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A PUBLICATION OF THE INTERNATIONAL PLANT NUTRITION INSTITUTE (IPNI)
2018 NUMBER 1

Benefits of Implementing 4R Nutrient Management in

Smallholder Cocoa Systems

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Vol. CII (102) 2018, No. 1

Our cover: Close-up view of cocoa pods growing on a smallholder plantation in South Sulawesi, Indonesia.
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BETTER CROPS WITH PLANT FOOD (ISSN:0006-0089) is published quarterly by IPNI. Changes to personal subscription details and preferences can be submitted to http://www.ipni.net/subscribe or may be e-mailed directly to circulation@ipni.net.

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IPNI thanks the Government of Saskatchewan for their support of this publication through its resource tax funding.

Cocoa Yield under Good Agricultural Practices and 4R Nutrient Management in Indonesian Smallholder Systems

By Thomas Oberthür, Marianne Samson, Noel Janetski, and Kate Janetski

Researchers combined a suite of good agricultural practices with 4R-consistent nutrition to achieve a rapid improvement in cocoa bean yield and quality under the guidance of local Cocoa Carers and Monitors. Close monitoring of the soil nutrient balances will be required to sustain this early gain.

KEYWORDS:
sustainable intensification;
cocoa fertilization;
dry bean yield; bean size;
good agricultural practices

ABBREVIATIONS AND NOTES:
N = nitrogen; P = phosphorus;
K = potassium; Mg = magnesium;
S = sulfur; Ca = calcium;
OM = organic matter;
ROI = return on investment.

IPNI Project IDN-27

https://doi.org/10.24047/BC10213

Cocoa global production has surged strongly over the past 20 years to nearly 4.6 million (M) t, mostly from West Africa (FAO, 2013, 2016). Between 2020 and 2025, consumers' demand for cocoa will increase by 1 M t (ICCO, 2015), mainly driven by the growing consumption in the Asia-Pacific region, particularly China and India (Squicciarini and Swinnen, 2016). Growth in West African production has stagnated over the last 10 years at a level of about 2.7 M t, and continued growth in demand has encouraged new producers into the market. Indonesia is now the world's third largest producer, with a planted area between 0.8 to 1.1 M ha, seemingly well placed to benefit from global market developments.

Until recently, growth of production has been almost entirely through expansion of area. With the exception of Central America, which has shown a steady improvement over the past 20 years, yield in many areas has plateaued at an average close to 0.5 t/ha (Baah et al., 2011; Assiri and Koko, 2009), well below a theoretical potential of 11 t/ha (Corley, 1983). Indonesia is no exception, and since 2010 yield has dipped below 0.5 t/ha, undermining cocoa farm profitability and presenting substantial risks to the survival of the industry in Indonesia. At the same time, global markets are strong. The opportunity for Indonesia is to benefit from growth in global demand by pushing yield consistently beyond 1 t/ha. With adequate management in place, cocoa dry bean yields between 1 and 3 t/ha can be achieved in commercial fields (Ahenkorah, 1997; Butler, 2004; Maharaj et al., 2005; Pang, 2006, Koko et al., 2013). The role of adequate crop nutrition as part of adequate agronomic management for high cocoa yields has long been known (Cunningham and Arnold, 1962). Application of fertilizer increased yields from a low 0.25 to 1.5 t/ha after four years (Ghana Cocoa Board, 2002). Trials in Colombia have shown average dry bean yields over five years exceeding 1 t/ha with balanced fertilization (Uribe et al., 2001).

