important roles in the metabolism of carbon (C) and nitrogen (N), but studies of K deficiency affecting C-N balance are lacking. This study explored the influence of K deficiency on C-N interaction in cotton leaves by conducting a field experiment with cotton cultivar DP0912 under two K rates (K0: 0 kg $K_2O$ $ha^{-1}$ and K67: 67 kg $K_2O$ $ha^{-1}$) and a controlled environment experiment with K-deficient solution (K1: 0 mM $K^+$) and K-sufficient solution (K2: 6 mM $K^+$). The results showed that leaf K content, leaf number, leaf area, boll number, reproductive dry weight and total dry weight were significant lower under K deficiency (K0 or K1). Lower total chlorophyll content and Chl a/b ratio, and decreased *Pn* along with lower *Gs* and higher *Ci* were measured under K deficiency, suggesting that the decrease in *Pn* was resulted from non-stomatal limitation. Leaf glucose, fructose, sucrose and starch contents were higher under K deficiency, because lower sucrose export was detected in phloem. Although leaf nitrate and ammonium contents significantly decreased, free amino acid content was increased by 40-63% under K deficiency, since lower amino acid export was also measured in phloem. K deficiency also induced lower soluble protein content in leaves. Leaf ATP level was significantly increased under K deficiency, indicating ATP utilization was lower, so that less energy was supplied to C and N metabolism. The ratio of soluble sugar to free amino acid and the C/N ratio markedly increased under K deficiency, and one reason was that the phloem export reduced more prominent for sucrose (54.6-78.0%) than amino acid (36.7-85.4%) under K deficiency. In addition, lower phosphoenolpyruvate carboxylase activity limited malate and citrate biosynthesis under K deficiency, causing a decrease of C flux into the amino acids, which was not beneficial for maintaining C-N balance. Sucrose phosphate synthase and nitrate reductase activities were lower under K deficiency, which would limit sucrose biosynthesis and nitrate assimilation. This was another factor altering soluble sugar to free amino acid ratio and C/N ratio in the K-deficient leaves.

### Antioxidant and Antibacterial Activities, Mineral and Essential Oil Composition of Spearmint (*Mentha spicata* L.) Affected by the Potassium Levels

Chrysargyris, A., P. Xylia, G. Botsaris, and N. Tzortzakis. 2017. Industrial Crops and Products 103:202-212. DOI: https://doi.org/10.1016/j.indcrop.2017.04.010.

**Abstract:** Mint family is considered of great importance all over the world with increasing needs for cultivation under controlled environment, but only narrow information is available about their response in relation to potassium supplementation. The present study determines the effects of different potassium levels (K: 275-300-325-350-375 mg/L) on the morphological and biochemical characteristics of spearmint (*Mentha spicata* L.). The results indicated that the middle K levels of 325 mg/L increased biomass dry matter content without differences on fresh weight. Mineral content was affected, mainly for the micronutrients. High K application increased spearmint polyphenols content

and antioxidant activity (DPPH, FRAP), while K > 325 mg/L revealed oxidative stress (increased $H_2O_2$), followed by the activation of antioxidant enzymes (SOD, APX, CAT) providing protective action to the plant. The main essential oil components were carvone, limonene, 1,8-cineole, germacrene D, β-pinene and β-caryophyllene. Considering greater carvone content, the 325 mg/L K treatment could be appropriate for spearmint cultivation and production for essential oil uses, improving their antioxidant and antibacterial activity against foodborne pathogens.

### Potassium: The Overlooked Nutrient in Crop Production

Silva, G. 2017. Michigan State University Extension.

Although potassium (K) is listed among the top three macronutrients (N-P-K) needed for crop production, nitrogen (N) and phosphorus (P) receive most of our attention. This is partly because N and P have potential to cause long-term environmental implications. Also, N and P get incorporated into key complex molecules within the cell such as DNA, proteins, enzymes, etc. In contrast, K rarely poses a threat to the environment. It remains in the plant and animal tissues in its ionic form $K^+$. When crop and animal residues decompose on the soil surface, the soluble K will seep into the soil.

### Salinity Stress Induced Alterations in Antioxidant Metabolism and Nitrogen Assimilation in Wheat (*Triticum aestivum* L.) as Influenced by Potassium Supplementation

Mohammad Abass Ahanger, and R.M. Agarwal. 2017. Plant Physiology and Biochemistry 115:449-460. DOI: https://doi.org/10.1016/j.plaphy.2017.04.017.

