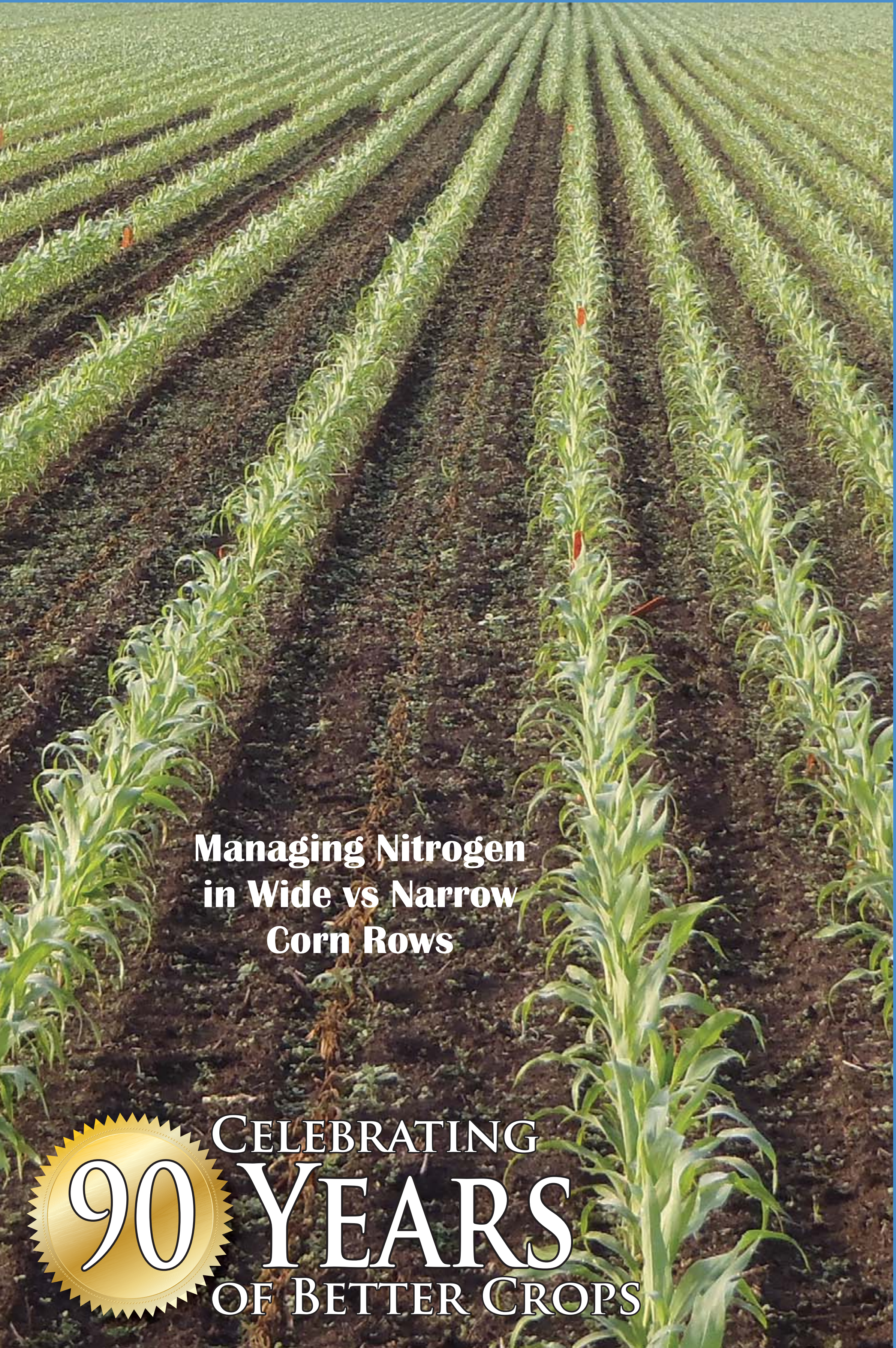
BETTER CROPS
WITH PLANT FOOD

A Publication of the International Plant Nutrition Institute (IPNI)

2013 Number 2

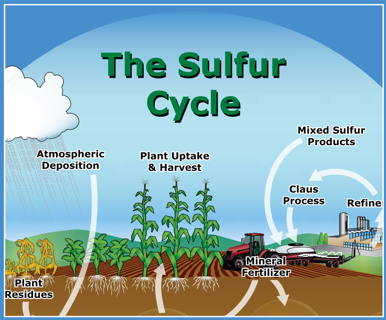


Managing Nitrogen in Wide vs Narrow Corn Rows

CELEBRATING 90 YEARS OF BETTER CROPS

In This Issue...

Series on Sulfur Nutrition



Managing for High Yield Cotton in Brazil

Potassium Use in Western Siberia

Also:

Sustainable Oil Palm Fertilization

What is "Sustainable" Anyway?

...and much more

IPNI

www.ipni.net

BETTER CROPS
WITH PLANT FOOD

Vol. XCVII (97) 2013, No. 2

Our cover: Wide- and narrow-row corn spacings in a N response experiment in North Carolina, U.S.
Photo by: Carl R. Crozier, NCSU
Editor: Gavin D. Sulewski
Assistant Editor: Danielle C. Edwards
Circulation Manager: Wendy Hollifield
Design: Rob LeMaster

BETTER CROPS WITH PLANT FOOD (ISSN:0006-0089) is published quarterly by the International Plant Nutrition Institute (IPNI). Periodicals postage paid at Norcross, GA, and at additional mailing offices (USPS 012-713). Subscriptions free on request to qualified individuals; others $8.00 per year or $2.00 per issue. Address changes may be e-mailed to: whollifield@ipni.net

POSTMASTER: Send address changes to *Better Crops with Plant Food*, 3500 Parkway Lane, Suite 550, Norcross, GA 30092-2844. Phone (770) 447-0335; fax (770) 448-0439. Website: www.ipni.net.

Better Crops with Plant Food is registered in Canada Post.
Publications mail agreement No. 40035026
Return undeliverable Canadian addresses to:
PO Box 2600
Mississauga ON L4T 0A9 Canada

The Government of Saskatchewan helps make this publication possible through its resource tax funding. We thank them for their support of this important educational project.

CONTENTS

Note to Readers: Articles which appear in this issue of *Better Crops with Plant Food* can be found at: >**www.ipni.net/bettercrops**<

Global TraPs World Conference

IPNI will be participating at the First Global TraPs (Transdisciplinary Processes for Sustainable Phosphorus Management) World Conference, which is dedicated to the theme "Learning from Cases – Exploring Policy Options." The conference offers a new stage for discussions on sustainable P management.

Day one of the conference will be devoted to learning and dialogue sessions with days two and three being a joint conference with the United Nations Environment Program's – Global Partnership for Nutrient Management (UNEP-GPNM).

Lead Organizers: Franhofer Institute, China Agricultural University, Global Partnership on Nutrient Management, International Fertilizer Development Center.

Dates/Location: June 18-20, 2013, China Agricultural University, Beijing, China.

Program Details: http://www.globaltraps.ch/

The 2013 InfoAg Conference

IPNI invites you to consider attending InfoAg if you have an interest in learning about the very latest agricultural technologies and how these tools are being put to use in production agriculture today. InfoAg is the premier conference on precision ag technology and its practical applications. Last InfoAg attendance topped 730 crop advisers, farmers, ag retailers, ag services, state and federal agents, researchers, extension, and other agribusiness professionals.

The conference format features multiple concurrent speaker sessions providing a wide range of topics from high-level discussions among key executives to boots on the ground decisions in producing a crop. "We offer a blended program hitting on key aspects of precision ag," said Dr. Steve Phillips, IPNI Regional Director, Southeast U.S. "Our program attracts participants from all aspects of the industry, which builds on InfoAg's strength as a networking tool for participants, speakers, exhibitors and sponsors."

Lead Organizer: International Plant Nutrition Institute

Dates/Location: July 16-18, 2013 at Crowne Plaza, Springfield, Illinois.

InfoAg Website: www.infoag.org

Improving Nitrogen Use Efficiency in Crop and Livestock Production Systems

IPNI is pleased to be a sponsor of this important meeting that will bring together agronomists, biogeochemists, farmers, economists, sociologists, extension agents, educators, and policy experts from both public and private sectors to identify the major impediments to improved nutrient management and to make recommendations for overcoming those impediments.

Conference Goals for Participants:

- Review the current suite of tools and knowledge used to optimize N management for crop and livestock production and promising new technologies under development.
- Review case studies of successes and failures to policies and projects designed to encourage improved nutrient management.
- Identify the major socio-economic and educational impediments to more widespread adoption of improved nutrient management practices.
- Recommend existing opportunities for actions and policies to improve nutrient management using current knowledge and technology.
- Identify and prioritize goals for additional agronomic or socio-economic research needed to overcome impediments to better nutrient management practices.

Lead Organizer: Soil Science Society of America

Dates/Location: August 13-15, 2013 at Marriott Country Club Plaza, Kansas City, MO.

Program Agenda: https://www.soils.org/files/meetings/web-nue-agenda.pdf

For more information, please contact Emma Suddick at esuddick@whrc.org

4R Potassium Management in Processing Tomato Production in Xinjiang

By Shutian Li and Yan Zhang

Production of processing tomato in the northwestern province of Xinjiang, China is often restricted by inadequate K nutrition. This article provides examples of K application practices that follow 4R Nutrient Stewardship guidelines, and the associated yield and quality benefits that can be gained through their implementation.

The province of Xinjiang is the largest center for processing tomato production in China. The area planted has increased from 22,000 to 93,000 ha between 2001 and 2010, and total fruit production has reached 5 million t. Xinjiang has high sunlight intensity (2,600 to 3,400 hours annually), large differences in temperature between day and night, and low humidity, all of which favor growth and dry matter accumulation in tomato plants.

Tomatoes for processing need large amounts of K for adequate growth. Often the K requirement exceeds its N requirement. Regardless, traditional beliefs that their desert grey soils can provide sufficient quantities of K have led farmers to omit K fertilizer application for years causing significant soil K depletion and decreased K availability (Zhang et al., 2006). As is evident from this review, the general principle of 4R Nutrient Stewardship as outlined by Roberts (2007)—apply the right source at the right rate, time, and place—can be adopted to guide the management of K applications in processing tomato.

The Right Source

The most common sources of fertilizer K in China are potassium chloride (KCl), mono potassium phosphate (KH_2PO_4), potassium nitrate (KNO_3), and potassium sulfate (K_2SO_4). Out of these sources, KCl is the least expensive. Locascio et al. (1997) cites a majority of studies showing no significant influence of K source on fruit yield or leaf K concentration in field-grown tomatoes. Chapagain et al. (2003) observed that KCl could fully or partially replace KNO_3 in tomato production through fertigation without affecting growth and yield. In fact, KCl improved some fruit quality parameters such as fruit firmness and freshness of calyx and reduced the number of rotten and blotchy fruits compared with KNO_3. Fan et al. (2009) showed that in processing tomato grown under drip irrigation and mulch, the organic-inorganic fertilizer complex containing 5% humic acid and 49% NPK produced 6,230 kg/ha more fruits and US$196/ha more income than conventional drip-irrigated fertilizers with 50 to 55% NPK. Also, there was a significant ($p<0.05$) increase in soluble solids, vitamin C, and lycopene contents, thereby improving fruit quality with the combined application of organic-inorganic fertilizer. Hu et al. (2007) showed that at the same fertilizer application rate of 179-108-90 kg N-P_2O_5-K_2O/ha, KCl produced 7.2% and 7.3% more processing tomato yield and $277 and $264 more income than potassium magnesium sulfate ($K_2SO_4{\cdot}2MgSO_4$) and K_2SO_4, respectively (**Table 1**). Zhang et al. (2008) also showed that at the same K rate, KCl produced 7.0 to 9.2% more tomato fruit than K_2SO_4 (**Table 2**).

Table 1. Effect of different sources of K on yield and quality of processing tomato in Xinjiang.

K source	Yield, kg/ha	Lycopene, mg/100g	Solids, %	Vitamin C, mg/100g	Income from fertilizer application, US$/ha
KCl	97,366 a*	2.26 a	1.50 a	6.14 a	407**
$K_2SO_4{\cdot}2MgSO_4$	90,862 b	3.05 a	2.33 a	7.96 a	130
K_2SO_4	90,725 b	3.04 a	2.17 a	7.96 a	143

*Within a column, numbers followed by a different letter are significantly different at $p<0.05$.
** Prices used: tomato fruit = US$0.03/kg; K_2O = US$0.64/kg KCl, US$0.67/kg K_2SO_4, US$0.84/kg $K_2SO_4{\cdot}2MgSO_4$. Income was calculated based on the difference between K treatment and K omission plots.
N-P_2O_5-K_2O rates were 179-108-90 kg/ha.

Table 2. Effect of K source and rate on fruit yield of processing tomato in Xinjiang.

Location	K source	Rate, kg K_2O/ha	Yield, kg/ha
Toutunhe 5*	KCl	50	63,225
	K_2SO_4	50	57,900
	Control	0	42,345
Toutunhe 1*	KCl	72	78,510
	K_2SO_4	72	73,350

*N and P_2O_5 rates at Toutunhe 5 were 173 and 110 kg/ha and at Toutunhe 1 were 173 and 104 kg/ha, respectively.

The Right Rate

Tang et al. (2009) observed that an average of 3.27 (2.88 ± 0.84) kg N, 0.86 (0.76 ± 0.13) kg P_2O_5 and 4.02 (3.85 ± 0.17) kg K_2O was required for producing each tonne of processing tomato within the desired yield range of 75 to 112 t/ha. Tang et al. (2010) showed that when processing tomato yields were between 90 to 95 t/ha crop NPK uptake averaged 285 kg N/ha, 31 kg P_2O_5/ha and 290 kg K_2O/ha. These data suggest that at least 300 to 400 kg K_2O/ha is required for producing 75 to 100 t/ha of processing tomato. The rate of K applied depends on the soil supply of K and the expected target yield. Wang et al. (2011) provided an equation to calculate K rate based

Abbreviations and notes: N = nitrogen; P = phosphorus; K = potassium; US$1 = ¥6.24 (Chinese yuan).

Irrigation must be managed carefully and nutrients must not be limiting to obtain high yields and high quality fruit of processing tomatoes under drip irrigation and plastic mulch in Xinjiang.

on target yield:

$$R_K = 830.3427/(1+e^{-0.00002\times(TY-99019.6011)})$$

where, R_K is the rate of K (kg K_2O/ha); TY is target yield (kg/ha)

Experiments conducted by IPNI China Program also found increased processing tomato yield, fruit quality and profits with application of K fertilizer. For example, in 2003-04 applications of 180 kg K_2O/ha together with 180 kg N/ha and 108 kg P_2O_5/ha increased fruit yield by 14.6 to 17.8% over the zero-K treatment and improved fruit quality characters such as lycopene, soluble solids and vitamin C (**Table 3**). In 2008, application of 105 kg K_2O/ha produced 11% more yield and $326/ha more income than the zero-K treatment in Ma'nasi County. The following year balanced fertilizer application (360-150-105 kg N-P_2O_5-K_2O/ha) produced 17% more yield and $530 more income over farmer's fertilizer practice (272-195-45 kg N-P_2O_5-K_2O/ha).

Cheng et al. (2007) determined the optimum rate of fertilizer for a drip-irrigated yield goal of 112 t/ha was 300-105-75 kg N-P_2O_5-K_2O/ha when soil available K was 260 mg/kg. Drip irrigation can result in a small volume of soil being explored by the root system. With higher expected yields, the amount of nutrients extracted from this reduced volume of soil should be taken into consideration in any fertilizer management program, especially when soil available K is in the low-to-medium category.

The Right Time

Studies have indicated that 7.7, 27.4, 25.2, and 32.3% of plant K is taken up by tomato plants at seedling, flowering/fruit setting, fruit ripening, and harvesting stages, respectively (Xue et al., 2004; Liang et al., 2006). This suggests that most of the K uptake by tomato plants happens in the later crop growth stages (i.e., after flowering and especially at fruit ripening and harvesting stages). Therefore, the timings of fertilizer K applications are important to achieve high yield and quality of fruits. More than 90% of the recommended fertilizer K should be applied after flowering and fruiting stage. Conventional practice applies 50 to 60% of recommended K fertilizer basally

Table 3. Effect of K rates on yield, quality and income from fertilizer application in processing tomato in Xinjiang

	K_2O rate, kg/ha	Yield, t/ha	Lycopene, mg/100g	Solids, %	Vitamin C, mg/100g	Income from fertilizer application, US$***
2003*	0	86.1 b**	-	-	10.48	-
	90	92.6 b	-	-	19.21	159
	180	101.3 a	-	-	11.08	388
	270	91.7 b	-	-	9.17	11
2004*	0	95.1 b	6.11 b	8.9	8.03	-
	90	98.8 b	7.97 ab	8.9	8.33	64
	180	109.0 a	10.48 a	10.5	9.73	341
	270	95.4 b	8.60 ab	8.5	8.92	-164

*N and P_2O_5 rates were 180 and 108 kg/ha, respectively.
**Within a column, numbers followed by a different letter are significantly different at $p<0.05$.
***Prices: US$0.03/kg tomato fruit; US$0.64/kg K_2O.

and 40 to 50% as topdressing at the fruit ripening stage, which is not consistent with the plant K uptake.

The timing of K application also usually depends on water management. Due to water shortage, most of the processing tomato in Xinjiang is drip-irrigated, which can affect nutrient distribution and movement in soil, and then influence K availability and plant uptake. Fu et al. (2005) observed that the movement of K with water was similar to N, which was distributed within 30 cm of the soil surface. So, in drip-irrigated systems most of the N (63 to 84%) and K (61 to 74%) were applied in the later stages from flowering to maturity (Wang et al., 2011).

The Right Place

Drip irrigated tomato is usually planted after plastic mulching. Since the irrigation pipelines are under the mulch between two rows of tomato plants, except for the pre-plant fertilizers applied before plastic mulching, the majority of N and K fertilizers are injected into the drip system via fertigation for delivery to the root system with water.

For the direct-seeded, furrow-irrigated processing tomato, fertilizers are usually side-dressed. In subsurface drip irrigation, the water is moving "from the inside out," whereas in furrow irrigation water moves in the opposite direction, carrying side-dressed N or K into the bed. This has implications on the placement of any banded fertilizer. Fertilizer bands located near the edge of the beds, which is an appropriate placement in furrow irrigation, is not effective in the drip-irrigation system.

Other Practices

The nutrient content in tomato fruit depends largely on genetic and environmental factors during the fruit ripening stage (Javanmardi and Kubota, 2008). Consistency and color parameters of tomato fruits was positively influenced by high water availability for plants, while the ascorbic acid content was positively affected by less frequent irrigations (Mitchell et al., 1991). Favati et al. (2009) indicated that extending irrigation intervals and limiting irrigation volume to the later part of the tomato crop cycle appeared to be the best management practice to optimize yield and nutritional quality of processing tomato.

With drip irrigation, we can precisely match the crop's nutrient needs using the right source and right rate so that high production goals can be achieved. Future extension efforts must focus on popularizing 4R Nutrient Stewardship in processing tomato production as a means of optimizing production and nutrient use efficiency. BC

Dr. Li is Deputy Director for IPNI Northwest China Program; e-mail: sli@ipni.net. Ms. Zhang is a Professor, Soil and Fertilizer Institute, Xinjiang Academy of Agricultural Sciences.