On the other hand, the use of fertilizer in Southeast Asian smallholder cocoa systems is not common, and widespread nutrient deficiencies are prevalent (Nelson et al., 2010). Unfortunately, most nutrition knowledge has been developed for West Africa and Malaysia under conditions not representative of Indonesian production regions. Furthermore, farmers often view fertilizer use as risky because of uncontrollable effects of weather and disease, and there remains substantial uncertainty amongst farmers. An essential part of a change process would be knowledge that increases farmers' certainty as they manage fertilizer. The knowledge base must be locally specific, trusted by farmers to reflect what is happening on the ground, and relevant to the needs of small-scale operations and their suppliers. Farmers need support if we expect them to fertilize for rapid yield gains. This project illustrates how good agricultural practices consistent with 4R Nutrient Stewardship (IPNI, 2012) can impact cocoa bean yields and quality. The project demonstrates how such knowledge is developed in an on-farm setting that is conducive to increasing certainty amongst farmers about the effects of changed management, and enables the generation of credible knowledge on cocoa crop nutrition.

On-Farm Experiments

Twenty-two farms in Soppeng, South Sulawesi, Indonesia, ranging from 0.3 to 1.65 ha, were selected in similar environmental conditions, with trees of 3 to 5 years of age. Tree density and their individual location were mapped, and replanting done where trees were missing or unproductive. Cocoa grew typically under the leguminous tree species *Gliricidia sepium* providing on average 30% shade cover. All farmers received training in good agricultural practices (GAP) at the Mars Cocoa Academy. Farms were divided in two equal-sized parts. In one half, GAPS without additional fertilizer nutrients were implemented, while the other half received GAP with 4R-consistent nutrient management (GAPN). Good agricultural practices involve regular pruning, weeding, and phyto-sanitation (i.e., diseased pods are removed and pest and disease are controlled). In 4R Nutrient Stewardship, the right source of fertilizer is used, at the right rate, the right time, and in the right place. Our fertilizer recommendation was developed based on the replacement of exported nutrients by a target yield of 2 t/ha. Inorganic fertilizer nutrients were selected, because compost was limited. They were applied twice a year with the onset of the rainy season (Dec./Jan., July/Aug.). Nutrients were buried in four, 20-cm deep holes with 10 cm diameter, equally spaced around the tree, along the edge of the canopy to match root growth. In each treatment, 50 trees were monitored from June 2013 to June 2015. Trees were harvested bi-weekly to determine dry bean yield per tree and bean size as the number of beans in a 100-g sample. "Cocoa Carers", (i.e., highly trained farmers), conducted the monitoring and data were captured in a portable tablet and sent to Cocoa Care. Cocoa Carers and associated Cocoa Monitors, (i.e., extension agents with an academic background), employed by Cocoa Care, routinely met with farmers to discuss the progress of the on-farm experiments. Such discussions usually included neighboring farmers and were conducive to group learning and socializing the experimental process with farmers not included in the core group. Baseline soil samples were taken in June 2013, with subsequent sampling in June 2014 and December 2015. Leaf samples for nutrient tissue content analyses were taken in June 2013, and then in December 2013, June 2014, December 2014, and December 2015. All samples were analyzed by P.T. London Sumatra.

Production System Improvements

Table 1 lists the amounts for nutrients applied in the GAPN treatment. Assuming 1,100 trees/ha, they amounted to 160 kg N, between 30 and 60 kg P, 90 to 165 kg of K, 11 to 17 kg Mg, and 70 to 110 kg Ca applied per year. More P was applied in year 1 to account for the low P status. The application of K was gradually increased to avoid economic burden.

Today, cocoa yield in smallholder cocoa production systems of Sulawesi rarely exceeds 0.4 t/ha. With GAP, yields increased to almost 0.6 t/ha in the first year of engagement, and to 0.8 t/ha in the second year (**Table 2**). Combining GAP with 4R-consistent nutrition further increased yields to 0.8 t/ha and over 1.1 t/ha in years 1 and 2, respectively. These are average yields for the group. Top-performing farmers exceeded 1 t/ha during the first year, and the 2 t/ha barrier

Table 1. Nutrients applied per tree in the treatment including good agricultural practices and fertilizer nutrients (GAPN) over a period of two years.