**Abstract:** Experiments were conducted on two wheat (*Triticum aestivum* L.) cultivars exposed to NaCl stress with and without potassium (K) supplementation. Salt stress induced using NaCl caused oxidative stress resulting into enhancement in lipid peroxidation and altered growth as well as yield. Added potassium led to significant improvement in growth having positive effects on the attributes including nitrogen and antioxidant metabolism. NaCl-induced stress triggered the antioxidant defence system nevertheless, the activity of antioxidant enzymes and the content of non-enzymatic antioxidants increased in K fed plants. Enhancement in the accumulation of osmolytes comprising free proline, sugars and amino acids was observed at both the developmental stages with K supplementation associated with improvement of the relative water content and ultimately yield. Potassium significantly increased uptake and assimilation of nitrogen with concomitant reduction in the Na ions and consequently Na/K ratio. Optimal K can be used as a potential tool for alleviating NaCl stress in wheat to some extent.

### Phosphate and Potassium-Solubilizing Bacteria Effect on the Growth of Rice

Esmaeil Bakhshandeh, Hemmatollah Pirdashti, and Khadijeh Shahsavarpour Lendeh. 2017. Ecological Engineering 103(Part A):164–169. DOI: https://doi.org/10.1016/j.ecoleng.2017.03.008.

**Abstract:** The objective of this study was to investigate the ability of three phosphate-solubilizing bacteria (PSB), including *Pantoea ananatis* (KM977993), *Rahnella aquatilis* (KM977991) and Enterobacter sp. (KM977992), to release potassium (K) from mica and also to evaluate their effect in promoting the growth of rice (cv. 'Tarom Hashemi') plants at an early stage of development. These isolates significantly solubilized K from mica in both solid and liquid medium *in vitro*. After 25 days of growth in liquid AM medium, K-solubilization (KS) for *P. ananatis, Enterobacter* sp. and *R. aqautillis* was 38.9, 33.6 and 15.5 μg $ml^{-1}$, respectively. KS of the isolates increased as pH of the culture medium declined ($r$ = -0.83, $P$ < 0.0053), as a result of organic acid production. Single KSB inoculations increased plant height (PlHe), stem diameter (SD), root length (RL), leaf area (LA) and biomass dry weight (BDW) by 4.09-10.8%, 4.07-10.4%, 8.0-13.1%, 19.8-21.4% and 7.53-15.7%, respectively, in a pot experiment while PlHe, BDW, SPAD value, K uptake in the leaves, stem, and root of rice seedling also increased by 10.8-15.1%, 27.4-65.3%, 8.64-12.0%, 38.5-76.9%, 17.6-52.9% and 25.0-75.0%, respectively, in a field experiment, when compared to the control. The results of both experiments indicate that the values of all measured parameters were higher when rice seedlings were inoculated with *P. ananatis* than with *Enterobacter* sp. and *R.aquatilis*. Based on our results, these isolates can be used as both PSB and KSB to enhance rice growth and also can be worthy of commercial development.

### Prognosis of Physiological Disorders in Physic Nut to N, P, and K Deficiency During Initial Growth

Elcio Ferreira Santos, Fernando Giovannetti Macedo, Bruno José Zanchim, Giuseppina Pace Pereira Lima, and José Lavres. 2017. Plant Physiology and Biochemistry 115:249-258. DOI: https://doi.org/10.1016/j.plaphy.2017.04.001.

**Abstract:** The description of physiological disorders in physic nut plants deficient in nitrogen (N), phosphorus (P) and potassium (K) may help to predict nutritional imbalances before the appearance of visual symptoms and to guide strategies for early nutrient supply. The aim of this study was to evaluate the growth of physic nuts (*Jatropha curcas* L.) during initial development by analyzing the gas exchange parameters, nutrient uptake and use efficiency, as well as the nitrate reductase and acid phosphatase activities and polyamine content. Plants were grown in a complete nutrient solution and solutions from which N, P or K was omitted. The nitrate reductase activity, phosphatase acid activity, polyamine content and gas exchange parameters from leaves of

N, P and K-deficient plants indicates earlier imbalances before the appearance of visual symptoms. Nutrient deficiencies resulted in reduced plant growth, although P- and K-deficient plants retained normal net photosynthesis (*A*), stomatal conductance (*gs*) and instantaneous carboxylation efficiency (*k*) during the first evaluation periods, as modulated by the P and K use efficiencies. Increased phosphatase acid activity in P-deficient plants may also contribute to the P use efficiency and to *A* and *gs* during the first evaluations. Early physiological and biochemical evaluations of N-, P- and K-starved plants may rely on reliable, useful methods to predict early nutritional imbalances.