References

Chapagain, B.P., Z. Wiesman, M. Zaccai, P. Imas, and H. Magen. 2003. J. Plant Nutr. 26(3): 643–658.
Cheng, X.J., J. Wang, X.P. Huang, C. Li, L.P. Tian, L. Xue, and J.R. Zhao. 2007. J. Anhui Agri. Sci. 35(35): 11509-11511. (In Chinese).
Fan, Q.L., F.H. Yin, X.Y. Guan, and Y. Chen. 2009. Xinjiang Agri. Sci. 46 (4): 746-750. (In Chinese).
Favati, F., S. Lovelli, F. Galgano, V. Miccolis, T.D. Tommaso, and V. Candido. 2009. Sci. Hortic. 122: 562-571.
Fu, M.X., G.Y. Wang, and M.Y. Bao. 2005. Xinjiang Agri. Sci. 42(6): 426-429.
Hu, W., Y. Zhang, H.Y. Wang, G.H. Qi, and L.C. Yang. 2007. Xinjiang Agri. Sci. 44 (4): 494-497. (In Chinese).
Javanmardi, J. and C. Kubota. 2008. Postharvest Biol. Technol. 41, 151–155.
Liang, C.F., Z.F. Chen, and W.X. Li. 2006. Chinese J Eco-Agri. 14(2): 79-81. (In Chinese).
Locascio, S.J., G.J. Hochmuth, S.M. Olsan, R.C. Hochmuth, A.A. Csizinszky, and K.D. Shuler. 1997. HortSci. 32, 1204–1207.
Mitchell, J.P., C. Shennan, S.R. Grattan, and D.M. May. 1991. J. Am. Soc. Hortic. Sci. 116, 215–221.
Roberts, T.L. 2007. *In* Fertilizer Best Management Practices. IFA International Workshop on Fertilizer Best Management Practices (FBMPs). 7-9 March, 2007. Brussels, Belgium. pp. 29-32.
Tang, M.R., Y. Zhang, W. Hu, G.Z. Hu, Q.J. Li, Y.K. Yao, and Y. Gao. 2010. Plant Nutr. Fert. Sci. 16(5): 1238-1245. (In Chinese).
Tang, M.Y., Y. Zhang, and W. Hu. 2009. Soil Fert. Sci. China, 3: 26-30. (In Chinese).
Wang, J.C., S. Gao, L.P. Chen, and F.Y. Ma. 2011. Chinese J. Eco-Agri. 19(2): 285-292. (In Chinese).
Xue, L., L.P. Tian, and J. Wang. 2004. J Shihezi Univ. (Natural Sci.). 22(5): 289-292. (In Chinese).
Zhang, Y, J.H. Shi, and G.H. Luo. 2006. Xinjiang Agri. Sci. 43 (5): 375-379. (In Chinese).
Zhang, Y., H.G. Ma, W.L. Xu, H.Y. Wang, G.H. Qi, and L.C. Yang. 2008. Soil Fert. Sci. China. 3: 40-51. (In Chinese).

IPNI Scholar Award Application Deadline is June 30

The International Plant Nutrition Institute (IPNI) is proud to continue its support of the IPNI Scholar Award program in 2013 and would like to remind all prospective candidates that the June 30 deadline for submitting applications is quickly approaching. This Award of US$2,000 is available to selected students enrolled in graduate degree programs supporting the science of plant nutrition and crop nutrient management including: agronomy, horticulture, ecology, soil fertility, soil chemistry, and crop physiology. Graduate students must also attend a degree-granting institution located in any country with an IPNI Program.

Regional committees of IPNI scientific staff select the recipients. The selection committee adheres to rigorous guidelines while considering each applicant's achievements. The Award can be presented directly to the student at their universities and no specific duties are required of them.

More information on the IPNI Scholar Award is available from our Awards website at www.ipni.net/awards, IPNI Staff, or from participating universities. BC

Soil and Fertilizer Sulfur

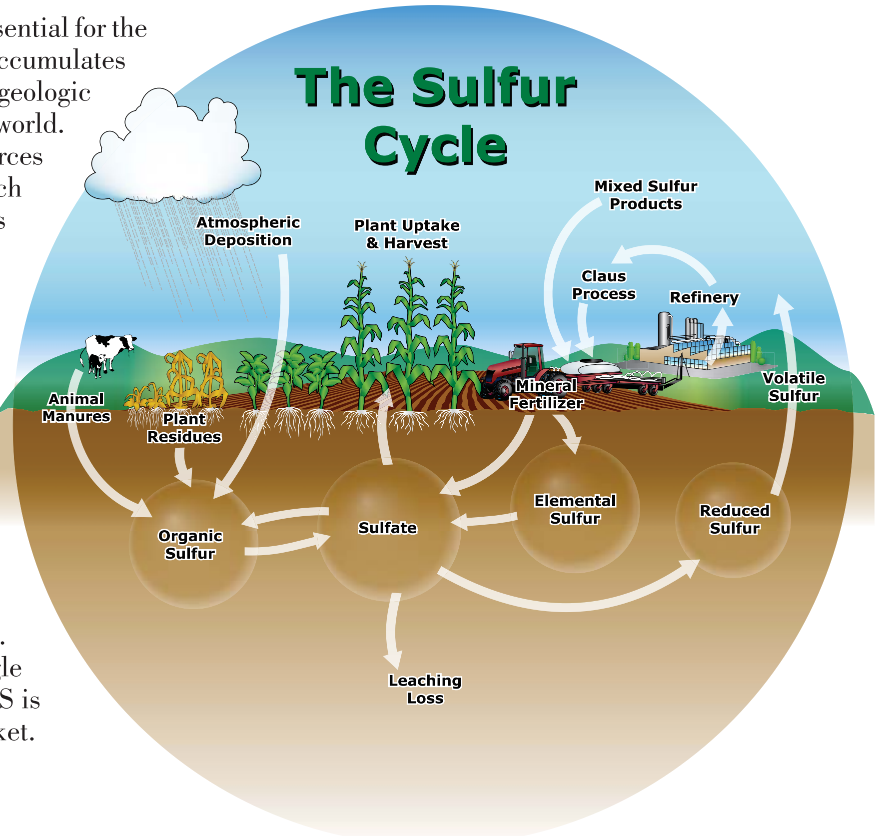
By Robert Mikkelsen and Robert Norton

A continual supply of sulfur (S) is essential for plant growth. Organic matter is the largest reservoir of S in soil, but it must be converted to soluble sulfate before plants can take it up. The major source of S fertilizer is obtained from scrubbing fossil fuels. There are many excellent soluble and slowly soluble sources of S fertilizer that can meet plant nutritional requirements when applied at the right rate, time and place.

Sulfur is widely distributed in nature and essential for the health of both plants and animals. It often accumulates in areas with volcanic activity, and large geologic deposits of elemental S are scattered across the world. Volcanic S and pyrite (Fe_2S) were the primary sources of S until recently. In the 20th century, the Frasch process of melting S in underground deposits was developed, making S more accessible for agricultural and industrial purposes.

Fossil hydrocarbons contain S since it was present in the organic material that formed them. This fossil S is now recovered as a by-product from materials such as oil, methane, oil sands, and coal. Sulfur removal also reduces air pollution during combustion of the fossil fuel. Elemental S is currently extracted wherever oil or gas is processed and refined. Sulfur is traded globally in a solid or in a molten form.

Sulfur is an important product in many industrial processes, especially as sulfuric acid. The production of phosphate fertilizer is the single largest use of S. The global supply and price of S is closely linked with the phosphate fertilizer market.



Sulfur in the Soil

Organic S

The majority of S in soil is present as organic compounds found in crop residues and soil organic matter (up to 98% of the total S). There is a variety of complex S-containing compounds in organic matter (such as ester sulfates and carbon-bonded S) but plant roots are not able to assimilate these forms until they are first converted into soluble sulfate by microbial action.

Sulfur in the soil is continually transformed between organic and inorganic compounds by microbial action. Mineralization occurs when sulfate is released as a by-product of microbial activity. Immobilization results when sulfate is incorporated into microbes during their growth.

One simple technique for predicting whether net mineralization or immobilization will occur is to measure the ratio of carbon (C) and S in the soil. Sulfate is generally released when the C:S ratio of organic matter is lower than 200:1 and immobilization typically occurs when the C:S ratio exceeds 400:1. When the C:S ratio is between these two benchmarks, the fate of S is less predictable.

Sulfur mineralization from soil organic matter is often too slow to meet the nutritional demands of high-yielding crops. This nutrient deficit must be overcome with supplementation from mineral or organic fertilizers.

Abbreviations and notes: N = nitrogen; P = phosphorus; S = sulfur; Fe = iron; Mn = manganese; Zn = zinc; ppm = parts per million.

Inorganic S

Only a small fraction of the total S in soil is found as inorganic compounds. Sulfate is the most abundant form of inorganic S in soil. It is found dissolved in water, retained on the surface of soil minerals, or in minerals such as gypsum. In wetlands and poorly-drained soil, sulfide minerals (such as pyrite) can accumulate.

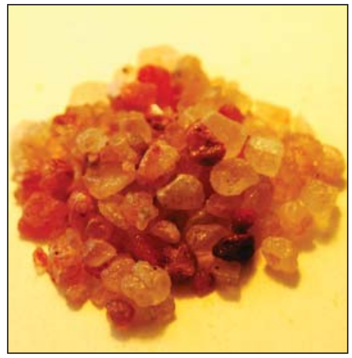
Sulfate is generally soluble and moves with soil water. It is only weakly retained (adsorbed) by a variety of clays and soil minerals, especially in low-pH conditions. Soil-adsorbed sulfate can represent an important reservoir of nutrition for plants, especially in acidic subsoils. Specific adsorption of sulfate also occurs in some soils, especially those with high levels of free Fe and aluminum oxides and hydroxides. The extent of non-specific sulfate adsorption is reduced by liming and by adding phosphate fertilizer.

Sulfate leaching

Sulfate leaching from the root zone with rainfall or irrigation water can be a major pathway of loss. The magnitude of sulfate loss through leaching will vary depending on the soil and environmental factors, but annual losses are often in the range of 5 to 60 kg S/ha (4 to 54 lb/A). Sulfate leaching is generally

Elemental S

Ammonium Sulfate



Langbeinite

Potassium Sulfate

lower from soils with vigorously growing crops compared with unplanted soils. Cover crops are commonly used to minimize nitrate-leaching losses, but they can also help with the recovery and recycling of sulfate that may also be at risk of loss.

Volatilization

In anaerobic soil conditions, sulfate is chemically reduced by bacteria to a variety of compounds that are largely unavailable for plant uptake. These include carbon disulfide, carbonyl sulfide, dimethyl disulfide, methyl mercaptan, and volatile hydrogen sulfide gas. Sulfide compounds commonly react with Fe to form pyrite minerals.

Atmospheric S

Sulfur dioxide (SO_2) is one of a group of highly reactive gases that are emitted during fossil fuel combustion. Since SO_2 emissions are linked to respiratory damage and acid rain, government restrictions limit its release. Much of the S contained in fossil fuel (especially hydrogen sulfide) is scrubbed prior to combustion, providing the major source of commercially available S.

Environmental Considerations

There are no government limits on sulfate in drinking water, but the U.S. Environmental Protection Agency suggests a limit of 250 mg/L due to taste and odor concerns. When hydrogen sulfide is found in well water, only a few mg/L (ppm) can result in poor taste and odor. In surface water, sulfate is rarely a limiting nutrient for stimulating aquatic organisms, but it can be involved in secondary reactions.

Sulfur as a Plant Nutrient

Harvesting crops from a field can gradually deplete the soil reservoir of S if it is not replaced. Soils with a large organic reserve may not require supplemental S, but many soils and crops benefit from regular additions of S.

Soil and Tissue Testing

A variety of soil testing tools have been developed to predict the availability of S for plants. These tests have been more successful in some regions than others. Since estimating plant-available S is partially dependent on mineralization of soil organic matter, soil testing has met with mixed success in making predictions. Plant growth responses to S fertilizer are most common in coarse-textured soils with low organic matter content, but positive responses to added S are observed in many areas of the world.

Because sulfate is mobile in soil, it can accumulate at depths below the topsoil. Soil samples for S analysis should reflect the full root depth to account for S below the surface layer. The inclusion of deeper soil layers in the analysis will often improve the predictability of soil S tests, particularly on coarse-textured soils.

Plant tissue analysis has been a reliable tool for evaluating the need for additional S. The specific plant part that is analyzed and the time of sampling will vary for each crop species, but generally it involves analysis of young plant parts during a period of high S demand. The caution here is that where nutrient stratification occurs, S located deeper in the soil will not be accessible until roots reach this depth.

Sources of Sulfur for Plant Nutrition

If diagnostic tools suggest a need for additional S, there are many excellent sources of S that can be used to supplement the soil supply.

Elemental Sulfur (99% S): Elemental S is insoluble and requires microbial oxidation to sulfate before plants can take it up. The rate of oxidation is largely governed by the properties of the elemental S and various soil environmental conditions.

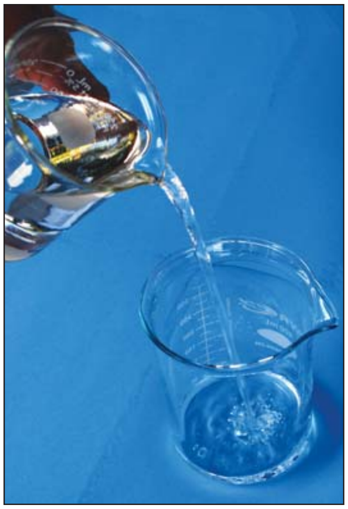
The surface area per unit of mass of S granules is inversely proportional to the particle size. Very small particles are oxidized more rapidly by soil bacteria than large particles since there is more surface area. However fine S particles are difficult to uniformly apply and air-borne S dust can present a fire hazard and a respiratory irritant, making it impractical as a common fertilizer. Maximizing the particle surface area exposed to soil speeds the conversion of elemental S to sulfate, so mixing S with the soil is generally preferred over a band application.

Elemental S is oxidized by various soil microorganisms, especially by the genus *Thiobacilli (Acidithiobacillus)*. When conditions of soil temperature, moisture, pH, and aeration are favorable for microbial growth, S oxidation will be much more rapid than in cool and dry conditions.

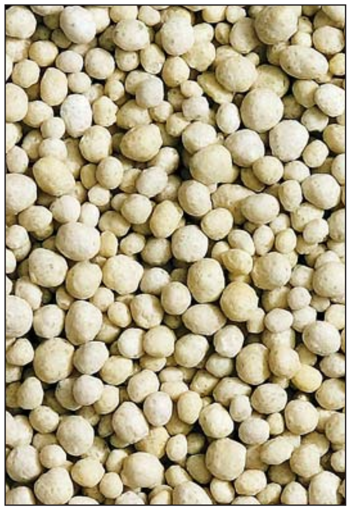
$$\underset{\text{elemental S}}{2S^\circ} + 3O_2 + 2H_2O \rightarrow \underset{\text{sulfuric acid}}{2H_2SO_4}$$

Elemental S is also used as a source of acid to lower the pH of soils and water. A common approximation is that 1 t of elemental S will neutralize 3 t of limestone. It also has a long history as a fungicide.

Clay-amended Sulfur (90% S): Molten S is mixed with approximately 10% bentonite clay to form a pellet (or pastille). When the clay becomes wet in the soil, it swells and breaks the pellet into many small pieces with a very large reactive surface area. Many clay-amended S products are amended with

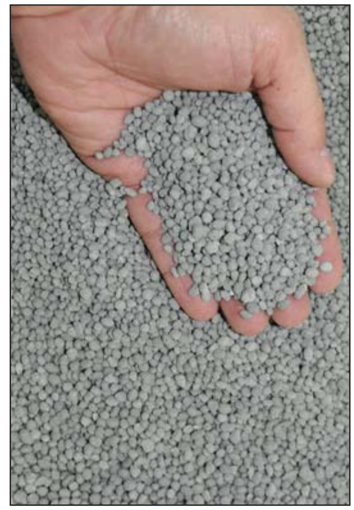


Potassium Thiosulfate



Kieserite

Gypsum



Single Superphosphate

various micronutrients (including Zn, Fe and Mn) that may benefit from the acidity produced during S oxidation.

Gypsum (16 to 18% S): Calcium sulfate ($CaSO_4 \cdot 2H_2O$) is only slightly soluble in water (0.2 g/L) and provides sulfate for plant nutrition as it slowly dissolves. Additionally, gypsum is used as a calcium source where it is lacking and also in the reclamation of sodic soils.

Single Superphosphate (11 to 12% S): This fertilizer is made by reacting sulfuric acid with rock phosphate to produce a mixture of monocalcium phosphate and gypsum. The popularity of this fertilizer has declined because more concentrated forms of P fertilizers are less expensive to transport and handle.

Ammonium Sulfate (24% S): Ammonium sulfate [$(NH_4)_2SO_4$] is a commonly used fertilizer to supply both N and S. Most of this fertilizer is produced as a by-product from various industrial processes, although it is sometimes made by the reaction of ammonia and sulfuric acid. Ammonium sulfate is very soluble and frequently used in fluid fertilizers. The soil acidification that occurs following application of $(NH_4)_2SO_4$ arises during the nitrification of ammonium (to nitric acid), rather than from the sulfate that is applied.

Potassium Sulfate (17 to 18% S): This common fertilizer [K_2SO_4] can be recovered directly from saltwater brines or produced by reaction of various minerals and acids. It is very soluble and makes an excellent source of sulfate for plants.

Potassium Magnesium Sulfate (Langbeinite) (20 to 22% S): The langbeinite mineral ($K_2SO_4 \cdot 2MgSO_4$) is extracted from geologic sources and provides a soluble source of three essential plant nutrients. It is highly soluble.

Ammonium Nitrate Sulfate (6 to 14% S): This material is formed by reaction of nitric and sulfuric acid neutralized with ammonia. The S content will vary depending on the reaction products. More recently, a new fertilizer is available that results from fusing ammonium nitrate and ammonium sulfate into a single granule (14% S).

Sulfur-enriched Fertilizer: Common fertilizers (such as monoammonium phosphate or diammonium phosphate) are sometimes amended with a mixture of fine particles of elemental S and soluble sulfate to provide an immediate and extended release of S. The acidity that develops surrounding the elemental S can be beneficial in maintaining the solubility of nutrients such as P and Zn.

Thiosulfate (10 to 26% S): Thiosulfate fertilizers are clear liquids that contain S in the form of $S_2O_3^{2-}$. These fluids are commonly mixed with other fertilizer solutions. In the soil, thiosulfate is converted to sulfate within a week or two in warm conditions.

Magnesium Sulfate (14 to 22% S): Two common sources of this material include the minerals kieserite ($MgSO_4 \cdot H_2O$) and Epsom salt ($MgSO_4 \cdot 7H_2O$). These materials are quite soluble and provide a readily available source of sulfate.

Manure and Compost: The S content of manures and composts is quite variable depending on the animal species, diet and handling. On a dry weight basis, the S content of manures and composts generally ranges between 0.3 and 1%. A period of mineralization is required to convert organic S-containing compounds to sulfate prior to plant uptake.

The selection of the appropriate source of S will depend on the soil properties such as leaching potential, pH and organic matter content. The need for additional nutrients present in the S fertilizer is also a consideration. The requirement for an immediately soluble source of S will also influence the selection of a specific fertilizer source. BC

Dr. Mikkelsen is Western Director, IPNI North America Program, Merced, CA, U.S.; e-mail: rmikkelsen@ipni.net. Dr. Norton is Director, IPNI Australia and New Zealand Program, Horsham, Australia; e-mail: rnorton@ipni.net.

Sulfur for Plant Nutrition

By Rob Norton, Robert Mikkelsen and Tom Jensen

Sulfur (S) is essential for plant nutrition, but its concentration in plants is the lowest of all the macronutrients. Plants are able to assimilate sulfate and reduce it to essential amino acids, where S is involved in a range of metabolic functions, including protein synthesis. Greater attention needs to be paid to the role of S in balanced crop nutrition in many global regions.

Sulfur is an essential macronutrient for plants and animals, and is required for many important metabolic functions. Plants are able to convert sulfate (SO_4^{2-}) into organic compounds, but animals must consume S-containing amino acids (methionine and cysteine) for their dietary requirement.

The need for S in crops has taken a higher profile in recent years as many farming systems have fewer S inputs than previously. Higher crop yields, slower organic matter turnover, reduced use of S-containing crop inputs, and changing crop patterns have also contributed to the need for additional S fertilization.