	- - - - - - - - - Nutrients applied, g/tree - - - - - - - - -					
	N	P	K	Mg	S	Ca
July 2013	99	23	44	-	35	-
January 2014	45	33	37	15	30	236
Subtotal Year 1	144	56	81	15	65	236
July 2014	74	13	75	5	54	-
January 2015	74	13	75	5	54	-
Subtotal Year 2	148	26	150	10	108	0
Total	292	82	231	25	173	236

Notes: 22 farms. Fertilizers included an NPK compound source (15-15-15), urea, ammonium sulphate, potassium chloride, dolomite, and rock phosphate.

Growers sorting their harvested cocoa pods.

A look inside an open pod.

Indonesia is now the world's third largest producer of cocoa and strong market demands present an opportunity for Indonesia's smallholders, which can be met by lifting yields beyond traditional thresholds with 4R-consistent nutrient management. Cocoa Care & T. Oberthür/IPNI Images

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TAKE IT TO THE FIELD

Yields above 1,000 kg/ha were common for fertilized farms throughout most of the study and this progress instilled confidence amongst cocoa growers about their investment in fertilizer. Improving agronomic skills is a critical part of shielding this vulnerable group against a loss in their investment, which typically takes place during periods of adverse market or weather conditions.

in year 2. One farmer came close to 3 t/ha in the second year of management change.

Quality of beans is a criterion for sales transactions. Large beans have less shell, hence waste, and typically higher fat content, which may attract price premiums. We used bean count as proxy for size. The industry considers bean counts lower than 100 as very good, and counts above 120 are outside commercial standards. Farms participating in the Cocoa Care/IPNI program recorded bean counts far below 100, with year 2 better than year 1, and GAPN significantly improving on GAP (**Table 2**).

Table 2. The effects of good agricultural practices without fertilizer nutrients (GAP), and GAP including fertilizer nutrients (GAPN) on dry bean yield (t/ha) and bean size of cocoa (as number of beans per sample of 100 g) over a period of two years.

	Dry bean yield, t/ha		Bean size, Number/100 g	
Treatment	Year 1	Year 2	Year 1	Year 2
GAP	0.582	0.790	93.6	73.4
GAPN	0.791	1.169	90.2	69.5
Significance at 5%	***	****	****	****

Notes: 22 farms. Yield was converted to a per ha basis using a tree density of 1,100 trees/ha.

Traditionally, most cocoa in Sulawesi is harvested between June and August. Cash income is restricted to these months, and curtails significantly farmers' ability to invest in farm inputs required during other times of the year. Good agricultural practices induced production in months during which little crop is normally harvested, and adding nutrients further improved the distribution of marketable cocoa beans (**Figure 1**). The typically low period between January and June was remarkably productive. Year 2 data indicate that adding nutrients successively increased the yield gap over good agricultural practices only.

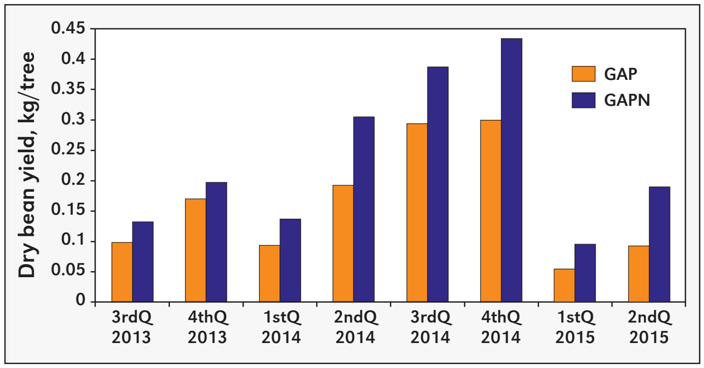

Figure 1. The effects of good agricultural practices without fertilizer nutrients (GAP), and GAP including fertilizer nutrients (GAPN) on dry bean yield distribution over eight quarterly measurement periods. Average values of yield from 22 farms.