### Impact of Potassium and Nitrogen Fertilization on Bahiagrass Herbage Accumulation and Nutrient Concentration

Yarborough, J.K., J.M.B. Vendramini, M.L. Silveira, L.E. Sollenberger, R.G. Leon, J.M.D. Sanchez, F.C. Leite de Oliveira, F.A. Kuhawara, V. Gomes, U. Cecato, and C.V. Soares Filho. 2017. Agron. J. 109(3):1099-1105. DOI: 10.2134/agronj2016.10.0589.

**Abstract:** Bahiagrass (*Paspalum notatum* Flügge) is the most utilized forage for beef cattle (*Bos* spp.) in Florida, but there is concern that bahiagrass pastures are declining due to insufficient K fertilization. Two studies determined the effects of K and N fertilization on bahiagrass herbage mass (HM) and nutritive value in field plots (Exp. 1), and greenhouse (Exp. 2). At two locations from May to December 2014 and 2015, Exp. 1 evaluated the combinations of three N fertilization levels (0, 50 kg N $ha^{-1}$ in May, or 50 kg N $ha^{-1}$ in May and August) and two levels of K fertilization (0 or 42 kg K $ha^{-1}$). Potassium fertilization did not affect HM, crude protein (CP), or in vitro digestible organic matter (IVDOM); however, tissue K concentration increased from 10.6 to 11.2 g $kg^{-1}$ with increasing K fertilization. Plots fertilized with N had greater HM than the control, but there was no difference between plots fertilized in May only vs. those fertilized in May and August. Experiment 2 was conducted in a greenhouse in 2014 and 2015 with a factorial combination of three levels of N fertilization (0, 50, and 100 kg N $ha^{-1}$) and four levels of K fertilization (0, 16, 33, and 66 kg K $ha^{-1}$). There was a quadratic relationship between tissue K concentration and herbage accumulation (HA) and maximum HA occurred with tissue K concentration of 17 g $kg^{-1}$. Bahiagrass tissue K concentration and response to K fertilization are variable and can be related to fertilization levels.

### Corn Era Hybrid Dry Matter and Macronutrient Accumulation across Development Stages

Woli, K.P., J.E. Sawyer, M.J. Boyer, L.J. Abendroth, and R.W. Elmore. 2017. Agron. J. 109(3)751-761. DOI: 10.2134/agronj2016.08.0474.

**Abstract:** Evaluating corn (*Zea mays* L.) aboveground dry matter (DM) and macronutrient accumulation patterns across era hybrids is necessary to understand changes in plant nutrient requirements and effects on accumulation timing and fertilization management. Two popular hybrids for each of five era-decades from 1960 to 2000 were grown in 2007 and 2008. Whole plant samples were collected at 10 development stages, with dry matter (DM), N, P, and K determined. Era hybrids differed in DM and nutrient accumulation, with differences in nutrient content mainly related to DM production. The 1960 to 1990 era hybrids were more similar in DM and nutrient content across development stages compared to the 2000 era hybrids which had the greatest content. Dry matter and P accumulation was linear (V6-R5 stages), however, N and K accumulation slowed during the reproductive stages. While the fraction of maximum plant content at R1 averaged 48, 71, 58, and 83% across hybrids for DM, N, P, and K, respectively; the ranges were 43 to 52% for DM (1990 and 1960), 64 to 78% for N (1990 and 1960), 55 to 60% for P (2000 and 1960), and 69 to 93% for K (1990 and 1960). Although the absolute DM production and nutrient content was greater with the most recent hybrids, relative to the maximum DM, N, P, and K content and the accumulation rate, growing degree unit based, remained the same across era hybrids. This indicates that overall DM production and yield potential has been mainly responsible for changes in corn macronutrient requirements with development of new hybrids.