While most S in soils is present in organic matter, soluble sulfate is present in most soils and is the primary source of S nutrition for plants. It is actively transported into the root, especially in the root hair region, and moves into plant cells through a variety of sulfate transporters. Within the plant, sulfate moves in the transpiration stream until it is stored in cell vacuoles or participates in a variety of biochemical reactions. Leaves are also able to assimilate sulfur dioxide (SO_2) from the atmosphere, but this amount is usually no more than 1 kg S/ha/yr. Plant leaves can also emit hydrogen sulfide (H_2S) gas, which is assumed to be a type of detoxifying mechanism after exposure to high SO_2.

Most of the sulfate taken up by roots is converted to cysteine in leaf chloroplasts. Cysteine is the primary starting point from which most other organic S compounds in plants are formed. This synthesis process begins with sulfate reduction to adenosine phosphosulfate and ultimately to various S-containing organic compounds (**Figure 1**). Sulfate reduction requires considerable plant energy. Other important S amino acids include the amino acids cystine (a linkage of two cysteine molecules), and methionine (**Figure 2**). Smaller amounts of S are incorporated into important molecules such as coenzyme A, biotin, thiamine, glutathione, and sulfolipids.

Once sulfate is converted to organic compounds, they are exported through the phloem to the sites of active protein synthesis (esp. root and shoot tips, fruits and grains) and then become largely immobile within the plant. The symptoms of S deficiency occur first in the younger tissues and are seen as leaves and veins turning pale green to yellow. These chlorosis symptoms look similar to those that occur with N deficiency, but because of its higher internal mobility a low N supply becomes first visible in the older leaves. When S deficiencies are first observed, some crops may not entirely recover the lost growth following S fertilization.

There are a large number of secondary S compounds that provide biochemical benefit to specific plant species. Some crops (e.g. *brassicas* such as canola and mustard) have a relatively high S requirement and produce glucosinolate compounds. Members of the *Allium* species (e.g. garlic and onions) produce alliin compounds that may contain >80% of the total plant S. The characteristic flavor and smell of onions and garlic related to these volatile S compounds are enhanced when plants are grown in high S soil. These and other S-containing compounds are linked with resistance to various pests and environmental stress.

Abbreviations and notes: N = nitrogen; Cu = copper; Fe = iron, Mn = manganese; Mo = molybdenum; Ni = nickel; Se = selenium; Zn = zinc.

Sulfur deficiency in wheat. The inset image compares a normal leaf (right) to a deficient leaf (left). (Sharma and Kumar, 2011).

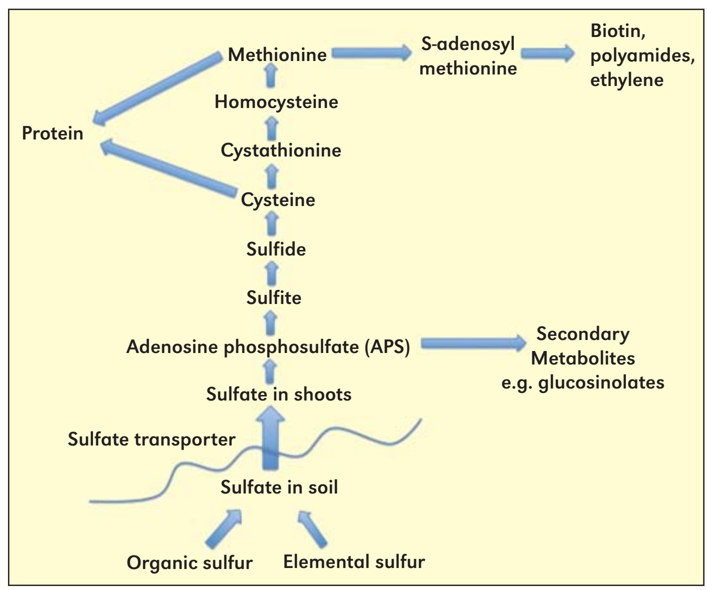


Figure 1. The general process of sulfate reduction and assimilation in plants. (Adapted from Hawkesford, 2012)

Crop Sulfur Requirement

Crops differ widely in their S requirement, with plant dry

Table 1. Sulfur removal in the harvest portion[1] of some typical crops. Grain values are at 10% moisture content.

Cereals	kg S/t	lb S/unit[2]	Oilseed	kg S/t	lb S/unit
Wheat	1.4	0.084 (bu)	Canola	5.0	0.25 (bu)
Barley	1.2	0.058 (bu)	Sunflower	1.7	0.17 (cwt)
Corn	1.1	0.062 (bu)	Cottonseed	2.9	0.29 (cwt)
Rice	0.9	0.041 (bu)	Flaxseed	2.0	0.11 (bu)
Pulses	**kg S/t**	**lb S/unit**	**Other Crops**	**kg S/t**	**lb S/unit**
Soybean	3.5	0.21 (bu)	Sugarcane (fresh wt.)	0.26	0.52 (ton)
Chickpea	1.8	0.11 (bu)	Alfalfa Hay (13% moist)	2.6	5.2 (ton)
Field Pea	2.1	0.12 (bu)	Grass silage (fresh wt.)	2.2	4.4 (ton)
Lentil	1.4	0.08 (bu)	Hops (dry)	3.6	7.2 (ton)

[1]The unharvested portion of the plant may contain as much or more S than the harvested crop.
[2]Unit of yield shown in parentheses.
Source: National Land and Water Resources Audit, 2001.

matter concentrations typically between 0.1 and 1% S. The S requirement is typically greatest for *brassicas* (such as cabbage, broccoli and rapeseed), followed by legumes, and then by cereal grasses.

The S demand will vary during the growing season. For example, S demand for canola is greatest during flowering and seed set. Uptake of S by maize is fairly constant through out the growing season, with grain accounting for >50% of the total S accumulation. Wheat may lose up to half of the total plant S between flowering and maturity. Each crop species needs to be examined for its specific nutrient requirement (**Figure 3**).

Removal of S during crop harvest is typically in the range of 10 to 30 kg S/ha depending on the crop and yield, but total plant uptake can be as high as 70 kg S/ha for some *brassica* species (**Table 1**).

Crop Quality

Crops grown in S-deficient soils can suffer reduced yields as well as poor product quality. An adequate S supply is a major factor in supporting plant protein quality, where it plays a major factor in the structure and function of enzymes and proteins in leafy tissues and seeds. For example, an adequate supply of cysteine plays a central role in giving cereal proteins their shape and functional properties. Because of this, bread baked with low-S wheat will not rise, and results in dense and poorly shaped loaves.

Sulfur Interactions

Because of the importance of both S and N in protein synthesis, these nutrients are intimately linked and are often considered to be co-limiting. It has been established that for every 15 parts of N in protein, there is approximately 1 part of S (i.e., 15:1 ratio of N:S). However this general guide will vary for different crops. For example, wheat grain has an N:S ratio of around 16:1, while the N:S ratio for canola seed is around 6:1.

Other crops such as wheat, sugar beet and peanut are generally considered to have a low S demand. There are many examples of how an adequate supply of both S and N are required to achieve desired yields (**Figure 4**). Sulfur deficiencies in legumes also decrease proper N utilization, since the number of root nodules and the effectiveness of atmospheric N fixation are reduced with low S.

An over-reliance on the N:S ratio for diagnostic purposes

Cysteine: HOOC–CH–CH2––SH
(NH2 on the CH)

Cystine: HOOC–CH–CH2–S–S–CH2––COOH
(NH2 on each CH)

Methionine: CH3–S–CH2–CH2–CH––COOH
(NH2 on the CH)

Figure 2. Three essential S-containing amino acids.

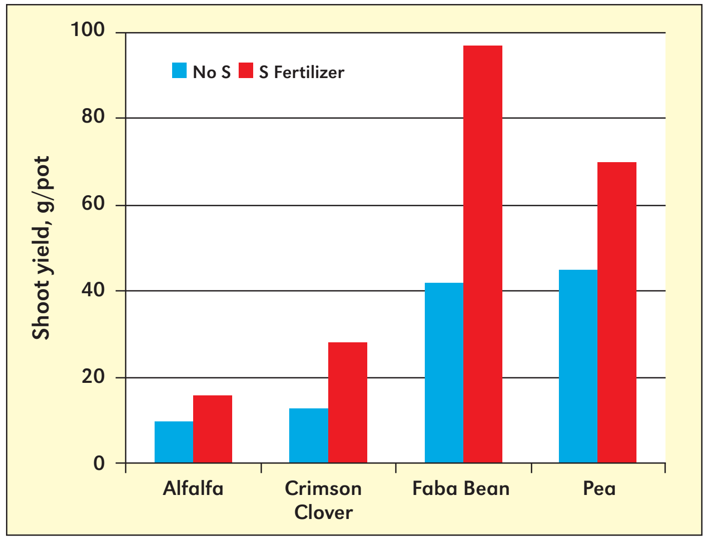


Figure 3. An adequate S supply improves the yield of alfalfa, crimson clover, faba bean, and pea. (Adapted from Lange, 1998).

can be misleading because this ratio can be maintained even when both N and S are both low. Also, an excess of either N or S can be falsely misinterpreted as a deficiency of the other.

An inadequate S supply will not only reduce yield and crop quality, but it will decrease N use efficiency and enhance the risk of N loss to the environment. Studies have demonstrated that supplying S to deficient pastures increased yields, N use efficiency, and lowered N losses from the soil. Due to the close linkage between S and N, Schnug and Haneklaus (2005) estimated that one unit of S deficit to meet plant demand can result in 15 units of N that are potentially lost to the environment. They calculated that S deficiencies in Germany may be contributing to an annual loss of 300 million kg of N (or 10% of the total N fertilizer consumption of the country).

Sulfur fertilization is known to induce Mo deficiency at high application rates. This is due to antagonism between sulfate and molybdate (MoO_4^{2-}) during root uptake as they compete for root membrane transporters. Coincidentally, Mo is an essential component of an enzyme that regulates the formation of organic S. Sulfur and Se (especially selenate, SeO_4^{2-}) are also antagonistic for essentially the same reason. Sulfur fertilization on soils with normally sufficient Se can reduce the pasture Se concentration, with consequences for grazing animals requiring adequate dietary Se. Sulfate additions have been shown to be an effective method of reducing the uptake by plants of

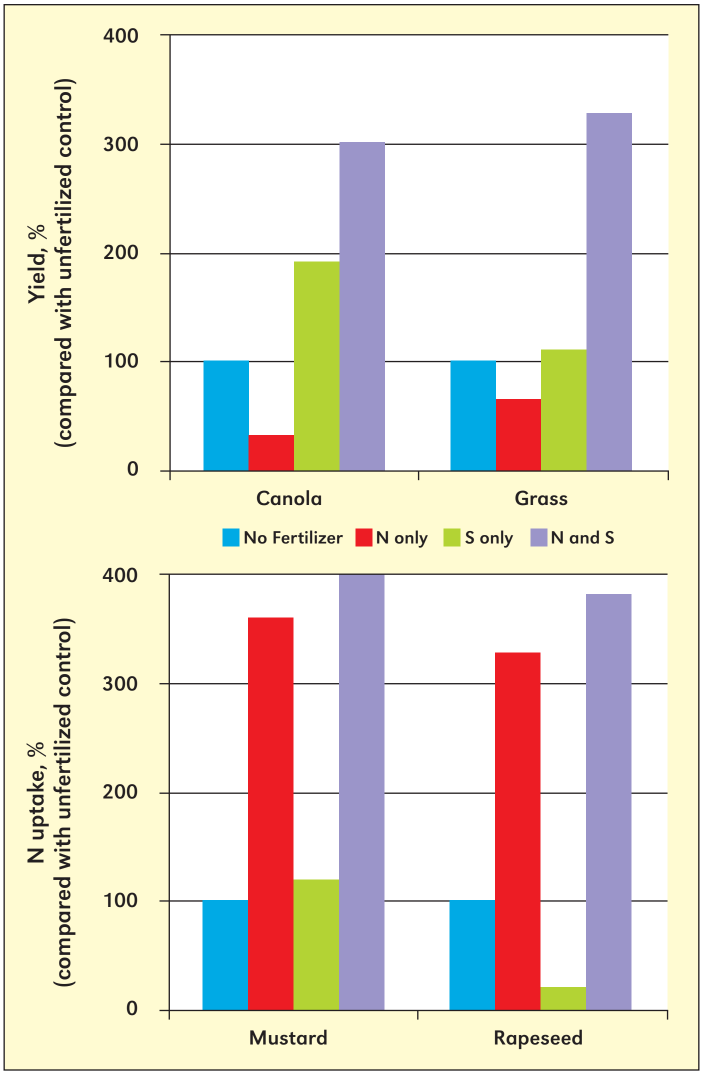


Figure 4. The influence of fertilization with N or S alone, or their combined benefit, on crop yield (top) and plant N uptake (bottom). (Aulakh and Malhi, 2004).

other elements in contaminated soil. However, fertilization with elemental S can stimulate the uptake of metal micronutrients (i.e., Cu, Mn, Zn, Fe, and Ni) due to rhizosphere acidification as S oxidation occurs.

Sulfur Management using the 4R Nutrient Stewardship Principles

The 4R Nutrient Stewardship principles (Right Source of nutrient applied at the Right Rate, Right Time, and Right Place) apply to all plant nutrients. Since S can be supplied from many different sources, including animal manures, the 4R principles help with efficient nutrient delivery. As an example of these 4R concepts, ammonium sulfate [Source] is commonly used in the seed-row [Place] of small-seeded crops at planting [Time], but fertilizer additions [Rate] must be low to reduce the risk of ammonia (NH_3) damage, especially with wide rows and when grown in dry and sandy soils. The following are considerations in applying the 4R Nutrient Stewardship principles to properly supply S for crop nutrition.

SOURCE: Sulfur fertilizers contain either soluble sulfate or a form of S that will be converted to sulfate. An estimate must be made of the time that will be required for conversion of insoluble S to plant-available sulfate. A variety of excellent dry and fluid fertilizers that contain various forms of S are available for blending or direct application. A combination of soluble sulfate and elemental S may be useful to provide both an immediate and a prolonged source of plant nutrition. The particle size of elemental S can be a key property for making this estimate, as smaller S particles tend to oxidize to sulfate more quickly than large particles.

TIME: Sulfate sources of fertilizer can be applied to match the time of crop demand since they are readily available. However elemental S must be applied far enough in advance of the crop need to allow microbial oxidation. In areas with cold winter temperatures, application may need to precede plant uptake by many months. The release of sulfate from soil organic matter and crop residues will proceed more quickly in warm soils and can supply significant amounts of S during the growing season. A constant supply of soluble sulfate is required by most plants.

PLACE: Placement of sulfate fertilizers in a band near the seed row of annual crops can be quite effective. However, avoid large amounts of sulfate in direct contact with seedlings to avoid osmotic damage to roots. Since sulfate is fairly mobile in soil, it will tend to move with water through the root zone. Elemental S is most effective when broadcast onto the soil and tilled into the ground. In flooded soils, elemental S is best left at the surface so it can be converted to sulfate in the thin aerobic zone at the soil-water interface.

RATE: Sulfur application rates should be adjusted for the crop demand, soil conditions (such as soil texture and organic matter content), and environmental factors (such as temperature and rainfall). Sulfur applications are commonly adjusted to account for multi-year crop rotations. For example in a canola-barley-wheat rotation in Western Canada, the high S demand by canola can be met with a single S application to supply nutrition over the three-year cycle.

An adequate supply of S is required for sustaining crop yields and quality. Inadequate S will reduce protein synthesis and will result in poor utilization of applied N and reduced N_2 fixation by legumes. Application of the 4R Nutrient Stewardship principles will identify the need for supplemental S to overcome potential limitations to plant nutrition. BC

Dr. Norton is Director, IPNI Australia & New Zealand Region; e-mail: rnorton@ipni.net; Dr. Mikkelsen is Director, IPNI Western North America Region; e-mail: rmikkelsen@ipni.net; Dr. Jensen is Director, Northern Great Plains Region; e-mail: tjensen@ipni.net.

References

Aulakh, M.S. and S.S. Malhi. 2004. *In* A.R. Mosier, J.K. Syers, and J.R. Freney (eds.) Agriculture and the nitrogen cycle: Assessing the impacts of fertilizer use on Food production and the environment. pp. 181-191. Scope no. 65. Island Press, Washington, USA.

Hawkesford M., 2012. *In* L.J. De Kok et al. (eds.) Sulfur metabolism in plants: Mechanisms and application to food security, and responses to climate change. Proc. Int Plant S Workshop, Springer Netherlands, pp.11-24.

Lange, A. 1998. *Cited In* S. Haneklaus, E. Bloem, and E. Schnug. 2007. *In* M.J. Hawkesford (ed.) Sulfur in Plants: An ecological perspective. Springer, pp.17-59.

National Land and Water Resources Audit. 2001. Commonwealth of Australia, Canberra. p.290.

Schnug, E. and S. Haneklaus 2005. *In* L.J. de Kok and E. Schnug (eds.) Proc. First Sino-German workshop on aspects of sulfur nutrition of plants. Braunschweig, Federal Agricultural Research Centre (FAL), p.131.

Sharma, M.J. and P. Kumar. 2011. IPNI, Norcross, GA, USA and CIMMYT, El Batan, Mexico. p. 50.

Sulfur Management for Optimizing Oilseed and Pulse Production in Rain-fed Jharkhand

By Surendra Singh and A.K. Sarkar

Sulfur (S) deficiency in Indian soils is increasing due to extensive use of S-free fertilizers coupled with the increasing area under high S demanding crops such as oilseeds and pulses. On-farm experiments conducted on rain-fed upland soils of Jharkhand showed that S application could improve yield and quality of these crops. Significant direct and residual effects of S application on crop yields were found in mustard-black gram and groundnut-mustard cropping systems. Sulfur application was beneficial over existing recommendations that omit S for niger, mustard, groundnut, black gram, lentil, and soybean.

The state of Jharkhand, with an area of 795,000 ha, forms part of agro-climatic zone VII (Eastern plateau and hill region) of India. Of the total net sown area, 90% is rain-fed. Upland rain-fed soils are Alfisols, acidic in reaction, low in base saturation, high in P fixation capacity, poor in OM content and poor in water and nutrient retention capacities. Oilseeds and pulses grown on these soils have low average yields (less than 300 kg/ha).

A systematic evaluation of soil available S status was initiated in this region during the early 1990s. The S fertility status of oilseed- and pulse-growing areas were rated as low, which seemed to be one of the main causes of low productivity and quality in these crops. Analysis of a large number of surface samples revealed S deficiency in more than 50% of Jharkhand soils (Singh et al., 2000). The major reasons for S deficiency in these soils are: i) coarse-texture with low OM content, ii) leaching and erosion, iii) imbalanced use of S-free fertilizers, and iv) deficit application of S fertilizers in all crops, but mainly in oilseeds and pulses.

Field experiments on oilseed and pulse crop responses to S application were conducted in Dumka (sub-zone IV), Ranchi (sub-zone V), and East Singhbhum (sub-zone VI) districts of Jharkhand in *Kharif* and *Rabi* seasons from 1995 to 2006. Soils had pH values ranging from 5.5 to 6.4, OC from 0.26 to 0.47%, and soil available S (extracted with 0.15% $CaCl_2$) from 8.8 to 17.6 kg/ha.

Gypsum, phosphogypsum (PG) and single superphosphate (SSP) were evaluated as S sources. Gypsum contained 13% S, PG 15% S, and SSP contained 12% S plus 16% water-soluble P. Whenever SSP was used as S source, the P rate was adjusted accordingly. All sources were applied basally at the time of sowing and mixed uniformly with the soil. Recommended rates of N, P and K were applied to each crop as urea, triple superphosphate and potassium chloride (KCl). Rates of N, P, K and S applied to each crop are given in **Table 1**.

Table 1. Locations and nutrient application rates in major oilseed and pulse crops of Jharkhand.