Tables 3 and **4** present the results from the laboratory analyses of soil and tissues samples, respectively. Both GAP and GAPN improved soil pH to an optimal point for cocoa. Soil organic matter dropped somewhat in Year 1, but increased again in Year 2 under both management options. This is likely an effect of regular pruning in all farms. Total soil N remained stable, except for an increase in GAPN in Year 2, which was expected given the optimal supply of external fertilizer N. Soil P and K was considered somewhat low at the start of the program, and fertilizer inputs were designed to increase concentrations, and then maintain them. Decreased exchangeable Mg in Year 2 in both treatments signal that the reduction of fertilizer Mg in that year was an incorrect decision. Year 2 values indicate that high yields under GAPN may have started excessive soil Mg removal that needs correction in the coming years. Higher yields under both treatments will have extracted more Mg than was replaced by fertilizer applications. Calcium was initially high and were acceptable after Year 2. Adequate nutrient management is required to maintain the Ca concentration to ensure that cation balances remain at present ratios to prevent

Table 3. Soil properties at baseline sampling before treatment implementation in June 2013, and as affected by good agricultural practices without fertilizer nutrients (GAP), and GAP including fertilizer nutrients (GAPN) determined in 2014 and 2015.

	pH	OM	Total N	Bray P	Exch. K	Exch. Mg	Exch. Ca	Ca:Mg ratio	(Ca+Mg):K ratio
		- - - - - % - - - - -		mg/kg	- - - - - - meq/100 g - - - - - -				
Base 06/2013	5.4	4.4	0.19	40.5	0.68	5.5	26.6	6.8	50.6
GAP 06/2014	7.0	4.0	0.18	43.6 a	0.54	4.3	20.3	5.7	52.5
GAPN 06/2014	7.0	3.9	0.19	28.6 b	0.56	4.8	18.9	4.8	50.3
GAP 12/2015	6.9	4.4	0.18 b	59.0	0.90	3.1 a	15.8	5.2	27.8
GAPN 12/2015	6.8	4.3	0.30 a	78.6	0.69	2.9 b	16.1	5.6	28.4

Notes: June 2013/2014, 22 farms; December 2015, 12 farms; others had applied fertilizer in GAP. Differences within each year between GAP and GAPN were tested for statistical significance. Values without letters are not significantly different from one another within the same year at $p < 0.05$.

Table 4. Measured concentration of nutrients in leaf tissue, as affected by good agricultural practices without fertilizer nutrients (GAP), and GAP including fertilizer nutrients (GAPN), at four different sampling dates.

	GAPN	GAP	Difference	Significance[1]
		N concentration, %		
December 2013	1.856	1.689	0.171	**
June 2014	1.935	1.916	0.019	ns
December 2014	1.714	1.779	-0.065	ns
December 2015	1.818	1.874	-0.057	ns
		P concentration, %		
December 2013	0.136	0.149	-0.012	**
June 2014	0.140	0.141	-0.001	ns
December 2014	0.127	0.126	0.001	ns
December 2015	0.113	0.108	0.005	ns
		K concentration, %		
December 2013	1.621	1.644	-0.024	ns
June 2014	0.747	0.738	0.010	ns
December 2014	1.596	1.514	0.082	ns
December 2015	1.482	1.548	-0.066	ns
		Mg concentration, %		
December 2013	0.563	0.545	0.018	ns
June 2014	0.215	0.226	-0.011	ns
December 2014	0.447	0.439	0.008	ns
December 2015	0.298	0.258	0.039	ns
		Ca concentration, %		
December 2013	2.436	2.402	0.035	ns
June 2014	1.716	1.748	-0.032	ns
December 2014	2.131	2.098	0.033	ns
December 2015	1.220	1.033	0.188	ns

Notes: 22 farms sampled at all dates. [1] ** = significance difference at $p < 0.05$; ns = not significant.

antagonistic uptake effects on K and Mg by Ca.

For the last two sampling dates, leaf tissue concentrations of P, Mg, and Ca were higher in GAPN, and somewhat lower for N and K, compared to GAP. With both management options, a common trend is observed for all monitored nutrients—tissue concentration was highest at the initial sampling dates.