### Potassium Application Regulates Nitrogen Metabolism and Osmotic Adjustment in Cotton (*Gossypium hirsutum* L.) Functional Leaf under Drought Stress

Zahoor, R., W. Zhao, M. Abid, H. Dong, and Z. Zhou. 2017: J. Plant Physiol. 215:30-38. DOI: https://doi.org/10.1016/j.jplph.2017.05.001.

**Abstract:** To evaluate the role of potassium (K) in maintaining nitrogen metabolism and osmotic adjustment development of cotton functional leaves to sustain growth under soil drought and rewatering conditions, the plants of two cotton cultivars Siza 3 (low-K sensitive) and Simian 3 (low-K tolerant), were grown under three different K rates (K0, K1, and K2; 0, 150, and 300 kg $K_2O$ $ha^{-1}$, respectively) and exposed to drought stress with 40 ± 5% soil relative water content (SRWC). The drought stress was applied at flowering stage by withholding water for eight days followed by rewatering to a well-watered level (75 ± 5% SRWC). The results showed that drought-stressed plants of both cultivars showed a decrease in leaf relative water content (RWC) and osmotic potential in the functional leaves and developed osmotic adjustment with an increase in the contents of free amino acids, soluble sugars, inorganic K, and nitrate as compared to well-watered plants. In drought-stressed plants, nitrogen-metabolizing enzyme activities of nitrogen reductase (NR), glutamine synthetase (GS), and glutamate synthase (GOGAT)

were diminished significantly ($P \leq 0.05$) along with decreased chlorophyll content and soluble proteins. However, drought-stressed plants under K application not only exhibited higher osmotic adjustment with greater accumulation of osmolytes but also regulated nitrogen metabolism by maintaining higher enzyme activities, soluble proteins, and chlorophyll content in functional leaves as compared to the plants without K application. Siza 3 showed better stability in enzyme activities and resulted in 89% higher seed cotton yield under K2 as compared to K0 in drought-stressed plants, whereas this increase was 53% in the case of Simian 3. The results of the study suggested that K application enhances cotton plants' potential for sustaining high nitrogen-metabolizing enzyme activities and related components to supplement osmotic adjustment under soil drought conditions

### The Challenge of Imbalanced Nutrient Flows in Organic Farming Systems: A Study of Organic Greenhouses in Southern Germany

Zikeli, S., L. Deil, and K. Möller. 2017. Agriculture, Ecosystems and Environment 244:1-13. DOI: https://doi.org/10.1016/j.agee.2017.04.017.

**Abstract:** Organic greenhouse vegetable production is characterized by very high nutrient demands within short growing periods and high nutrient exports via products sold. Therefore, meeting crop nutrient demands and maintaining long-term sustainability in these systems is highly challenging. To gain insight in current practices this study assessed fertilization strategies and nutrient flows of ten organic horticultural farms (22 greenhouses and polytunnels) in Southwest Germany belonging to the two organic farming associations Bioland and Demeter (biodynamic) for a cropping period of three years. Soil samples were taken to analyze plant available phosphorus, potassium, soil organic carbon, pH and salinity. Crop rotations in the greenhouses were very diverse, though focused on tomatoes. Depending on association membership, fertilization was based either on the use of solid animal manures (26.1 Mg $ha^{-1}$ $a^{-1}$) and composts (7.9 Mg $ha^{-1}$ $a^{-1}$) for the biodynamic Demeter farms or on commercial complementary fertilizers on the Bioland farms (e.g. keratin products, food industry waste products). All farms showed strong imbalances in their nutrient flows with high average surpluses for all nutrients (197 kg $ha^{-1}$ $a^{-1}$ for nitrogen, 47.9 kg $ha^{-1}$ $a^{-1}$ for phosphorus, 119 kg $ha^{-1}$ $a^{-1}$ for sulfur) except potassium with an average deficit of 143 kg $ha^{-1}$ $a^{-1}$ and low nitrogen use efficiencies. In addition, a risk for increased soil alkalinity and salinity existed and concentrations of plant available phosphorus in the soil were very high (average 332 mg phosphorus $kg^{-1}$). The results show that today's fertilization strategies for organic greenhouses are not sustainable, which calls for a thorough revision of the core ideas on soil fertility in the organic horticultural sector.