		Rates of nutrient application, kg/ha			
Locations	Crops	N	P	K	S
Dumka (sub-zone IV)	Niger	20	20	20	15-60
Ranchi (sub-zone V)	Mustard	40	20	20	20-80
Ranchi (sub-zone V)	Groundnut	25	50	20	20-60
Ranchi (sub-zone V)	Black gram	20	40	20	12-36
East Singhbhum (sub-zone VI)	Lentil	20	40	20	10-40
East Singhbhum (sub-zone VI)	Soybean	20	60	20	20-60

Sulfur deficiency symptoms visible on groundnut (top) and black gram (right), which are initially expressed on the young, upper leaves that turn a pale green to yellow color.

Variable response to applied S was found in three oilseed and pulse crops compared to the NPK fertilizer recommendation (**Table 2**). Among oilseeds, niger grain, mustard grain

Table 2. Response of sulfur application to major oilseed and pulse crops of Jharkhand.

Crops	S sources	S rate, kg/ha	Yield with NPK, kg/ha	Yield with NPK + S, kg/ha	Response, %	Critical difference (p=0.05)
Oilseeds						
Niger	PG[1]	45	330	460	40	59
Mustard	PG	60	1,200	1,500	26	26
Pulses/legumes						
Groundnut	Gypsum	40	2,350	3,000	28	94
Black gram	PG	24	973	1,212	24	52
Lentil	PG	30	1,490	1,750	17	50
Soybean	PG	60	1,210	1,720	42	80

[1]PG = phosphogypsum
Sources: Singh et al., 2000; Singh and Singh, 1996; Singh et al., 1998; Singh et al., 2006.

Abbreviations and notes: N = nitrogen; P = phosphorus; K = potassium; OM = organic matter; OC = organic carbon; Kharif = rainy season; Rabi = dry season; ₹ = Indian rupee (US$1 = ₹54.17).

Table 3. Direct and residual effect of sulfur in oilseed-based cropping systems of Jharkhand.

			Yield, kg/ha					
			Direct			Residual		
Cropping systems	S source	S rate, kg/ha	With NPK and S	With NPK	Response, %	With NPK and S	With NPK	Response, %
Mustard-black gram	PG[1]	60	1,520	1,280	19	1,080	880	23
Critical difference (p=0.05)				41			26	
Groundnut-mustard	SSP	45	1,510	1,290	17	1,040	800	30
Critical difference (p=0.05)				65			93	

[1]PG = phosphogypsum; SSP = single superphosphate.

Table 4. Effect of sulfur on quality of oilseed and pulse crops of Jharkhand.

			Quality parameters, %			
Crops	S rate, kg/ha	Content	With N, P and K	With N, P, K and S	Response, %	Critical difference (p=0.05)
Niger	60	Oil	39	44	11	0.9
Mustard	80	Oil	38	41	7	0.6
Groundnut	40	Oil	36	40	11	0.4
Black gram	36	Protein	15	18	14	0.2
Lentil	40	Protein	17	18	6	0.3
Soybean	60	Protein	35	37	6	1.4

Table 5. Economics of sulfur application in oilseeds and pulses of Jharkhand.

Crop	S rate, kg/ha	S response, kg/kg	S response, ₹/ha	Value: cost ratio	Benefit: cost ratio
Niger	45	2.9	67	9.2	8.2
Mustard	60	9.0	165	22.6	21.6
Groundnut	40	16.3	342	46.9	45.9
Black gram	24	10.0	275	37.6	36.6
Lentil	30	8.7	256	35.0	34.0
Soybean	60	8.5	189	25.8	24.8

Prices/costs per kg were: ₹23.2 (niger), ₹18.3 (mustard), ₹21 (groundnut), ₹27.6 (black gram), ₹29.5 (lentil), ₹22.5 (soybean); ₹7.3/kg S in gypsum/phosphogypsum.

and groundnut pod yields were significantly increased by 130 (40%), 300 (26%) and 650 (28%) kg/ha with added S levels of 45, 40 and 60 kg/ha, respectively, over the recommended rate of NPK application. Similarly among pulses, application of 24, 30 and 60 kg S/ha significantly increased black gram, lentil and soybean yields by 239 (24%), 260 (17%) and 510 (42%) kg/ha. Since these fields were deficient in available S status (less than 10 kg/ha), an increase in crop yield may be expected due to external application of S.

Results on direct and residual effects of S sources are presented in **Table 3**. In general, application of S benefits more than one crop grown in sequence and produces a significant residual response. Residual response depends on rate of S application, nature of S source, and the crop being grown. Data of two field experiments revealed significant direct and residual response of added S in mustard–black gram and groundnut–mustard cropping systems. Application of 60 kg S/ha as PG significantly increased mustard grain yield by 240 kg/ha and that of the succeeding black gram crop by 200 kg/ha. Application of 45 kg S/ha added through SSP also significantly increased the yield of groundnut pods by 220 kg/ha, and the yield of the succeeding mustard grown on residual S increased by 240 kg/ha. For both cropping systems, the direct effect of S application contributed about 17 to 19% more yield while crops grown on residual S showed a greater response that ranged between 23 to 30%.

Sulfur applied to these low S soils not only increased crop yields, but also affected crop quality such as oil content of oilseeds and protein content of pulses (**Table 4**). As S is an important constituent of some essential amino acids (e.g., cysteine, cystine and methionine), soil S deficiency can lower protein quality. Cruciferous crops contain S in secondary plant substances such as oils, whose synthesis is inhibited in S deficient soil. Application of S through gypsum and PG resulted in a significant increase of oil content in niger (11%), mustard (7%) and groundnut (11%); and also a significant increase in protein content in black gram (14%), lentil (6%) and soybean (6%).

Data in **Table 5** provides the value-to-cost ratios (VCR) for S application, which are indicators of gross return. The rate of net return (benefit-to-cost ratio or BCR) is calculated by subtracting 1 from the VCR. The rate of return from S application varied between crops and was generally higher in the groundnut, black gram and lentil crops that required less S (between 24 and 40 kg/ha) compared to the niger, mustard and soybean crops that required 45 to 60 kg S/ha. The highest BCR of 45.9 was obtained in groundnut.

Conclusions

It is recommended that the S-deficient, rain-fed upland soils of Jharkhand should receive S application through gypsum, PG or SSP along with the recommended rates of N, P and K fertilizers. The economic optimum S rate was found to be 40 to 80 kg S/ha for the major oilseeds and 24 to 40 kg S/ha for pulse crops that are extensively grown within the region. BC

Dr. Singh is Professor and Head, Department of Soil Science and Agricultural Chemistry, Institute of Agricultural Sciences Banaras Hindu University, Varanasi, India, e-mail: ssinghssac@yahoo.co.in Dr. Sarkar is the Retired University Professor and Dean, Faculty of Agriculture, Birsa Agricultural University, Ranchi, India; e-mail: aksarkarranchi@gmail.com.

References

Sarkar, A.K., S. Singh, and P.B. Saha. 2000. TSI/FAI/JFA, New Delhi pp 65-72.
Singh, R.N., S. Singh, and B. Kumar. 2006. J. Indian. Soc. Soil. Sci. 54: 516-518.
Singh, S., A.K. Sarkar, and K.P. Singh. 2000. SSAC (BAU) Res. Bull No. 1/2000.
Singh, S. and K.P. Singh. 1996. J. Indian. Soc. Soil. Sci. 44: 695-697.
Singh, S, K.P Singh, and A.K. Sarkar. 1998. J. Res. (BAU), 10 : 131-134.
Singh, S., K.P. Singh, A.K. Sarkar, and S.K. Singh.1998. Indian J. Ag. Sci, 68: 341-343.
Singh, S., K.P. Singh, S.K. Singh, and G. Kumar. 1998. J. Indian. Soc. Soil. Sci. 46: 257-260.
Singh, S. S.K. Sinha, R.N. Singh, P.B. Saha, and B.P. Gupta. 2000. J. Indian. Soc. Soil. Sci. 48: 121-124.

Nutrient Management for High Yield Cotton in Brazil

By Eros Francisco and Haroldo Hoogerheide

Guidelines to interpreting analysis data and recommended fertilization practices are outlined for this unique cotton production center located within the Brazilian Cerrado.

Brazil's cotton production has seen large changes over the last four decades. During the 1980s, cotton production in Brazil was severely affected by the introduction of the boll weevil pest. Strong subsidies for foreign cotton also brought down internal demand for domestic lint. Those two factors, together with low technology adoption by growers, caused a drastic decline of cultivated land within the traditional growing regions of the Northeastern and Southern states. In the second half of the 1990s, cotton production migrated to the Cerrado, a vast tropical savanna eco-region of Brazil, where soybean growers sought an alternative crop for their rotation. Climate conditions, flat lands, domestic subsidies, and high technology adoption drove cotton production forward into a period of increasing yields and good lint quality making the cropping system competitive. In 2010, Brazil was the fifth largest cotton lint producer after China, India, United States, and Pakistan followed closely by Uzbekistan (FAO, 2012). Today, the states of Mato Grosso and Bahia represent 81% of Brazil´s total lint production of 1.88 M t. Brazil´s cotton production now occurs on a fourth of the cultivated area it did in the late 1970s, but total production has more than doubled while yield is over 10 times greater (**Figure 1**).

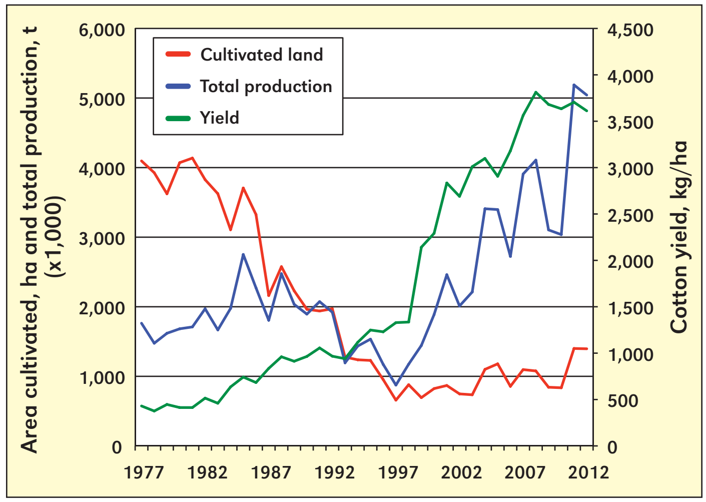


Figure 1. Cultivated land, total production and cotton yield in Brazil from 1977-2012 (Conab, 2012).

Table 1. Guidelines for interpretation of soil analysis for P and K in the Cerrado.

Interpretation class	P level: Soil clay content, g/kg <150	160-350	360-600	>600	K level: CEC <40 $mmol_c/dm^3$	CEC >40 $mmol_c/dm^3$
	mg/dm^3					
Very low	0-6	0-5	0-3	0-2	-	-
Low	6.1-12	5.1-10	3.1-5	2.1-3	<15	<25
Medium	12.1-18	10.1-15	5.1-8	3.1-4	16-30	26-50
Optimum	18.1-25	15.1-20	8.1-12	4.1-6	31-40	51-80
High	>25	>20	>12	>6	>40	>80

P and K extracted with Mehlich1.
Source: Souza and Lobato (2004).

Table 2. Guidelines for interpretation of soil analysis for other nutrients in the Cerrado.

Interpretation class	Mg $mmol_c/dm^3$	S	B	Cu	Mn	Zn
		mg/dm^3				
Low	<5	≤4	0-0.2	0-0.4	0-1.9	0-1.0
Medium	5-10	5-9	0.3-0.5	0.5-0.8	2.0-5.0	1.1-1.6
High	>10	≥10	>0.5	>0.8	>5.0	>1.6

S level should be an average of the top 0 to 0.4 m soil layer.
Mg extracted with KCl 1 mol/L; S extracted with $Ca(H_2PO_4)$; B extracted with hot water; Cu, Mn and Zn extracted with Mehlich 1.
Source: Souza and Lobato (2004).

Cotton production systems in Brazil are very diverse. In Mato Grosso, growers are sowing cotton as a second crop after soybeans. This means the crop will grow during a period of shortened water supply (autumn) that favors fiber quality (no rain at harvesting) but it will also be more susceptible to failures in soil management practice. Cotton growers from Bahia sow their fields during the summer due to the rainfall concentration of this period which is adequate for plant growth. These situations permit the use of different nutrient rates and sources, as will be discussed later, and means that a wide range in fertilizer application rates is found in these regions.

Soil Analysis Guidelines

Guidelines for the interpretation of soil P, K and other nutrients specific to Cerrado soils are provided in **Tables 1 and 2**. As a general recommendation, cotton growers should maintain soil levels for nutrients within the optimum ranges, thus preventing deficiencies or excesses, since both limit yield and fiber quality.

Leaf Analysis Guidelines

Guidelines used for interpretation of leaf analysis are provided in **Table 3**. Cotton fertilization programs should also be adjusted so that the leaf nutrient concentrations are maintained within the optimum range.

Abbreviations and notes: N = nitrogen; P = phosphorus; K = potassium; S = sulfur; Ca = calcium; Mg = magnesium; C = carbon; Al = aluminum; OM = organic matter; CEC = cation exchange capacity.

Table 3. Guidelines for interpretation of cotton leaf analysis for regular and high yield production systems.

Production system	N	P	K	Ca	Mg	S
	- - - Macronutrients - - -					
	- - - g/kg - - -					
Regular	35-43	2.5-4	15-25	20-35	3-8	4-8
High yield	40-45	3-4	20-25	25-35	4-8	4-6
	- - - Micronutrients - - -					
	B	Cu	Fe	Mn	Mo	Zn
	- - - mg/kg - - -					
Regular	30-50	5-25	40-250	25-300	0.5-1	25-200
High yield	40-80	8-15	70-250	35-80	1-3	30-65

Cotton leaf diagnosis is the fifth from the top at maximum blooming.
Source: Carvalho et al. (2007).

Soil Liming

Soil acidity is the major factor causing low cotton yields due to cotton's high sensitivity to Al toxicity. Also, low levels of Ca, Mg and the short availability of other nutrients such as P can affect cotton production. The goal of liming is to raise the base saturation to 60% in the topsoil (0 to 0.2 m layer), which generally brings Al availability down to zero in most Cerrado soils. It is also recommended to manage lime application so the level of Mg in the soil is raised and maintained to a minimum of 7, or ideally 10 $mmol_c/dm^3$ (Carvalho et al., 2007).

The evaluation of soil acidity should be a routine practice within a cotton fertilization program due to the continued use of acidifying N fertilizers. **Table 4** provides a comparison between the original chemical condition of a typical Cerrado soil and two current Cerrado soils under high yield cotton.

One important detail in these examples is the level of Al in the top 0 to 0.4 m layer for both situations: zero. This is crucial for any attempt to achieve high cotton yield along with avoidance of soil compaction, which reduces root growth preventing water and nutrient uptake.

Fertilizer Application

The recommendations of N, P and K fertilizer rates for cotton are based on yield expectation and soil analysis (**Table 5**) and may vary widely depending on different conditions. Nitrogen is a nutrient taken up in large amount by cotton, which depending upon the climate, cultivar, yield, soil conditions, and fertilizer rates can use 125 to 210 kg of N per tonne of lint produced (Carvalho et al., 2007). Due to its high mobility and dynamics in soil, farmers in the Cerrado have to take texture, OM content, crop rotation, and soil management into consideration to define the right N rate to be applied. In clay soils with high OM content (25 to 35 g/kg) under crop rotation and no-tillage, cotton will not be as responsive to N rate as it is in sandy soils low in OM (15 to 25 g/kg) or under annual tillage. The type of crop preceding cotton also matters to efficiently manage N fertilization (e.g., pasture or grasses with high C:N ratio may cause N immobilization during the early stages of cotton). Zancanaro and Tessaro (2006) suggest that N rates are managed as: 10 to 25 kg N/ha at planting as starter (in-furrow), 40% of recommended N rate at first square, and 60% at first flower (broadcast).

Initial K deficiency symptoms on a high yield cotton field.

Phosphorus application is necessary to achieve high cotton yields. In soils low in P, the response of cotton to P application may exceed the effect of other nutrients. In some Cerrado soils, P fixation is extreme and creates a strong competition between the soil and the plant, therefore liming becomes a best management practice to increase P availability and promote an efficient use by plants. Despite the intense response of cotton to P application, recent research has shown that in well-managed soils high in P, yield was not increased when P rates exceeded 100 kg P_2O_5/ha (Carvalho et al., 2007). Zancanaro and Tessaro (2006) also describe research results in clay soils high in P where no response was observed with P rates higher than 80 to 100 kg P_2O_5/ha and recommend the application of 60 to 70 kg P_2O_5/ha as sufficient to maintain soil fertility and high yields. Regularly, P application is made at planting time (in-furrow).

A very large amount of K is taken up by cotton. For high yields, the total uptake may reach 175 to 200 kg K_2O/ha per tonne of lint produced (Ferreira et al., 2004). Therefore, K application is the heart of the fertilizer management program

Table 4. Original and current soil chemical conditions in high yield cotton production systems in the Cerrado.

Depth	pH	OM	P†	K	Ca	Mg	Al	H	CEC	BS	Al‡
cm	$CaCl_2$	g/kg	mg/dm^3		- - - $cmol_c/dm^3$ - - -					%	
- - - Original (uncultivated) Cerrado, 17% clay - - -											
0 - 10	3.8	14	1.4	19	0.2	0.2	0.8	3.5	4.7	10	63
10 - 20	3.9	9	1.1	15	0.2	0.2	0.6	2.7	3.7	12	58
20 - 30	4.0	7	0.8	12	0.2	0.1	0.6	2.0	2.9	11	64
30 - 40	4.1	6	0.6	9	0.1	0.1	0.5	1.8	2.5	9	69
- - - Current conditions – site A, 17% clay - - -											
0 - 10	5.9	12	42	31	2.2	0.8	0.0	1.0	4.1	76	0
10 - 20	5.8	9	24	27	2.0	0.7	0.0	0.9	3.7	75	0
20 - 30	5.7	8	9	23	1.6	0.6	0.0	1.1	3.4	67	0
30 - 40	5.7	5	6	20	1.5	0.5	0.0	0.8	2.9	72	0
- - - Current conditions – site B, 42% clay - - -											
0 - 10	5.3	33	22	62	3.0	1.1	0.0	3.6	7.8	55	0
10 - 20	5.3	33	18	59	2.9	1.1	0.0	3.5	7.6	54	0
20 - 30	5.1	31	15	55	2.3	0.9	0.0	4.0	7.4	46	0
30 - 40	4.7	22	8	47	1.4	0.6	0.2	3.6	5.9	36	9

Soil conditions: (i) original Cerrado and site A: cotton field of a farm located in the state of Bahia, northeast region of Brazil; (ii) site B: cotton field of a farm located in the state of Mato Grosso, midwest region of Brazil.
† P-Mehlich 1.
‡ Al saturation.

Table 5. Fertilizer recommendations for cotton in the Cerrado, based on soil analysis and yield expectation.

Yield expectation[1]	N In-furrow	N Broadcast	Soil P Optimum	Soil P High[4]	Soil K Very low	Soil K Low	Soil K Medium	Soil K Optimum	Soil K High[4]
kg/ha	N, kg/ha		P_2O_5, kg/ha		K_2O, kg/ha				
3,000	15-20	60-80[3]	60	30	130	100	80	60	30
4,000	15-20	80-100	90	45	150-170	120-140	100-120	80	40
5,000[2]	15-20	100-120	110	55	170-190	140-160	120-140	100	50
6,000[2]	15-20	120-140	135	70	190-210	160-180	140-160	120	60

[1] Based on the highest attainable yield of the region or field with similar conditions of soil, cultivar and management practices.
[2] Less likely to obtain in areas with soil fertility under construction or precipitation under 1,200 mm on the first 160 days of the plant.
[3] Highest rates refer to areas with high potential yield response to N: low OM content; first year of no-till after grass crop. Lowest rates refer to areas with low potential yield response: crop rotation with legumes; several seasons of no-till and high OM content.
[4] On high P and K soil levels fertilization may be reduced or suppressed in years of high input:product ratio.