### Tailoring NPK Fertilizer Application to Precipitation for Dryland Winter Wheat in the Loess Plateau

Cao, H., Z. Wang, G. He, J. Dai, M. Huang, S. Wang, L. Luo, V.O. Sadras, M. Hoogmoed, S.S. Malhi. 2017. Field Crops Research 209:88-95. DOI: https://doi.org/10.1016/j.fcr.2017.04.014.

**Abstract:** Over-fertilization is economically and environmentally undesirable, and under-fertilization contributes to yield gaps. In dryland cropping systems, where precipitation is a major source of variation in yield, matching fertilizer to precipitation is critical. The aim of this study was to outline and test a method to match nitrogen (N), phosphorus (P), and potassium (K) fertilizer rate to precipitation for dryland winter wheat in the Loess Plateau of China. Based on field experiments at 52 sites from 2009 to 2013, the grain yield of winter wheat was found to increase quadratically with the precipitation in two periods: summer fallow, and summer fallow until jointing stage. The shoot N, P, and K nutrient uptake were linearly correlated with grain yield. Basal fertilizer requirement was calculated from target grain yield estimated as a function of fallow precipitation. The need for topdressing was determined by re-estimating target grain yield as a function of precipitation during summer fallow until jointing stage. Validation of this method using an additional dataset from long term studies in the same area suggested that adjusting fertilizer rates to summer fallow and summer fallow until jointing precipitation could correct the over application for N and P fertilizer, and deficient application for K fertilizer in the Loess Plateau.

### Potassium and Zinc Increase Tolerance to Salt Stress in Wheat (*Triticum aestivum* L.)

Amin Ullah Jan, Fazal Hadi, Midrarullah, Muhammad Asif Nawaz, and Khaista Rahman. 2017. Plant Physiology and Biochemistry 116:139-149. DOI: https://doi.org/10.1016/j.plaphy.2017.05.008.

**Abstract:** Potassium and zinc are essential elements in plant growth and metabolism and plays a vital role in salt stress tolerance. To investigate the physiological mechanism of salt stress tolerance, a pot experiment was conducted. Potassium and zinc significantly minimize the oxidative stress and increase root, shoot and spike length in wheat varieties. Fresh and dry biomass were significantly increased by potassium followed by zinc as compared to control C. The photosynthetic pigment and osmolyte regulator (proline, total phenolic, and total carbohydrate) were significantly enhanced by potassium and zinc. Salt stress increases MDA content in wheat varieties while potassium and zinc counteract the adverse effect of salinity and significantly increased membrane stability index. Salt stress decreases the activities of antioxidant enzymes (superoxide dismutase, catalase and ascorbate peroxidase) while the exogenous application of

potassium and zinc significantly enhanced the activities of these enzymes. A significant positive correlation was found of spike length with proline ($R^2$ = 0.966 ***), phenolic ($R^2$ = 0.741*) and chlorophyll ($R^2$ = 0.853**). The MDA content showed significant negative correlation ($R^2$ = 0.983***) with MSI. It is concluded that potassium and zinc reduced toxic effect of salinity while its combine application showed synergetic effect and significantly enhanced salt tolerance.

### Potassium Fertilization Enhances Pepper Fruit Quality

Botella, M.Á., L. Arévalo, T.C. Mestre, F. Rubio, F. García-Sánchez, R.M. Rivero, and V. Martínez. 2016. J. Plant Nutr. 40(2):145-155. DOI: http://dx.doi.org/10.1080/01904167.2016.1201501.

**Abstract:** The effect of potassium ($K^+$) concentration on the nutritional quality and yield of pepper fruits was evaluated. Pepper plants were grown in a controlled-environment greenhouse under hydroponic conditions with different nutrient solutions obtained by modifying the Hoagland solution to achieve different $K^+$ concentrations. Potassium nutrition affected fruit yield parameters more than vegetative biomass in pepper plants. The maximum fruit yield was obtained with 7 mM $K^+$ in the nutrient solution. However, it is possible to improve the bioactive compounds of pepper fruits with a higher application of $K^+$ without reducing yield. The increase of $K^+$ in the nutrient solution improved pepper fruit quality by increasing fruit firmness, TSS content, soluble sugars and ascorbic acid concentration. Therefore, the fruit quality improvements obtained with adequate $K^+$ nutrition resulted in nutritionally enriched fruits, which, at little or no extra cost, benefits the consumer.