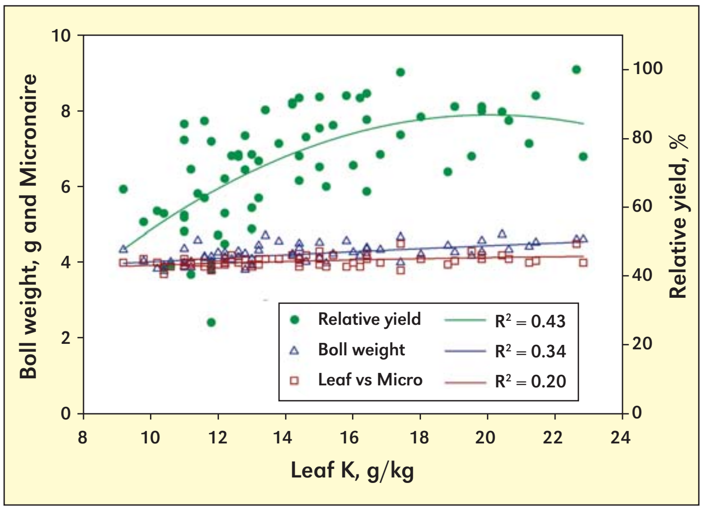


Figure 2. Response of cotton relative yield, boll weight and micronaire in relation to leaf K content (Francisco et al., 2011).

of any cotton production system in Brazil. Visual symptoms of K deficiency in cotton are: initial yellowing in between the veins of old leaves that will later develop brown spots, with the tips and margins showing a scorched appearance, and eventually turning reddish-brow and eventually falling off the plant. However, in modern cultivars with high yield potential and a short period of boll filling the intensity of K translocation in the plant is such that regular symptoms begin to show up on new mature leaves at the top of the plant.

Potassium recommendation may vary from 30 to 210 kg K_2O/ha depending on soil level and yield expectation (**Table 5**). Research has shown yield response with the application of 180 kg K_2O/ha in a soil low in K (30 mg/dm^3) and no response to the application of 60 kg K_2O/ha in a soil high in K (90 mg/dm^3). But caution is required regarding K leaching—especially in sandy soils. Carvalho et al. (2007) report results of a soil with 83% sand and CEC of 34 mmol$_c$/kg where only 66 mg/dm^3 of K was measured after an application of 320 kg K_2O/ha. They also report an increase in K levels at depth. Zancanaro and Tessaro (2006) recommend that K application must be split in sandy soils: 50 kg/ha of K at planting as starter (in-furrow) and the rest in two applications until first flower (broadcast).

In Mato Grosso state, where cotton is being grown as a second crop after soybeans in 60% of the cropped land farmers must keep watch on K status of plants due to the interaction with climate. Typically there is low rainfall during early reproductive stages followed by a total absence at harvesting time. Reeves and Mullins (2002) point out that K plays an important role for micronaire quality and is present at the highest proportion among cations in fiber composition. Therefore, low K status of the plants may severely affect fiber quality and yield. This is shown through the results of Francisco et al. (2011) with a study of K rates for cotton grown in a clay soil low in K and under the same condition described above (low rainfall during reproductive stages). **Figure 2** presents the relationship between leaf K content and relative yield, boll weight and micronaire. In all cases, a positive effect of better plant K status is observed.

Sulfur application generally occurs along with N or P fertilizers such as ammonium sulfate (22 to 24% S) and single superphosphate (10 to 12% S), or by the annual use of phosphogypsum at 400 to 600 kg/ha. But this management has become a challenge for growers since prices of ammonium sulfate and phosphogypsum have increased and the use of higher content P fertilizers, such as triple supherphosphate or monoammonium phosphate, has been preferred to reduce the time required to seed fields. The use of new phosphate fertilizers with high P and some S content is currently being evaluated and is being promoted for its convenience.

Boron is the only micronutrient applied regularly in cotton at rates ranging from 1.5 to 3.0 kg B/ha, generally as a soil application at planting. BC

Dr. Francisco is Deputy Director for the Midwest Region, IPNI Brazil Program, Rondonópolis, Mato Grosso; e-mail: efrancisco@ipni.net. Dr. Hoogerheide is Soil and Plant Nutrition Specialist in Sinop, Mato Grosso; e-mail: haroldoch@gmail.com.

References

Carvalho, M.C.S., G.B. Ferreira, and L.A. Staut. 2007. *In* Nutrição, calagem e adubação do algodoeiro, E.C. Freire, (ed). pp. 581-648. Brasília, DF: Abrapa.

Conab. 2012. Acompanhamento da safra brasileira: grãos. Accessed on-line on February 2012.

FAO. 2012. Food and Agricultural Commodities Production. Accessed on-line on February 2012.

Ferreira, G.B., L.S. Severino, J.L. Silva Filho, and M.B. Pedrosa. 2004. *In* Resultados de pesquisa com a cultura do algodão no Oeste e Sudoeste da Bahia, safra 2003/2004, Embrapa (ed). pp. 80-106. Campina Grande: Embrapa Algodão.

Francisco, E.A.B., L. Zancanaro, and C. Kappes. 2011. *In* Adubação nitrogenada, fosfatada e potássica na cultura do algodoeiro em sistema de cultivo adensado. Research Foundation MT, 2011. Internal Report.

Reeves, G. and G.L. Mullins. 2002. *In* Beltwide Cotton Conference. Atlanta-GA, 2002.

Sousa, D.M.G. and E. Lobato. 2004. Cerrado: correção do solo e adubação. Brasília, DF: Embrapa.

Zancanaro, L. and L.C. Tessaro. 2006. *In* Calagem e adubação, Facual (ed). pp. 57-81. Cuiabá, MT: Facual.

Nitrogen Management for High Population Corn Production in Wide and Narrow Rows

By Carl R. Crozier, Ronald J. Gehl, David H. Hardy and Ronnie W. Heiniger

A 3-year study of corn planted in wide and narrow rows in North Carolina found grain yields were significantly higher with narrow rows and side-dress N application than with other row width and timing combinations. The 19% grain yield increase in response to applications of N fertilizer could be attributed to changes in ear yield components: kernels per row increased by 17%, mean kernel weight increased by 8%, and rows per ear increased by 3% due to N application.

While corn plant population guidelines published in 1988 suggested 20,250/A rainfed or 24,300/A if irrigated (Olson and Sander, 1988), more recent studies have found advantages with higher populations up to 37,700/A (Novacek et al., 2013). Transitions to higher plant populations are sometimes associated with narrower row spacings in an effort to minimize intra-row competition. Planting in narrower rows complicates field accessibility and thus side-dress N application. The objectives of our research were to determine the optimum N timing and rate in high population corn production systems. Corn yield response and yield components (rows per ear, kernels per row, and kernel size) were compared among wide row (30- to 40-in.) and narrow row (15- to 20-in.) corn.

A series of 13 N fertilizer response experiments with corn for grain were conducted on Tidewater, Coastal Plain, Piedmont, and Mountain region sites in North Carolina. A starter band application of 6 lb N/A (5 gpa of 11-37-0) was applied to all plots in all experiments except the site in Perquimans Co 2011, which had already received 50 lb N/A broadcast uniformly. Check plots (0 N) and a range of N fertilizer rates (40, 80, 120, 160, and 200 lb N/A) were applied either at planting or at side-dress (between V-5 and V-7 stage) to both wide- and narrow-row corn plots. Seed densities and row spacings are shown in **Table 1**. Optimum populations vary across the state, and our "high population" targets represent 1.5 times the previous density recommended in North Carolina (Heiniger, 2004).

A split-plot experimental design was used, with row width as the main plot. Planters were adjusted to achieve approximately the same target population in both wide and narrow row configuration. The subplot factor was N management (rate and timing). Plot sizes varied depending on the planter arrangement, but subplots measured 3 to 4 wide-rows or 6 to 8 narrow rows in width, and at least 30 ft. in length. Corn grain yield was measured by hand harvesting 20 row ft. for wide rows and 40 row ft. for narrow rows, with shelling and adjustment to 15.5% moisture. Yield components were determined from plant and ear counts of the entire harvested segments, and from 5-ear samples for which rows per ear, kernels per row, and mean kernel weight were determined. For pooling across environments (site-years), relative grain yield was calculated based on the highest mean yield found at each environment. For each individual site, analysis of variance (ANOVA) was performed using SAS Proc GLM to calculate $LSD_{0.05}$ (or as noted $LSD_{0.1}$) for treatment mean grain yield comparisons. For assessment of factorial N rate x timing effects, check plots were excluded and SAS Proc Mixed was used, with row width, N timing, N rate, and their interactions considered fixed effects; and environment and its interactions considered as random effects.

Abbreviations and notes: N = nitrogen; gpa = gallons per acre. IPNI Project #NC-21.

Corn was planted in wide (40-inch) and narrow (20-inch) row configurations at a Tidewater region experiment.

Table 1. Sites, target populations and row width/seed spacing alternatives.

Region (No. of sites)	County (year)	Target population/A	Narrow row: Row width	Narrow row: Seed spacing	Wide row: Row width	Wide row: Seed spacing
			----------- inches	-----------	-----------	-----------
Tidewater (5)	Pamlico ('10,'11,'12) Tyrrell ('11) Pasquotank ('12)	37,500	20	8.4	40, 36	4.2, 4.6
Coastal Plain (3)	Perquimans ('10, '11,'12)	33,750	20	9.3	40	4.6
Piedmont (2)	Union ('10, '11)	30,000	15	13.9	30	7.0
Mountain (3)	Henderson ('10,'11,'12)	34,500	20	9.1	36	5.0

Grain yields are shown in **Figures 1, 2 and 3** (2010, 2011 and 2012). Substantial differences in residual N levels and degrees of response to N fertilization were noted among sites. **Table 2** identifies experimental treatments that were found to have significant effects on corn yield components or overall grain yields. These include simple main effects, such as response to N rate summarized in **Table 3**, or as interaction effects such as the interaction between row spacing and timing of N application shown in **Table 4**. Additional interaction effects were noted, many with the "environment", which indicates that there were differences in response to the management variables among the different experimental sites and years.

The N rate response data indicate that when

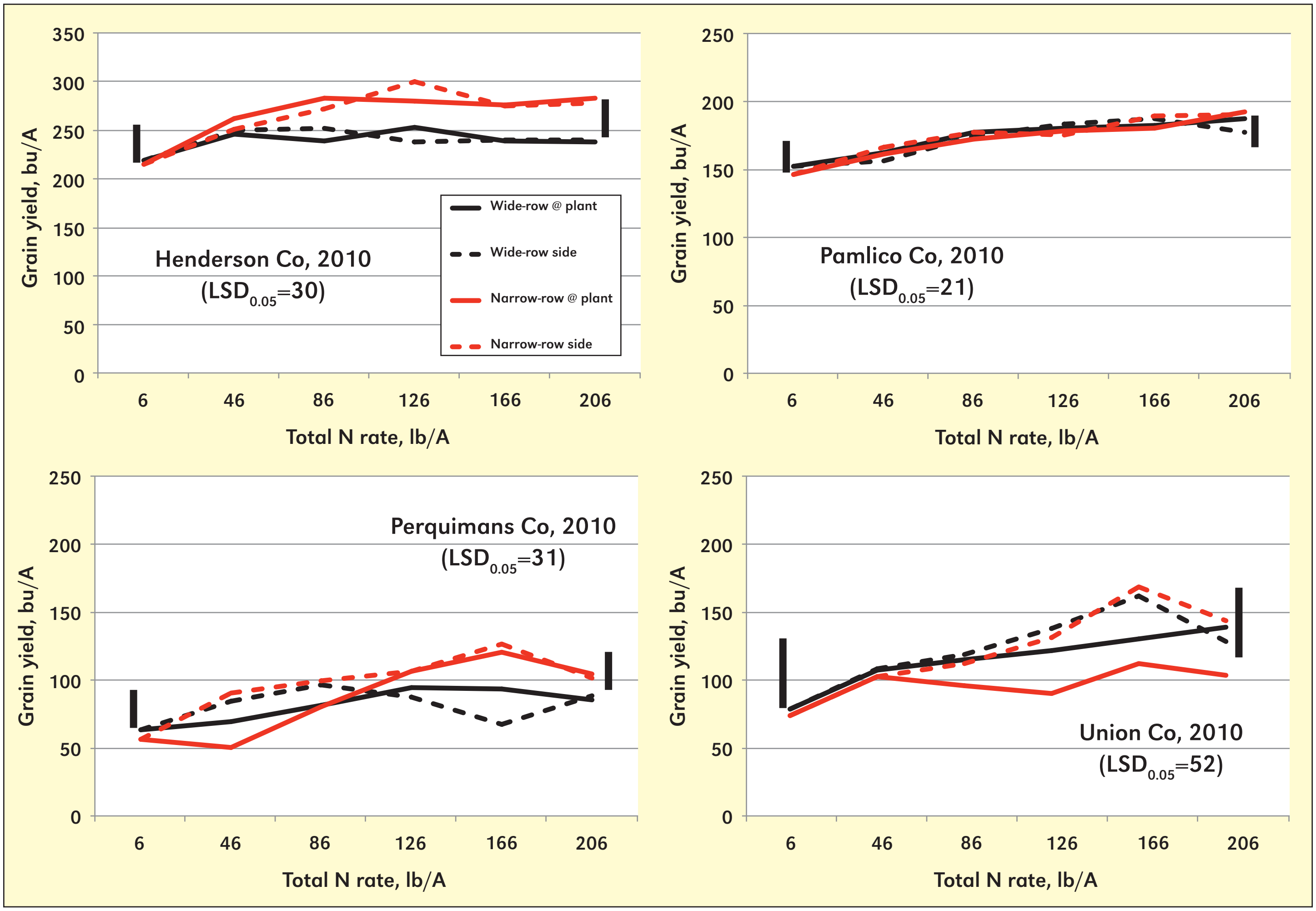


Figure 1. Corn grain yield response to N fertilization in 2010 experiments. Vertical bars represent the least significant difference ($p<0.05$) for comparison of treatment means.

averaged across sites, row spacings, and application timings, grain yield increased 19% above yields with the lowest N rate (**Table 3**). Comparing this yield increase to changes in individual yield components found no contribution by changes in plant density or mean numbers of ears per plant. However, mean numbers of rows per ear increased 3%, mean numbers of kernels per row increased 17%, and mean kernel weight increased 8%. Thus, the yield components determined earliest in

Table 2. Overall analysis of variance (ANOVA) results.

Effect	Plant density	Ear density	Rows per ear	Kernels per row	Kernel weight	Relative yield
Row width (RW)			+			
Timing of N application (Time)				*	*	*
N rate (N)			**	***	***	***
RW x Time				*		*
RW x N						
Time x N		*				
RW x Time x N						
Environment (Env)			***	***	***	**
Env x RW		***		***	**	**
Env x Time		*		+		**
Env x N						*
Env x RW x T			**		*	
Env x RW x N						
Env x T x N			**	+		*
Env x RW x T x N	*					

Statistical significance of each effect is indicated by symbols: +, $p<0.1$; *, $p<0.05$; **, $p<0.01$; ***, $p<0.001$. Absence of symbol indicates no statistical significance, i.e. $p>0.1$.

Table 3. Main effect of N when averaged across row widths, application timing, and all environments[1].

N rate, lb/A	Relative yield, % of max	Rows/ ear	Kernels/ row	Kernel weight, g
6	68	15.46	27.6	0.236
46	72 c	15.59 c	29.6 c	0.236 c
86	79 b	15.72 bc	31.2 b	0.243 b
126	83 ab	15.91 ab	32.0 ab	0.246 b
166	86 a	15.93 a	32.4 a	0.254 a
206	87 a	15.89 ab	32.1 ab	0.255 a
% increase[2]	+19%	+3%	+17%	+8%

[1]The N rate effect was significant for relative yield and all three ear yield components, with means (except for the lowest N rate) within a column not followed by the same letter differing significantly, $p<0.05$. The lowest N rate was not included in the statistical evaluation, which also considered factorial rate x timing effects.
[2]Maximum % increase in comparison with values of the lowest N rate treatment (6 lb N/A).

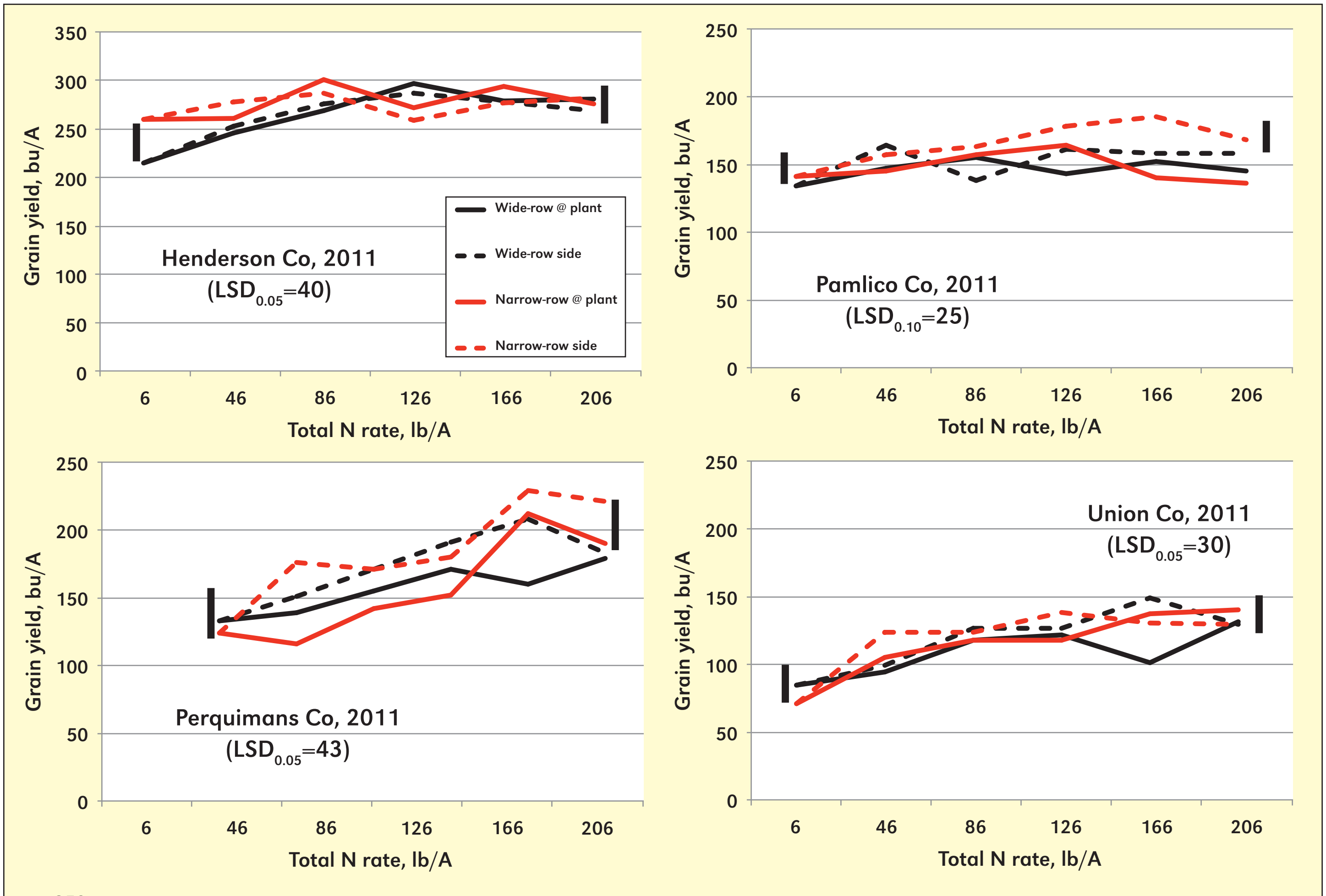
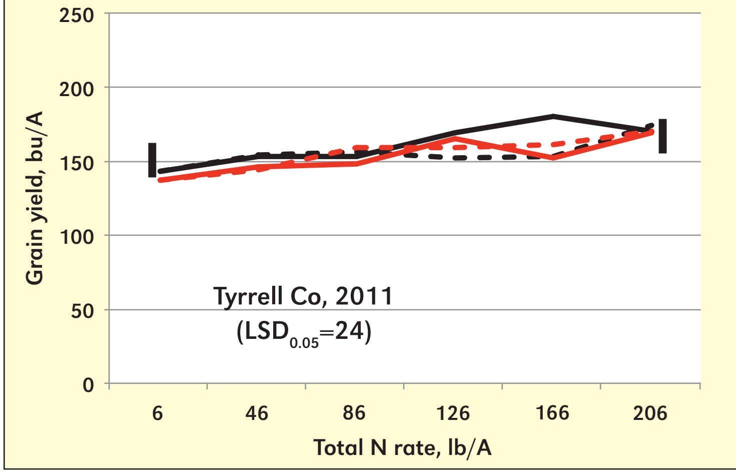



Figure 2. Corn grain yield response to N fertilization in 2011 experiments. Vertical bars represent the least significant difference for comparison of treatment means.