### Cation Selectivity in Cotton (*Gossypium hirsutum* L.) Grown on Calcareous Soil as Affected by Potassium Fertilization, Cultivar and Growth Stage

Tsialtas, I.T., S. Shabala, D. Baxevanos, and T. Matsi. 2017. Plant Soil 415(1-2):331-346. DOI: 10.1007/s11104-016-3164-y.

**Abstract:** Background and aims: Selective uptake of K over Na has been proposed as a mechanism employed by plants to tackle high soil salinity. However, the impact of other dominant soil cations such as Ca and Mg and essentiality of higher K/Ca and K/Mg selectivity for plant performance under adverse growing conditions have been studied much less. We addressed this topic by looking at cation selectivity in cotton grown on calcareous soil supplemented by K.
Methods: Cation selectivity in leaves was determined as a ratio of two cations to the respective ratio in the soil over two growth seasons, three growth stages, and two cotton cultivars. Concurrently, instantaneous and long-term leaf traits related to $CO_2$ assimilation, N and water use efficiency were assessed.
Results: Potassium addition did not affect on cation selectivity; growth stages and their interaction with years were allotted with the most of the variation found for cation selectivity and many of the physiological traits. Cultivar Carmen compared to Elina had higher K selectivity, was water conservative and had higher fiber quality. Elina took up Na selectively over Mg in an effort to sustain stomata open.
Conclusions: The reported results indicated an importance of improved cation selectivity to optimize $K^+$ nutrition in plants grown on calcareous soils. Under conditions of low $K^+$ availability, cotton cultivars took up selectively Na and Mg over Ca, to optimize its water relations and photosynthetic performance. Cation selectivity was largely affected by growth stages and was correlated with stomata functioning.

### Challenging the Potassium Deficiency Hypothesis for Induction of the Ripening Disorder Berry Shrivel in Grapevine

Griesser, M., S. Crespo Martinez, M.L. Weidinger, W. Kandler, and A. Forneck. 2017. Scientia Horticulturae 216:141-147. DOI: https://doi.org/10.1016/j.scienta.2016.12.030.

**Abstract:** Berry shrivel (BS) is a ripening dysfunction resulting in grapes with low sugar content, high acidity, reduced anthocyanins and flaccid berries. In this study we challenge the $K^+$-deficiency hypothesis as underlying cause for BS in grapevine. The hypothesis is based on empirical vineyard studies and proposes that $K^+$-deficiency or a disbalance of $K^+/Mg^{2+}$ in plant content cause of BS. Recent studies on more grapevine varieties and further geographical locations lack supporting evidence for the $K^+$ hypothesis. Here we review existing evidence from the field and apply physiological analyses to study processes involved in $K^+$ and nutrients transport in BS and non-symptomatic clusters. For the first time the molecular background of $K^+$ transportation is being studied over the course of BS disorder.
Our objectives were (1) to determine the distribution of nutrients in BS vines and clusters and (2) to evaluate the role of selected potassium transport proteins and channels during grape berry development and BS induction in pedicels and berries. Our results with ICP-MS show a strong and significant reduction of $K^+$ concentration in rachis and pedicels of BS grapes, whereas boron, zinc, copper and aluminum were increased. Concentration of nutrients in BS berries were either not changed or increased compared to non-symptomatic clusters. Expression analyses with qPCR in pedicels revealed no pre-symptomatic differences of genes involved in potassium transport (VviKUP1, VviKUP2 and VviK1.2), but later during ripening reduced expression was observed. In BS berries the expression of VviK1.2 was reduced before veraison. We show significant $K^+$ deficiency in BS rachis and pedicels along with partial reduced expression of $K^+$ transporter genes. Consequently $K^+$ phloem transport is involved

in BS induction, however our study did not provide conclusive evidence to support the $K^+$ deficiency hypothesis as a single factor for BS induction. Instead the idea that a combination of further stress factors influences $K^+$ and assimilates translocation towards sink organs before veraison is proposed.