Side-dress N application to corn planted in 20-inch rows.

the season (plant density, ear density, rows per ear) did not appear to vary as much as did the yield components whose value became fixed later in the season (kernels per row and kernel weight).

The row spacing x N timing interaction data demonstrate the importance of later-season N, at least for the narrow row corn (**Table 4**). For narrow row corn, both grain yields and the numbers of kernels per row were greater with side-dress application than with all N at planting; while no such timing effect was evident with the wide rows. When averaged across all sites and N rates, relative grain yields were significantly higher with narrow rows and side-dress N. This is an important interaction to note, since side-dress application is more complicated with narrow row systems and would probably be discouraged without such evidence of increased yield potential.

Table 4. Effect of row width x timing interaction averaged across all environments and N rates[1].

Row width	Timing of N application	Relative yield, % of max	Kernels/ row
Narrow	At plant	79 b[2]	30.3 b
	Side-dress	86 a	31.9 a
Wide	At plant	78 b	31.6 a
	Side-dress	81 b	32.1 a

[1]Lowest N rate excluded to permit evaluation of factorial effects.
[2]Means within a column not followed by the same letter differed significantly, $p<0.05$.

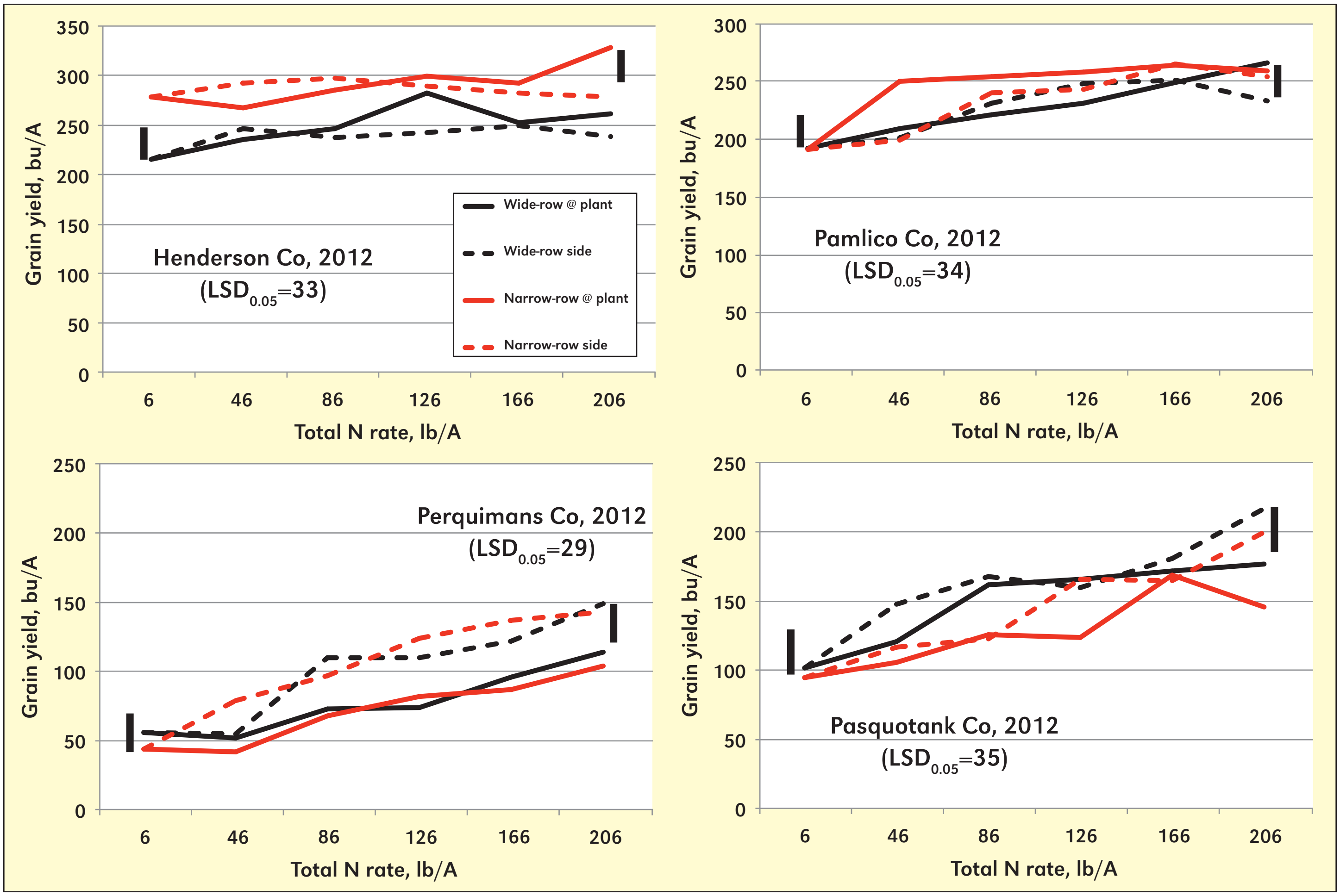


Figure 3. Corn grain yield response to N fertilization in 2012 experiments. Vertical bars represent the least significant difference ($p<0.05$) for comparison of treatment means.

Visually evident N status differences at the 2012 Pasquotank Co. site prior to V-5 side-dress.

Where significant N timing differences were noted (**Table 2**), relative grain yield, kernels/row, and mean kernel weight were all greater with side-dress application than with all N at planting. Current North Carolina recommendations call for 1/4 to 1/3 of the N to be applied at planting, with the remainder at side-dress. This ideal split scenario was not utilized in our experiments due to the already large number of experimental plots and since timing-related effects should be easier to measure given more extreme differences in management.

Summary

Highest grain yields were found with narrow rows and side-dress N applications. For these high population corn production systems, it appears to be critical to maintain sufficient N supply later in the season to contribute to the formation of the later-season ear yield components. Additional N timing and/or N source experiments should lead to the design of improved overall N management programs that reduce stress at all stages of the crop. BC

Acknowledgements

Support from IPNI and from the Corn Growers' Association of North Carolina, Inc. are greatly appreciated.

Dr. Crozier (e-mail: carl_crozier@ncsu.edu) is Professor located in Plymouth, NC and Dr. Gehl is Assistant Professor located in Mills River, NC, Dept. of Soil Science, North Carolina State University. Dr. Heiniger is Professor located in Plymouth, NC, Dept. of Crop Science, North Carolina State University. Dr. Hardy is Chief of the Soil Testing Section of the Agronomic Services Division, North Carolina Dept. of Agriculture and Consumer Services, Raleigh, NC.

References

Heiniger, R.W. 2004. NCSU. http://www.ces.ncsu.edu/plymouth/cropsci/corn-guide/ (verified Mar 4, 2013).

Novacek, M.J., S.C. Mason, T.D. Galusha, and M. Yaseen. 2013. Agron. J. 105:268-276.

Olson, R.A., and D.H. Sander. 1988. *In*, Sprague, G.F. and J.W. Dudley (eds.), Corn and Corn Improvement. 3rd Ed. Agronomy No. 18, ASA, Madison, WI. pp. 639-686.

The Efficiency of Potassium Fertilizer Use in Western Siberia

By Vladimir N. Yakimenko and Vladimir V. Nosov

A brief review shows that application of K fertilizer to cereal crops grown on soils of Western Siberia can contribute to 20 to 30% yield increases. Field experiments conducted in 'cereals-fodder crop' systems suggest a trend towards higher yields due to K application in both first spring wheat or spring barley crops. A significant yield response to K was obtained for second spring wheat and forage crops of maize or oat-pea mixes. Significant increases in carrot and potato yields were observed within the 'vegetable-potato' cropping system even at the lowest K rates.

Recent statistics highlight widespread nutrient depletion within the extensive farming systems of the Siberian Federal District of Russia. Agricultural enterprises only applied about 7 kg N, 2 kg P_2O_5 and less than 1 kg K_2O per hectare of sown area in 2011 (ROSSTAT, 2012). Farmers widely rely on a fallow year to gather plant-available N reserves, which is generated from nitrate (NO_3-N) accumulation through soil OM mineralization. However, this does have negative implications for soil OM reserves and their ability to maintain nutrient supplying power year after year. Crops also rely heavily on a continuous tapping of any available soil P and K reserve. Considering the need to intensify crop production in the Western-Siberian region, while recognizing the regional economic realities, the issues related to the most effective and efficient use of mineral fertilizers, including K fertilizers, seem very important.

Abbreviations and notes: N = nitrogen; P = phosphorus; K = potassium; CEC = cation exchange capacity; OM = organic matter; ppm = parts per million; ppm K_2O x 0.83 = ppm K.

Critical Field Trials

Nowadays, there are practically no field experiments in Western Siberia studying the use of K fertilizer. However, our brief review summarizes results obtained from the most recent critical research conducted in the region (**Table 1**). The highest K response in spring wheat was found on soddy-podzolic soils (Umbric Albeluvisol) because these soils have low plant-available K. The relative grain yield increase due to K ranged between 6 to 28%. The effect of K fertilizer on crop yield was much higher on coarse-textured soddy-podzolic soils, which have the lowest level of plant-available K. Application of K on grey forest soils and dark grey forest soils (Humic Luvisol) increased spring wheat yields by 2 to 11%. On leached chernozems (Luvic Chernozem), K fertilization contributed as much as 16% to grain yields; however, some field experiments conducted on these soils did not show any advantage to K use in cereal crops. Yield of maize grown for green forage on chernozem soils increased by 8 to 10% due to K application. On chernozemic soil, crop response to applied K is highly dependant on the level of plant-available K. Exchangeable K content in chernozems of Western Siberia can be very high at 600 ppm K_2O and above and a response to applied K is unlikely under such conditions, especially in cereal crops.

Long-term studies conducted on

Table 1. Summarized results of field experiments studied the efficiency of K fertilizer use in Western Siberia. Adapted from Yakimenko, 2003.

Soil type/subtype	Crop†	Yield, t/ha 0	NP	+K	Yield increase due to K, %	Reference
Soddy-podzolic (Umbric Albeluvisol)	Wheat	0.41	1.01	1.29	28	Kopotilov, 1980
		1.43	1.85	2.19	18	
		1.30	1.94	2.30	9	Sinyavskiy, 1989; Titova, 2000
		1.53	1.88	2.00	6	
Grey forest (Humic Luvisol)	Wheat	0.65	1.23	1.37	11	Karchevskiy, 1991
Dark Gray Forest (Humic Luvisol)	Wheat	1.50	2.02	2.06	2	Zakharov, 1982
Leached chernozem (Luvic Chernozem)	Oat	1.28	2.06	2.34	14	Zhukova, 1974
	Barley	1.48	1.94	2.25	16	
	Wheat	1.20	1.60	1.86	16	
	Wheat	2.82	3.19	3.13	-2	Guselnikov, 1973
	Forage maize	29.5	39.8	42.8	8	Rusakova, 1981
	Barley	3.09	3.61	3.85	7	
	Wheat	2.70	3.64	3.43	-6	
	Wheat	2.66	2.96	3.09	4	Khurchakova and Ostrovlyanchik, 1988
	White cabbage	47.0	68.9	70.8	3	Almazov and Kholuyako, 1983
	Carrot	41.2	50.6	53.9	7	
	Potato	28.2	32.7	34.1	4	
	Tomato	41.6	46.5	52.8	14	Almazov and Kholuyako, 1994
Southern chernozem (Calcic Chernozem)	Forage maize	21.8	30.2	33.1	10	Altunin et al., 1983

†Spring wheat and spring barley are indicated; yield of green forage is shown for maize.

Table 2. Soil-test interpretation classes for exchangeable K (ppm K_2O) in the forest-steppe zone of Western Siberia. Yakimenko, 2009.

Soil K test level	Soil texture: Light loam	Medium loam	Heavy loam
Low	< 100	< 150	< 200
Unstable	100 - 150	150 - 200	200 - 250
Optimal	150 - 200	200 - 250	250 -300
High	> 200	> 250	> 300

Content of particles <10 μm in light, medium and heavy loams is 20 to 30, 30 to 40, and 40 to 50%, respectively.

grey forest soils revealed that exchangeable K is a better indicator of soil K status compared to routinely measured available K (extracted with acetic acid [CH_3COOH] solution). Exchangeable K better reflects soil K depletion, and also build up, of soil fertility resulting from any K application (Yakimenko, 2009). In addition to the improved soil test interpretation classes for routinely measured available K in the forest-steppe zone; soil test interpretation classes for exchangeable K were also developed in consideration of soil textural classes (**Table 2**).

It is important to note that the majority of fertilizer experiments above have been short-term field trials with spring wheat and vegetable crop rotations (3 to 4 years) without long-term omission of K and hence without considerable soil K depletion. Moreover, crop yield levels were low in many of these experiments resulting in relatively low quantities of nutrients required for crop growth and development. Earlier reviews of fertilizer experiments conducted in forest and forest-steppe zones of Western Siberia indicate that K fertilizer use becomes necessary only when the yield level of cereal crops is higher than 3 t/ha (Gamzikov et al., 1989). A single season field experiment with spring wheat conducted in Omsk Oblast in 2011 on a leached chernozem with very high exchangeable K came to the same conclusion (unpublished IPNI data). There is a relative lack of regional experimental data on the efficiency of K fertilizer within high K demanding crops.

Cropping System Studies

Field experiments conducted from 1988 to 2005 help to answer many important questions regarding the efficiency of K fertilizer use in common cropping systems of Western Siberia. On previously uncultivated grey forest soil with medium loam texture at the surface, an initial exchangeable K level of 145 ppm K_2O, OM content of 4.9%, and CEC of 21 cmol/kg soil (Yakimenko, 2006), field experiments were simultaneously conducted in two experimental areas with different cropping patterns: 1) cereals and fodder crops, and 2) vegetables and potato. Three cycles of the following crop rotation were run at the first experimental area: spring wheat–spring wheat–spring barley–oat/pea (green forage mixture). Spring wheat was then cultivated during two years and maize for silage was grown in the subsequent years. Three cycles of crop rotation with vegetables and potato were similarly run at the second experimental area: white cabbage–tomato–onion–carrot. Then, potato was grown in monoculture till the end of experiment. Field experiments included the following treatments: 1) zero fertilizer (control); 2) NP; 3) NPK_1; 4) NPK_2; 5) NPK_3; 6) NPK_4.

An advantage of residual K during the cropping season of cereals may be taken in Western Siberia if value-to-cost ratios for K fertilizer use are not favorable.

Table 3. Fertilizer rates (kg N, P_2O_5 and K_2O/ha) in field experiments conducted on grey forest soil. Yakimenko, 2003.

Cropping pattern	Crop	N	P	K_1	K_2	K_3	K_4
Cereals and fodder crops	1st spring wheat	90	60	30	-	90	-
	2nd spring wheat	90	60	30	-	90	-
	Spring barley	120	60	39	-	117	-
	Oat + pea	120	60	36	-	108	-
	Maize	180	90	75	-	225	-
Vegetables and potato	White cabbage	200	140	111	222	333	444
	Tomato	120	120	47	94	141	188
	Onion	55	23	25	50	75	100
	Carrot	126	78	64	128	192	256
	Potato	180	60	81	162	243	324

Rates of N and P fertilizers were calculated based on a 100% replenishment of nutrient removal in high yielding crops and four levels of K were applied to replenish K removal by 25, 50, 75, and 100%, respectively. Fertilizer rates for each crop grown under two cropping systems are given in **Table 3**. Fertilizers were applied in spring before sowing or planting of seedlings as ammonium nitrate, triple superphosphate, and potassium chloride (KCl).

The long-term average yield data for the 'cereals-fodder crops' system reveal a trend towards higher yields within the 1st spring wheat and spring barley crops as a result of K fertilization (**Table 4**). A significant yield response in the 2nd wheat crop was obtained when the highest K rate was applied (90 kg K_2O/ha). The highest K rates (108 and 225 kg K_2O/ha) also resulted in a significant increase in green forage yield of both the oat-pea forage mixture and maize.

The experimental data obtained under the 'vegetable-potato' system found a significant yield increase for these high K demanding crops (potato, carrot) even under the lowest K application rates (64 and 81 kg K_2O/ha). Significant yield increases in cabbage, tomato and onion were only obtained with the highest K rates, but practically all K rates provided

Table 4. Crop yields (t/ha) in field experiments conducted on grey forest soil (1988-2005 average). Yakimenko, 2006.

Cropping pattern	Crop†	0	NP	$+K_1$	$+K_2$	$+K_3$	$+K_4$	$LSD_{0.05}$
Cereals and fodder crops	1st spring wheat	2.79	3.14	3.26	-	3.32	-	0.35
	2nd spring wheat	2.38	2.66	2.77	-	2.90	-	0.21
	Spring barley	3.49	4.02	4.25	-	4.52	-	0.65
	Oat + pea mixture	21.0	23.6	24.6	-	26.2	-	2.5
	Forage maize	43.5	49.8	60.6	-	67.6	-	10.9
Vegetables and potato	White cabbage	85.0	106.1	110.8	113.0	115.6	116.9	10.5
	Tomato	35.0	49.4	54.1	56.1	57.2	59.9	6.9
	Onion	16.6	17.6	19.6	21.1	21.7	20.1	3.8
	Carrot	59.6	57.4	68.6	71.7	73.8	77.1	6.7
	Potato	14.4	14.9	26.3	34.6	35.4	36.0	8.0

†Yield of green forage for oat-pea forage mixture and maize, and bulb yield for onion are shown.

Potato tuber yield increased by 1.8 to 2.4 times as a result of K applied at the four rates studied.

evidence towards higher vegetable crop yields with their use. The highest yield response to K fertilizer was found in potato. Potato tuber yield increased by 1.8 to 2.4 times as a result of K applied at the four rates studied. Forage maize was the second most K responsive crop as green forage yield was improved by 1.4 times under the highest K rate of 225 kg K_2O/ha. Carrot also responded well to fertilizer K. Yield of carrot roots was increased by 1.3 times at the highest K rate of 256 kg K_2O/ha.

The lowest rates of K fertilizer applied under the 'cereals-fodder crops' system (30 to 75 kg K_2O/ha) gave agronomic efficiencies for K (AE_K) values of 4.0, 3.7 and 5.9 kg grain/kg K_2O in 1st spring wheat, 2nd spring wheat and spring barley, respectively. Similarly, values for AE_K in the oat-pea mixture and maize were 28 and 144 kg green forage/kg K_2O. Respective AE_K values under the 'vegetable-potato' system at the lowest rates of K input (25 to 111 kg K_2O/ha) were 42, 100, 80, 175, and 141 kg production/kg K_2O in cabbage, tomato, onion, carrot, and potato. The inclusion of K certainly generated the most profitable return when applied to most K demanding crops such as vegetables, potato and forage maize because these crops provided the highest yield increase. It is more interesting to assess the current profitability of K input to cereal crops because of the large area involved. We estimate that K fertilizer use in spring wheat (3rd grade soft wheat: gluten 23 to 28%) and spring barley (fodder grain) could be profitable in 2012 with a AE_K higher than 2.4 to 2.5 kg grain/kg K_2O excluding the costs of fertilizer delivery to the farm, fertilizer application and additional harvesting and drying for the added grain yield. Our estimates indicate that K fertilizer use in cereal crops grown on grey forest soils of Western Siberia is quite profitable and the maximum economic response can be achieved in barley as compared to wheat.