### Nitrogen and Potassium in Production, Nutrition and Water Use Efficiency in Wheat Plants

Carvalho, J.M.G., E.M. Bonfim-Silva, T.J. Araújo da Silva, H.H.F. Sousa, S.L. Guimarães, and A.B. Pacheco. 2016. Ciencia e Investigacion Agraria 43(3):442-451. DOI: http://dx.doi.org/10.7764/rcia.v43i3.1733.

**Abstract:** Wheat (*Triticum aestivum* L.) is a cereal used in food and feed for its nutritional properties. For nitrogen and potassium management, efficient use of water is required for greater availability and transportation of these nutrients. The objective of this study was to evaluate the effect of combinations of nitrogen and potassium doses in production, nutrition and water use efficiency in wheat. The experiment was held in a greenhouse with 8-dm3 pots using Oxisol collected at a depth of 0-0.2 m under Cerrado vegetation. Base saturation was raised to 60%. The experimental design was a randomized block in a 5x5 factorial arrangement with five doses of nitrogen (0, 100, 200, 300 and 400 mg dm-3) and potassium (0, 90, 180, 270, 360 mg dm-3) with four replications. Soil moisture was maintained by an auto-irrigation system (3 kPa pressure). The experiment was collected at 95 days after plant emergence. We evaluated the dry mass of ears, shoots and roots, the total dry matter, nitrogen and potassium in grains, and the consumption and efficiency in water use. An analysis of variance and regression test at 5% probability was conducted using SAS statistical software (SAS Institute, Inc., Cary, North Carolina). The nitrogen and potassium alone increased the dry mass of ears by 31.47% and 20.91%, respectively. There was an interaction of nutrients on the dry mass of the shoots and the total dry matter. Potassium increases the concentration of nitrogen. Nitrogen and potassium promote gains in production, nutrition and water use efficiency.

### Effect of Potassium Fertilizer Split Applications together with Straw on Optimum Level in Leaf and Stem of Rice

Pavithira, E., D.N. Sirisena, and H.M.S.K. Herath. 2017. Journal of Agricultural Sciences. 12(1):24-33. DOI: http://doi.org/10.4038/jas.v12i1.8203.

**Abstract:** Effect of long term K fertilizer application together with rice straw on optimum K level in leaf and stem of rice plants was evaluated in a field experiment. No K fertilizer (T1), rice straw only (T2); 20 kg $K_2O$ $ha^{-1}$ of K (both at basal dressing and panicle initiation) with rice straw (T3), 20 kg $K_2O$ $ha^{-1}$ of K (at basal dressing) with rice straw (T4), 20 kg $K_2O$ $ha^{-1}$ of K (at panicle initiation) with rice straw (T5), and 20 kg $K_2O$ $ha^{-1}$ of K (both at basal dressing and panicle initiation) (T6) were applied. Rice straw was amended at the rate of 5 t $ha^{-1}$. Soil samples were analysed for exchangeable K and non-exchangeable K during the growing season and plant samples were analysed for K content in leaf and stem at maturity (12 weeks after planting). At harvesting, total grain yield and number of panicles were recorded. Soil and plant K contents under no K fertilizer (T1) were significantly lower ($P<0.05$) throughout the cultivation period compared to all other treatments. However, shoot dry matter, number of panicles, and grain yield were not significantly different ($P > 0.05$) among treatments. All K fertilizer applied plots depicted higher K content in leaves and stem of rice plants, compared to the no K fertilizer treated plots, irrespective of straw application. The highest exchangeable K and non-exchangeable K contents were recorded in the treatment received with K fertilizer at the rate of 20 kg $K_2O$ $ha^{-1}$(at basal dressing and panicle initiation) with rice straw, T3). When consider plant K uptake in relation to the non-exchangeable K there was a positive relationship irrespective of the type of treatment and the number of weeks after planting. According to these results it can be concluded that to maintain optimum K content (1.5 %) in leaf and stem of rice plant, it is needed to apply K fertilizer together with rice straw.

### Impact of Phosphorus and Potassium Fertilizers on Growth and Anthraquinone Content in *Rheum tanguticum* Maxim. ex Balf

Na Shen, Yulei Cui, Wenhua Xu, Xiaohui Zhao, and Lucun Yang. 2017. Industrial Crops and Products 107:312-319. DOI: https://doi.org/10.1016/j.indcrop.2017.05.044.

**Abstract:** The dried root of *Rheum tanguticum* plays an important role in formulations and prescriptions in traditional Chinese medicine and Kampo medicine. Due to over-exploitation, *R. tanguticum* resources have decreased sharply in recent years. The main objective of our investigation (a 3-year field experiment) was to explore the effect of different levels of phosphorus (superphosphate) and potassium (potassium sulfate) fertilizer on the biomass (root fresh weight, root increment, and root dry weight), yield, dry matter content, and anthraquinone content of this plant at different harvesting stages (green stage, growth stage, and wilting stage) under alpine conditions. The root fresh weight and root dry weight increased significantly at the wilting stage following treatment with 90 kg $P_2O_5$/ha (100% and 59%, respectively) in 2016 and 75 kg $K_2O$/ha (43% and 41%, respectively) in 2015 compared to the control. The yield of root dry weight obtained from three-year-old *R. tanguticum* plants was 9,200 kg/ha when 90 kg $P_2O_5$/ha of phosphorus fertilizer was applied, and 10,400 kg/ha when 75 kg $K_2O$/ha of potassium fertilizer was applied. This yield reached a maximum at the wilting stage. The anthraquinone content of two-year-old

*R. tanguticum* plants had already reached the standard level of the *Chinese Pharmacopoeia*; however, three-year-old plants had double the anthraquinone content of two-year-old plants. Phosphorus and potassium fertilizers had no obvious influence on the anthraquinone content of *R. tanguticum* at the same harvesting stage.

### Potassium Starvation Limits Soybean Growth More than the Photosynthetic Processes across $CO_2$ Levels

Singh, S.K., and V.R. Reddy. 2017. Front. Plant Sci. DOI: https://doi.org/10.3389/fpls.2017.00991.

**Abstract:** Elevated carbon dioxide ($eCO_2$) often enhances plant photosynthesis, growth, and productivity. However, under nutrient-limited conditions the beneficial effects of high $CO_2$ are often diminished. To evaluate the combined effects of potassium (K) deficiency and $eCO_2$ on soybean photosynthesis, growth, biomass partitioning, and yields, plants were grown under controlled environment conditions with an adequate (control, 5.0 mM) and two deficient (0.50 and 0.02 mM) levels of K under ambient $CO_2$ ($aCO_2$; 400 µmol $mol^{-1}$) and $eCO_2$ (800 µmol $mol^{-1}$). Results showed that K deficiency limited soybean growth traits more than photosynthetic processes. An ~54% reduction in leaf K concentration under 0.5 mM K vs. the control caused about 45% less leaf area, biomass, and yield without decreasing photosynthetic rate ($P_{net}$). In fact, the steady photochemical quenching, efficiency, and quantum yield of photosystem II, chlorophyll concentration (TChl), and stomatal conductance under 0.5 mM K supported the stable $P_{net}$. Biomass decline was primarily attributed to the reduced plant size and leaf area, and decreased pod numbers and seed yield in K-deficient plants. Under severe K deficiency (0.02 mM K), photosynthetic processes declined concomitantly with growth and productivity. Increased specific leaf weight, biomass partitioning to the leaves, decreased photochemical quenching and TChl, and smaller plant size to reduce the nutrient demands appeared to be the means by which plants adjusted to the severe K starvation. Increased K utilization efficiency indicated the ability of K-deficient plants to better utilize the tissue-available K for biomass accumulation, except under severe K starvation. The enhancement of soybean growth by $eCO_2$ was dependent on the levels of K, leading to a $K \times CO_2$ interaction for traits such as leaf area, biomass, and yield. A lack of $eCO_2$-mediated growth and photosynthesis stimulation under severe K deficiency underscored the importance of optimum K fertilization for maximum crop productivity under $eCO_2$. Thus, $eCO_2$ compensated, at least partially, for the reduced soybean growth and seed yield under 0.5 mM K supply, but severe K deficiency completely suppressed the $eCO_2$-enhanced seed yield.

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Chief editor Chinese edition: Youguo Tian, NATESC, Beijing, China

Layout and design: Martha Vacano, IPI

Address: International Potash Institute
Industriestrasse 31
CH-6300 Zug, Switzerland

Telephone: +41 43 810 49 22
Telefax: +41 43 810 49 25
E-mail: ipi@ipipotash.org
Website: www.ipipotash.org

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