Conclusions

When growers make decisions on K application it is necessary to consider the level of soil exchangeable K, expected crop yield, and hence the crop's need for additional K. Fertilizer distribution in Western Siberia is not yet well developed and regional farm gate prices for wheat may be not as attractive for growers because of existing logistical problems. Thus it is quite possible that value-to-cost ratios for K fertilizer use in wheat would be unfavorable. In such cases, it is reasonable to apply K to the most K demanding crops within the crop rotation and take advantage of any residual K during the spring wheat cropping season. BC

Dr. Yakimenko is a Leading Scientist at the Laboratory of Agrochemistry, Institute of Soil Science and Agrochemistry, Siberian Branch of Russian Academy of Sciences, Novosibirsk; e-mail: yakimenko@issa.nsc.ru. Dr. Nosov is Director, IPNI Southern and Eastern Russia Region, Moscow; e-mail: vnosov@ipni.net.

References

Gamzikov, G.P., V.B. Ilyin, V.M. Nazaryuk et al. 1989. Agrochemical parameters of soils and efficiency of fertilizers. Nauka, Siberian Branch, Novosibirsk. 254 p. (In Russian).

ROSSTAT. 2012. http://www.gks.ru

Yakimenko, V.N. 2003. Potassium in soils of Western Siberia agrocoenoses: PostDoc Dissertation. Novosibirsk. 306 p. (In Russian).

Yakimenko, V.N. 2006. Agrochemistry, 5: 3-11. (In Russian).

Yakimenko, V.N. 2009. Soil Fertility, 4 (49): 8-10. (In Russian).

Opportunities for Research and Development in Oil Palm Fertilization to Support Sustainable Intensification

By Thomas Oberthür, Christopher R. Donough, James Cock, Rahmadsyah, Gatot Abdurrohim, Kooseni Indrasuara, Ahmad Lubis and Tenri Dolong

The Southeast Asia Program of IPNI (IPNI SEAP) has developed a process to reduce yield gaps in oil palm plantations using Best Management Practices (BMPs). This process appraises the yield that can be obtained with BMPs on a set of commercial production blocks, evaluates the benefits from packages of management improvements, and also assesses the most appropriate BMP for a particular site. Estates can then identify BMPs suitable for yield intensification that work on a small set of commercial plots and use this information to make investment decisions for larger areas with a higher level of confidence.

Palm oil production over the last 50 years has increased mainly through area expansion. With limitations on expansion of agriculture into new areas, a major concern is how to increase productivity in order to meet future demand for palm oil (Corley, 2009). Yet, intensification of oil palm production to obtain higher yields is possible. The Unilever plantations in Malaysia, over a 40-year period, increased crude palm oil (CPO) productivity from 1.3 to 5.4 t/ha through breeding advances and improved management; with better fertilization alone accounting for 29% of the increase (Davidson, 1993).

Best management practices can be separated into those that contribute to *yield-taking* (crop recovery) and *yield-making* (crop management).

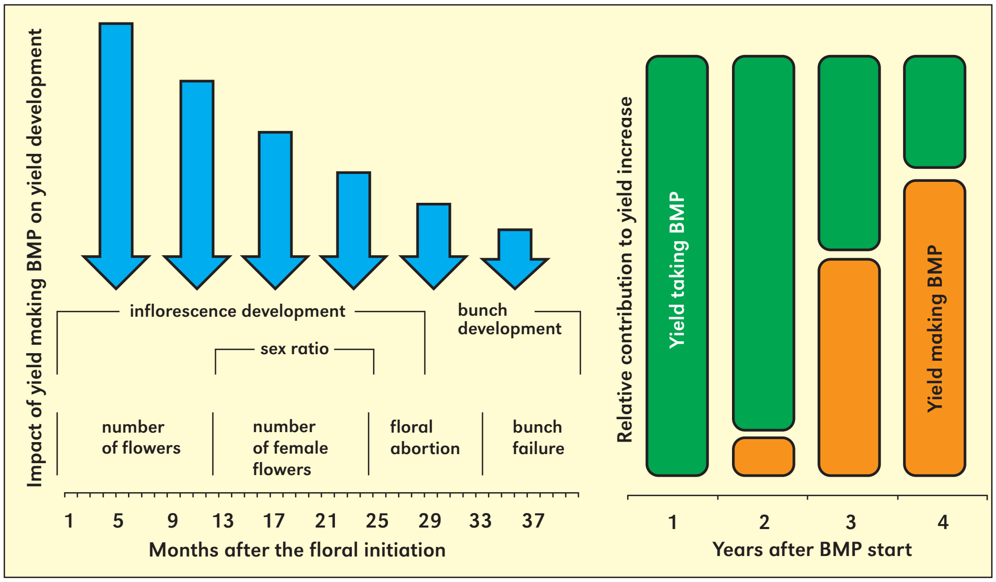


Figure 1. A conceptual description of the contribution from yield-making and yield-taking BMP towards the formation of fresh fruit bunch yield (Source Oberthür et al., 2012).

Yield-making is related to producing more fruit bunches (and therefore more oil) in the field, whereas yield-taking is ensuring that available fruit bunches are effectively harvested and transported to the mill. Yield-taking practices have an almost immediate effect after their implementation. On the other hand, there is a time lag between the implementation of improved agronomic yield-making practices and their impact on yield. Thirty-five to 40 months elapse between floral initiation and fruit bunch ripening (Breure, 2003). Hence, the impact of a BMP that affects floral initiation or other processes related to bunch formation might only manifest themselves in increased yields after periods of several months, with the full effects only observable after 3 to 4 years. Increased yields are due to impacts on the biological processes that drive bunch development. When palms become stressed because of suboptimal growth conditions, complex feedback mechanisms change the sex ratio and also promote abortion (**Figure 1**). Appropriate nutrition and water availability reduce these stresses in the earlier stages after floral initiation; hence the importance of the yield-making BMP in this phase. Later on, nutrition is important for bunch development, with soil fertility BMPs being crucial for yield-making.

The suite of BMPs contains several practices that impact directly or indirectly on plant nutrition. Direct impacts come mainly from providing nutrients for plant growth, whereas indirect impacts may arise from reducing competition for nutrients and by providing a healthy soil medium. While the IPNI SEAP BMP process improves all aspects of crop management, oil palm usually responds to improved nutrient management and adequate nutrition with higher yields. Furthermore, when fresh fruit bunches (FFB) are harvested, nutrients are removed from the field and only partially returned with empty fruit bunches (EFB). Unless supplemental nutrients are added to replace them, oil yields will be low (Chan, 2000). Hence, we present here opportunities for sustainable intensification of oil palm plantations through improved nutrient management. These opportunities have been identified from the analyses and interpretation of results from a large scale, 4-year BMP project in Indonesia (detailed results can be found in Oberthür et al., 2012).

Abbreviations and notes: N = nitrogen; P = phosphorus; K = potassium. IPNI Project # Southeast Asia SEA06.

BMP Case Study for Intensification of Oil Palm Production

In 2006, IPNI SEAP evaluated the BMP concept on 30 commercial blocks, established in partnership with five plantation companies in six sites in Indonesia (Donough et al., 2011). At each site, five pairs of commercial blocks, each of at least 25 ha, were selected so that each pair was planted in the same year with the same source of planting material, on

Returning empty fruit bunches back to the stand along with supplemental fertilizer nutrients is a critical part of the IPNI SEAP BMP strategy to sustainable intensification.

Table 1. Fresh fruit bunch (FFB) yields from the BMP project under different conditions in Sumatra and Kalimantan.

	---------- Annual FFB yield, t/ha ----------				
Location and treatment	Year 1	Year 2	Year 3	Year 4	Average[1]
Sumatra (Sites 1,2,3)					
Best management practices (BMP)	29.9	27.9	25.7	26.2	27.4
Reference block (REF)	26.6	24.0	21.2	22.4	23.5
Difference (%)	13	17	21	17	17
Kalimantan sites (Sites 4,5,6)					
BMP	23.0	23.6	26.6	25.5	24.7
REF	20.6	20.5	23.5	23.1	21.9
Difference (%)	12	15	13	11	13
Optimal site condition (Site 1,2,6)					
BMP	29.8	30.4	29.2	29.1	29.6
REF	27.8	27.1	25.7	25.2	26.4
Difference (%)	7	12	14	15	12
Sub-optimal site condition (Site 3,4,5)					
BMP	23.1	21.2	23.0	22.7	22.5
REF	19.4	17.3	19.0	20.3	19.0
Difference (%)	19	22	21	12	18

[1]Average values are for the 4-year project duration.
Source: Donough et al., 2011.

comparable terrain with similar soil characteristics. In each pair, the block with historically lower yields was designated for BMP implementation; the other became the reference (REF) block, where current estate practices were maintained. Sites were located in Sumatra (1, 2, 3) and Kalimantan (4, 5, 6). The trials were designed in such a manner that differences in yield-taking and yield-making effects could be separated. However, when plantation managers in most sites observed the benefits of simple measures to improve yield-taking they often adopted these protocols on their REF blocks. Therefore, it has not been possible to determine the relative importance of yield-taking and yield-making effects with absolute precision. Details about the BMPs and the deployment process can be found in the IPNI SEAP series of oil palm books.

The BMP blocks consistently out-performed the REF blocks (**Table 1**). Under optimal site conditions (sites 1, 2, 6), annual FFB yields with BMPs were close to 30 t/ha, and equivalent to about 6.5 t CPO/ha. The difference in annual FFB yields between the REF blocks and the BMP blocks increased from 2 t/ha in the first year to almost 4 t/ha in the fourth year in the optimal sites (**Table 1**). If we assume that the yield-making factors had little effect in the first year, then the yield-taking factors provided 2 t/ha extra FFB yield. By the fourth year, supposing that yield-taking factors remained constant, the yield-making factors were providing a similar gain of about 2 t/ha in addition to the yield-taking factors. At site 1, where harvesting was well managed from the beginning, the main gain in productivity occurred in years 3 and 4, indicating the yield-making gains from BMP.

The yield decline in the optimal sites in the REF blocks is largely explained by lower rainfall in the two Sumatran sites during the project period. It is noteworthy that the yield decline was very small in the BMP blocks in the same period, suggesting that if rainfall had not been limiting, yields in year 4 would have increased substantially in the BMP blocks. In the sites with sub-optimal conditions (sites 3, 4, 5), using similar reasoning, the yield-taking effect of BMPs could be as high as 3.7 t/ha of FFB yield as seen from the first year data. One would have expected the difference in FFB yield between the BMP and the REF blocks to be larger and total yield to increase further in the BMP blocks as yield-making effects kicked in. Neither of these effects was observed. However, the plantations on these sites had rapidly adopted the yield-taking BMPs in the REF blocks, skewing results, so that the substantial yield advantage of 4 t/ha in year 3 and 2.4 t/ha in year 4 in BMP blocks was essentially due to yield-making factors like changed fertilization.

Nutritional Status and Growth Indicators

Over the four years fertilizer budgets for BMP blocks were, in most sites, only slightly higher than those in the REF blocks (**Table 2**; site 2 data are not available). Site 1 had higher P inputs in the BMP blocks. In years 3 and 4, inputs were higher in the BMP than in the REF blocks. Nutrient inputs from inorganic fertilizers applied over four project years in the BMP blocks ranged from 414 to 586 kg/ha for N, 68 to 183 kg/ha for P, and from 430 to 881 kg/ha for K (**Table 2**).

Furthermore, the practice of mulching with EFB at a target rate of 40 t/ha, implemented only in the BMP blocks of sites 3, 4, 5, and 6, effectively contributed additional nutrients over and above those supplied via fertilizers. The target rate was not always achieved, and mulching was most complete at sites 5 and 6, where EFB was estimated to essentially triple the total supply of nutrients (**Table 2**). At the other sites mulching was done only in those BMP blocks that were close to palm oil mills. Hence, highest total nutrient inputs over four years from inorganic and organic sources were recorded at site 6 for N (1,268 kg/ha), P (273 kg/ha), and K (3,016 kg/ha), followed by site 5. Therefore, as discussed above, increased FFB yield in the BMP blocks in the later years of the project relative to REF blocks is attributable to yield-making, and we suggest that most of these increases are due to nutrition-related BMP.

However, the additional nutrient supply in BMP blocks did not appear to have any marked effect on the plant tissue content relative to the REF blocks. In both treatments, nutrient content in plant tissue was in the suggested optimal ranges (in our blocks, around 2.5% for N, around 0.16% P, around 1.2% K). Generally there were no significant differences in the percentage of nutrient contents between BMP and REF blocks among the sites. Only in site 1 where nutrient deficiencies were detected for K values (0.75 to 0.89% in both treatments). Furthermore, there was no clear effect on growth indicators, such as petiole cross-section area (Oberthür et al., 2012). The lack of a clear relationship between indicators such as plant tissue nutrient content and growth parameters on one hand, and the relative yields on the other, suggests that these conventional indicators may not be sufficient for nutrient management, as already discussed elsewhere (Foster, 2003). Amongst other factors, Breure (2003) linked canopy efficiency to cultural practices, particularly nutrition. While our data are not conclusive, there is an indication that there may indeed be a positive relationship between improved canopy efficiency, increased yields and yield-making nutrition-related BMPs that provide additional nutrients to the crop. This effect may not be easily uncovered in small-scale research trials and should be further evaluated at a commercial scale.

Table 2. Nutrient applications in the BMP and REF blocks from inorganic and organic fertilizer sources.

Treatment[3]	Site 1	Site 3	Site 4	Site 5	Site 6
	Nutrient inputs (kg/ha) over four project years[1,2]				
BMP IN	463	586	558	478	414
BMP IP	183	68	84	152	136
BMP IK	721	881	884	430	600
BMP ON	-	448	150	790	877
BMP OP	-	54	18	95	137
BMP OK	-	1,348	453	2,376	2,416
BMP TN	463	1,034	708	1,268	1,291
BMP TP	183	122	102	247	273
BMP TK	721	2,229	1,337	2,806	3,016
REF IN	469	583	552	483	404
REF IP	79	68	80	153	132
REF IK	621	882	924	435	571
REF ON	-	-	32	18	382
REF OP	-	-	4	2	115
REF OK	-	-	97	55	655
REF TN	469	583	585	501	785
REF TP	79	68	84	155	246
REF TK	621	882	1,021	489	1,226

[1]Average values from 5 blocks in each treatment for the 4-year project duration.
[2]Site 2 data are not available.
[3]BMP = Best Management Practices; REF = Estate Management Practice; I = Inorganic nutrient source (i.e. various commercial fertilizers); O = Organic nutrient source (i.e. compost or empty fruit bunches).

Opportunities for Fertilization to Support Intensification

R&D in Full Commercial Blocks

Our experience with these large-scale trials clearly demonstrates that it is possible to improve management practices, even on relatively well-managed mature plantations, and increase yield. We suggest that these commercial large scale trials (i) cost no more than conventional smaller-scale plot trials, (ii) require relatively little modification of commercial operations, (iii) do not cause major disruptions in the day-to-day management, and (iv) provide information that reflects real commercial conditions rather than extrapolating from small plot data. The full commercial scale evaluation of BMPs

Dr. Oberthür inspecting harvested fresh fruit bunches.

provides excellent information from applying a set of BMPs at a particular site, but provides little information on the specific contribution of individual factors such as nutrient applications. Thus the approach is excellent for looking at combinations of management practices that managers would like to test, but proves ineffective in determining how individual factors influence productivity. However, if the approach is implemented to develop an improved overall system, operational research principles can be used to test one factor at a time, including nutrient management options. Taking these ideas into account, one can conceive a process we call *Plantation Intelligence™*. Plantation intelligence involves a series of companies, estates and growers evaluating practices at the commercial block level, followed by information sharing to compare results across whole regions, rather than using only data generated within one estate.

Nutrient Rate Management

There is anecdotal evidence that plantations that are highly productive apply more fertilizer than standard recommended rates. Yet, there is little experimental evidence to support or reject the hypothesis that significantly higher rates of fertilizers increase yields sustainably at commercial scale. This is also due to the fact that most fertilizer recommendations are made based on the results of small, carefully managed experiments. There are large variations in the yield response to fertilizers, both within plantations and within single blocks. As a result we suggest that it may be better to over-fertilize than under-fertilize due to this high variability and associated asymmetry of risk (Corley and Tinker, 2003). Assuming a block is one-third low, one-third medium and one-third high fertility, applying fertilizer at a lower rate would run the risk of reducing FFB yields. This conclusion is consistent with the observed results from the BMP project sites analyzed earlier, where in spite of a lack of evidence of nutrient deficiencies in most of the REF blocks, and essentially no significant differences in plant tissue nutrient levels between BMP and REF blocks, there was a strong yield response to yield-making BMPs. Over-fertilizing parts of the commercial blocks will raise costs, but will likely provide higher pay-offs, particularly when CPO prices are high. The concept of 4R Nutrient Stewardship as promoted by IPNI is highly relevant to ensuring that intensified oil palm nutrition is implemented in an environmentally sustainable and yet profitable way (IPNI, 2012). BC

Dr. Oberthür is Director, IPNI Southeast Asia Program, Penang; e-mail: toberthur@ipni.net. Mr. Donough is Senior Oil Palm Consultant, IPNI Southeast Asia Program. Dr. Cock is Senior Advisor, IPNI Southeast Asia Program. Mr. Rahmadsyah is with Wilmar International Limited. Mr. Gatot Abdurrohim is with PT Sampoerna Agro Tbk. Mr. Kooseni Indrasuara is with Bakrie Agriculture Research Institute, PT Bakrie Sumatera Plantations Tbk. Mr. Ahmad Lubis is with Permata Hijau Group. Mr. Tenri Dolong is with PT REA Kaltim Plantations.

Acknowledgements

Data was generated by IPNI SEAP and its Indonesian BMP project partners, in alphabetical order, Permata Hijau Group, PT Bakrie Sumatera Plantations Tbk, PT REA Kaltim Plantations, PT Sampoerna Agro Tbk, and Wilmar International Ltd. The commitment and support from these partner companies, from top level management to the dedicated estate teams undertaking the challenges of project implementation, are reflected in the success at each project site. Funding for the project was contributed by IPNI, Canpotex International Pte Ltd, and K+S Kali GmbH.

References

Breure, C.J. 2003. *In* T.H. Fairhurst and R. Hardter (eds.) Managing Oil Palms for Large and Sustainable Yields, Singapore: PPI/PPIC-IPI, Singapore, pp. 59-98.

Chan, K.W. 2000. *In* B. Yusof, B.S. Jalani and K.W. Chan. (eds.) Advances in oil palm research, Kuala Lumpur (Malaysia): Malaysian Palm Oil Board, pp. 371-410

Corley, R.H.V. and P.B. Tinker. 2003. The Oil Palm. Fourth Edition, Blackwell. 562p.

Corley, R.H.V. 2009. Environmental Science & Policy 12:134-139.

Davidson, L. 1993. *In* B. Yusof et al. (eds.) Proceedings of 1991 PORIM International Palm Oil Conference, Module 1 – Agriculture, PORIM, Kuala Lumpur, pp. 153-167.

Donough, C.R., T. Oberthür, J. Cock, Rahmadsyah, G. Abdurrohim, K. Indrasuara, A. Lubis, T. Dolong, C. Witt, and T.H. Fairhurst. 2011. *In* Proc. PIPOC 2011 Int. Palm Oil Cong, – Agric, Biotech & Sustainability Conf., Malaysian Palm Oil Board, Kuala Lumpur, pp. 464-469.

Foster, H.L. 2003. *In* T. Fairhurst and R. Hardter (eds.) Oil Palm: Management For Large And Sustainable Yields Potash and Phosphate Institute (PPI), Potash and Phosphate Institute Canada (PPIC) and Int. Potash Inst. (IPI), Singapore: pp. 231-257.

The Magruder Plots: 120 years of Continuous Winter Wheat Research

By Brian Arnall

Over the decades several articles, journal publications, and many insights have been derived from this un-replicated fertility study consisting of six simple treatments.

In the summer of 1892 A.C. Magruder, the first professor of agriculture at the newly created Oklahoma Agricultural and Mechanical College, plowed under one acre of Tall Grass Prairie with an interest in producing continuous wheat without the addition of any fertilizer material. This acre would be used to demonstrate the need for fertility management. Over the next 120 years, treatments would be added and adapted. In 1898 a manure treatment was added, commercial fertilizer treatments were added in 1930, and N rates increased in 1967 to reflect higher yield potentials. Eventually the top 16 in. of soil from six treatments (**Table 1**) were moved to a new location in 1947.

Table 1. List of the six treatments in the Magruder Plots, established in Stillwater, OK in 1892.

Treatment	Description
Manure	1891 to 1967 – applied at a rate of 120 lb N/A every four years; 1968 to present applied at a rate of 240 lb N/A every four years
Check	No soil amendments added
P	1930 to 1967 – P applied as ordinary superphosphate at a rate of 30 lb P_2O_5/A; 1968 to present – applied as triple superphosphate
NP	1930 to 1945 – N applied as sodium nitrate at a rate of 33 lb N/A; 1946 to 1967 – N applied as ammonium nitrate at a rate of 33 lb N/A; 1968 to present – N applied a rate of 60 lb N/A; P application same as P only treatment
NPK	N and P applied same as NP treatment; 1930 to present – K applied as potassium chloride at a rate of 30 lb K_2O/A
NPKL	N, P and K applied the same as NPK treatment; lime applied when soil pH < 5.5

In a previous *Better Crops* article Mullen et al. (2001) described the onset of macronutrient deficiencies over the life span of the Magruder plots. When commercial fertilizer (P, NP, NPK, and NPKL) was first added in 1931 the crop immediately responded to P as is shown in **Figure 1**. A response to N fertilizer was not evident until the 1960s, it was also at this time that the impact of P was diminished. This occurred because at the outset P was the most limiting nutrient, but with time (by the 1960s) N became more limiting. It was not until the 1980s that soil reserves of K were depleted to the point that a response to K fertilizer was observed. The article by Mullen et al. documents the decline in soil test P and K.

One might wonder why there was no N response for so many decades. This can be explained by the original soil conditions. The virgin prairie soils of the Great Plains were rich in organic matter, and thus had high levels of organic N.

Abbreviations and notes: N = nitrogen; P = phosphorus; K = potassium; Ca = calcium; Mg = magnesium; L = lime.

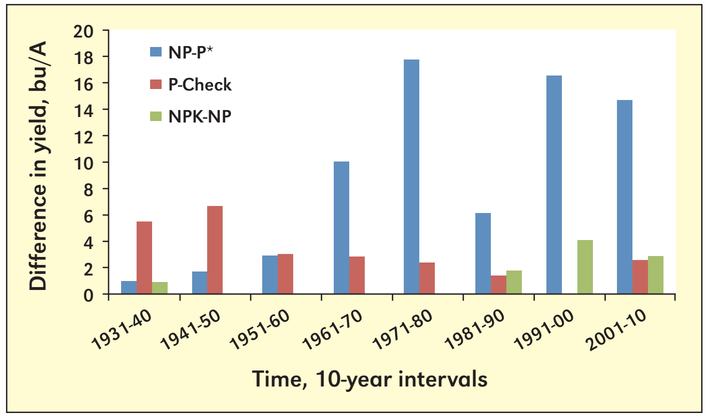


Figure 1. Difference among selected treatments of the Magruder Plots, 1930 to 2010.

*NP-P – difference in winter wheat yield between NP and P only treatments; P-Check – difference in winter wheat yield between P only and check treatments; NPK-NP – difference in winter wheat yield between NPK and NP treatments.

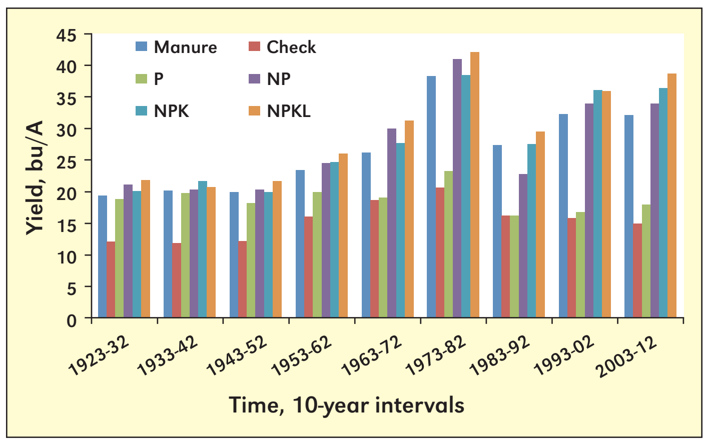
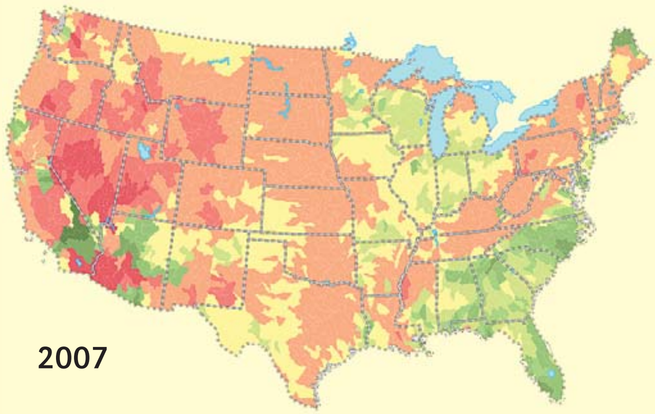
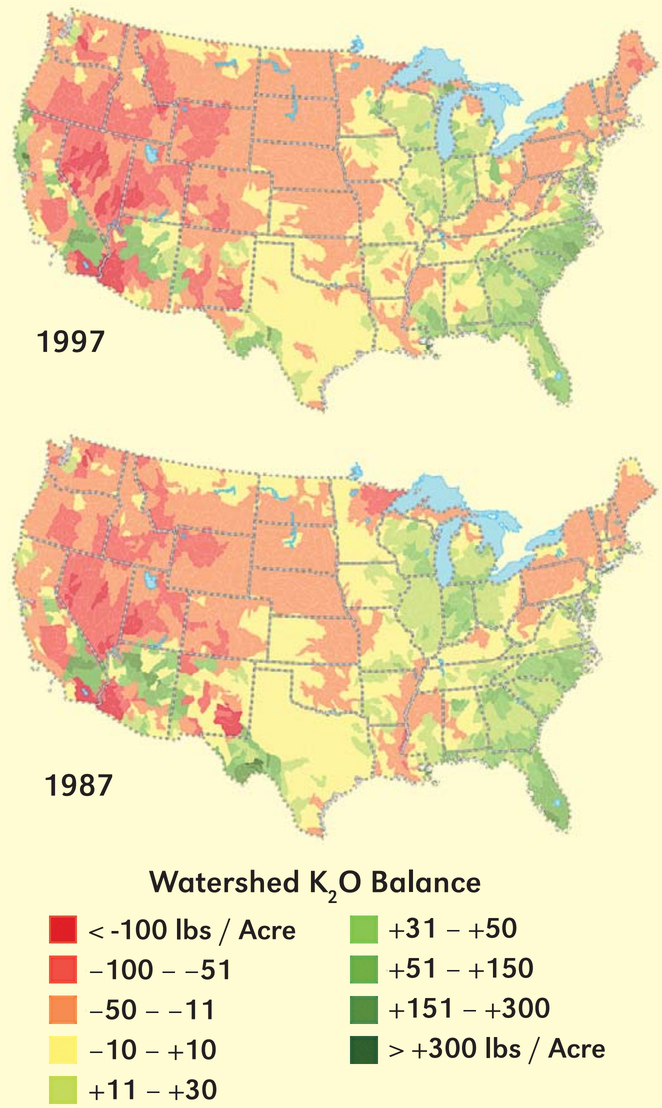


Figure 2. Ten-year average yields from the Magruder Plot treatments, Stillwater OK, 1923-2012. Data from 1893 to 1922 were not included as inorganic fertilizer was not applied during this time frame.

Before cultivation the reddish prairie soils of the Magruder Plots contained about 4% organic matter and over 8,000 lb N/A (Boman et al., 1996). This massive soil reservoir supplied enough N through mineralization to meet crop needs until the 1960s, when response to N was first observed.

Figure 2 documents the 10-year average yields for the six treatments shown in **Table 1**. In this figure it is evident why the researchers felt the need to increase N rate in the late 1960s as the 10-year average maximum yields increased from 20 to 30+ bu/A. Boman et al. (1996) attributed the yield jump in this time frame to the increased yield potential of the improved





Nutrient Balance and NuGIS

NuGIS (Nutrient Geographic Information System) is a web-based tool developed by scientists at the International Plant Nutrition Institute (IPNI) that is designed to assess nutrient balance and nutrient use efficiency on large scale, ongoing basis. NuGIS makes available both numeric and map-based information on nutrient balance and removal to use ratios for N, P and K for ag census years (every 5 years) going back to 1987. Information is available for the U.S. on the county, watershed and hydrologic unit levels. NuGIS maps show many interesting regional trends, including chronic K deficits in many areas of the Great Plains. Although soil K levels are generally high in the Great Plains, the reserves are not endless. NuGIS serves as a beacon, warning against over exploitation of our soil fertility resources. The treatment information provided in the Magruder article supports the need for tools such as NuGIS by showing how long-term production can ultimately lead to soil fertility depletion and reduced productivity.

For more on NuGIS go to http://www.ipni.net/nugis

varieties of the time. This figure also shows the increase in yield due to N, K and the application of lime.

An interesting aspect of the Magruder plots is the ability to evaluate nutrient mass balance (for more on nutrient balance see accompanying note on NuGIS). **Figure 3** documents the removal of N, P, K, Ca and Mg. **Table 2** lists the amounts of N, P, K, Ca and Mg both; added as manure and commercial fertilizer and removed by the grain from the manure, check and NPKL treatments. From these values N use efficiency can be calculated (grain N removed from fertilized plot – grain N removed from check plot / total N added) resulting in a 45% NUE. It should be noted that if the Magruder plot N rate was based on a yield goal recommendation (5-year average plus 20%) the application rate would be 100 lb/A, not 60.

Table 2. Amounts (lb/A) of N, P, K, Ca, and Mg added to the Manure treatment since 1899, and NPK treatment since 1929, and the amounts of N, P, K, Ca, and Mg removed by the Manure, Check and NPKL treatments since 1929.

Nutrient	Manure (1899)	NPK (1929)	Manure removed	Check removed	NPKL removed
N	4,920	3,888	3,412	1,980	3,723
P	1,877	1,073	496	288	541
K	4,254	2,017	653	379	712
Ca	11,562	.	364	211	397
Mg	2,165	.	182	106	199

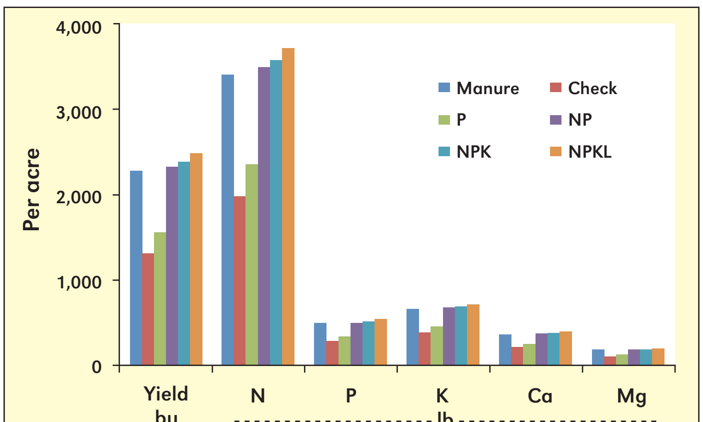


Figure 3. Total yield (bu/A) and total nutrients (lb/A) removed from each treatment from 1930 to 2012.

Another important observation from the Magruder Plots is the impact of crop production and fertilization on soil pH. **Figure 4** demonstrates the effect of crop removal (i.e., removal of base cations) and N fertilization on soil pH. The check plot, which has a total removal equal to half that of the fertilized plots has seen little change in soil pH, the NPK plots have documented a decline, and the manure plot soil pH has increased. It is interesting to note that the soil pH of all treatments remained relatively stable until yields increased and N application increased. For this reason data prior to 1975 is not shown.

The Magruder plots are one of the few historic and on-going soil fertility experiments in the world. The data collected from 120 years of monoculture winter wheat will surely continue to contribute to the advance of wheat production science in the years to come. BC

Dr. Arnall is Assistant Professor, Precision Nutrient Management, Oklahoma State University, Department of Plant and Soil Sciences; e-mail: b.arnall@okstate.edu.

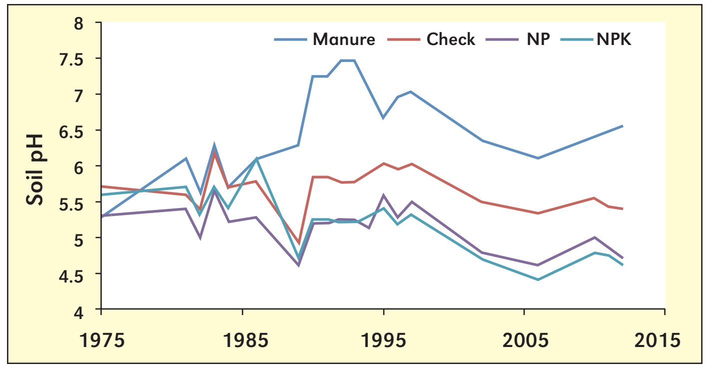


Figure 4. Soil pH trend in the Manure, Check, NP, and NPK plots from 1975 to 2012. Soil test results prior to 1975 show consistency of soil pH values.

References

Boman, R.K., S.L. Taylor, W.R. Raun, G.V. Johnson, D.J. Bernardo, and L.L. Songleton. 1996. Dept. of Agronomy, Oklahoma State Univ.

Mullen, R.W., K.W. Freeman, G.V. Johnson, and W.R. Raun. 2001. Better Crops with Plant Food, 85 4:6-8.

Conversion Factors for U.S. System and Metric

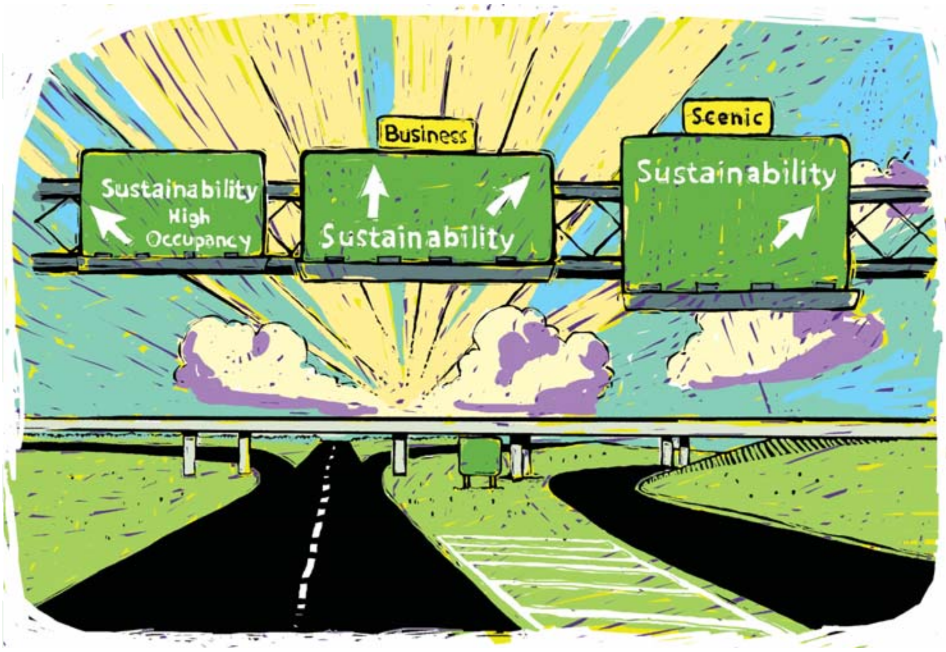
Because of the diverse readership of *Better Crops with Plant Food*, units of measure are given in U.S. system standards in some articles and in metric units in others…depending on the method commonly used in the region where the information originates. For example, an article reporting on corn yields in Illinois would use units of pounds per acre (lb/A) for fertilizer rates and bushels (bu) for yields; an article on rice production in Southeast Asia would use kilograms (kg), hectares (ha), and other metric units.

Several factors are available to quickly convert units from either system to units more familiar to individual readers. Following are some examples which will be useful in relation to various articles in this issue of *Better Crops with Plant Food*.

To convert Col. 1 into Col. 2, multiply by:	Column 1	Column 2	To convert Col. 2 into Col. 1, multiply by:
	Length		
0.621	kilometer, km	mile, mi	1.609
1.094	meter, m	yard, yd	0.914
0.394	centimeter, cm	inch, in.	2.54
	Area		
2.471	hectare, ha	acre, A	0.405
	Volume		
1.057	liter, L	quart (liquid), qt	0.946
	Mass		
1.102	tonne[1] (metric, 1,000 kg)	short ton (U.S. 2,000 lb)	0.9072
0.035	gram, g	ounce	28.35
	Yield or Rate		
0.446	tonne/ha	ton/A	2.242
0.891	kg/ha	lb/A	1.12
0.0159	kg/ha	bu/A, corn (grain)	62.7
0.0149	kg/ha	bu/A, wheat or soybeans	67.2

[1]The spelling as "tonne" indicates metric ton (1,000 kg). Spelling as "ton" indicates the U.S. short ton (2,000 lb). When used as a unit of measure, tonne or ton may be abbreviated, as in 9 t/ha. A metric expression assumes t=tonne; a U.S. expression assumes t=ton.

What is "Sustainable" Anyway?



Sustainability is a phrase that gets thrown around so frequently that there is little consideration about what the word really means. After all, who can be opposed to sustainable agriculture?

Sustainability was famously described as *meeting the needs of the present without compromising the ability of future generations to meet their own needs.*

The vision of sustainable agriculture is more philosophical than a well-defined goal. It certainly includes the stewardship of natural resources, financial security for farmers, and consideration of societal goals. However since there is no agreement on how to achieve these objectives, these terms can be twisted to meet personal agendas.

Many will agree that each person has an individual preference on how to balance current consumption with future enjoyment. Frequently we want things now, instead of waiting for a future reward. Some people are careful savers for the future, while others spend all that they earn. Achieving sustainability is a flexible goal that reflects individual priorities and incentives. There are also regional considerations that must be factored into sustainability objectives.

The unprecedented pressure on the global food supply to meet the growing population requires close examination of all our current practices. Our soil and water resources are under severe stress in some areas. Like all geologic resources, the supply of phosphate and potash is finite in the world. Although there is no risk of fertilizer shortage in the next centuries, consideration of appropriate conservation and recycling practices should always be in the forefront of their use. Modern food systems require the input of considerable energy. There are numerous changes that can be made to make our food supply more sustainable.

Some groups promote a return to organic fertilization practices, other voices suggest that agroecology or integrated nutrient management is the path towards sustainability. Being dogmatic about a single solution causes more conflict than progress. There is no single path towards achieving agricultural sustainability.

IPNI is dedicated to the development and delivery of the best scientific information about the responsible use of plant nutrients. Instead of arguing over which definition of agricultural sustainability is correct, let's get on with the task of using plant nutrients as efficiently and effectively as possible.

Rob Mikkelsen

Dr. Robert Mikkelsen
IPNI Western North American Program Director

BETTER CROPS
International Plant Nutrition Institute
3500 Parkway Lane, Suite 550
Norcross, Georgia 30092-2844
www.ipni.net