This trend confirms the indications from the soil analyses that higher yields under both management options are removing more nutrients than the soil and fertilizer can currently supply. Nutrient supply in the coming years, from inorganic and organic sources, will have to arrest the downward trend to prevent soil nutrient mining. Given the success of the Cocoa Care extension with Carers, Monitors, and the strong markets, farmers increasingly embrace sustainable intensification, of which responsible use of soil resources is an accepted component. The timely establishment of adequate nutrient supply chains has become critical.

Conclusions

Intensified cocoa smallholder production systems have been established under an extension approach led and driven by highly trained farmers, guided by Cocoa Care. The impact of 4R-consistent nutrient management as part of this approach has been demonstrated with an on-farm trial network. Peer learning between farmers, coupled to strong markets for quality cocoa, is leading to a rapid adoption of improved, intensive management. The fertilizer industry needs to engage in a timely manner with the cocoa sector to ensure accessible and affordable nutrient supply chains prevent soil resource depletion under intensive cocoa production systems. **BC**

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Estimating Nutrient Uptake Requirements for Soybean

By Fuqiang Yang, Dan Wei, and Ping He

Data from field experiments conducted in China were used to assess the relationship between soybean seed yield and nutrient uptake using the QUantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) model. Field validation indicated that QUEFTS could be used to estimate nutrient requirements and help develop fertilizer recommendations for soybean.

KEYWORDS:
QUEFTS; internal efficiency; balanced nutrient requirement; fertilizer recommendation

ABBREVIATIONS AND NOTES:
N = nitrogen; P = phosphorus; K = potassium.

IPNI Project CHN-NES

https://doi.org/10.24047/BC10218

Soybean (*Glycine max* [L.] Merr) production in China has been declining steadily due to the lower yields and lagging technological progress. Fertilizer application has played an important role in increasing soybean yields. However, fertilizer recommendations could at times be misleading since soybean nutrient requirements are usually based on single values summarized from limited data extrapolated over large areas (Vitousek et al., 2009).

The QUEFTS model can quantify crop nutrient requirements for a target yield using a large number of data (Janssen et al., 1990) and can fully account the interactions between N, P, and K. To date, the model has been successfully implemented to match nutrient supply with maize, rice, and wheat crop demand in many countries including China (Pampolino et al., 2012). This model had not yet been tested in soybean, which was the objective of a study combining data from thousands of soybean field experiments from the International Plant Nutrition Institute (IPNI) China Program, the Modern Agricultural Industry Technology System for Soybean, and scientific literature between 2001 and 2015. On-farm field validation was conducted between 2014 and 2015 at 20 sites across northeast China, including Heilongjiang, Jilin, and Liaoning provinces.

Yield and Nutrient Uptake

The average seed yield of soybean was 2,470 kg/ha, according to the experiments carried out in China between 2001 and 2015, with the range being very wide at 525 to 6,515 kg/ha. The average harvest

Setting the Parameters for the QUEFTS Model

The maximum nutrient accumulation (*a*) and dilution (*d*) were calculated as the ranges of internal efficiency (IE, seed yield per unit of nutrient uptake in the aboveground parts) based on the actual N, P, and K uptake levels. These *a* and *d* values were then used as parameters to estimate the nutrient requirements of soybean through the application of the QUEFTS model.

Sets of *a* and *d* values for N, P, and K were calculated by excluding the upper and lower percentiles (Set 1 = 2.5, Set II = 5, Set III = 7.5) of nutrient IE for all soybean data in China. The curves of N, P, and K in the three sets were similar until the targeted yield approached the yield potential of 6.0 t/ha (**Figure 1**). In this study, Set I was used to estimate balanced nutrient uptake and the relationship between soybean seed yield and nutrient accumulation in the aboveground parts because it included a wider range of variability. The constant *a* and *d* values derived from all soybean data in Set I were 13.5 and 21.4 kg/kg for N, 60.4 and 234.6 kg/kg for P, and 27.8 and 79.9 kg/kg for K, respectively.

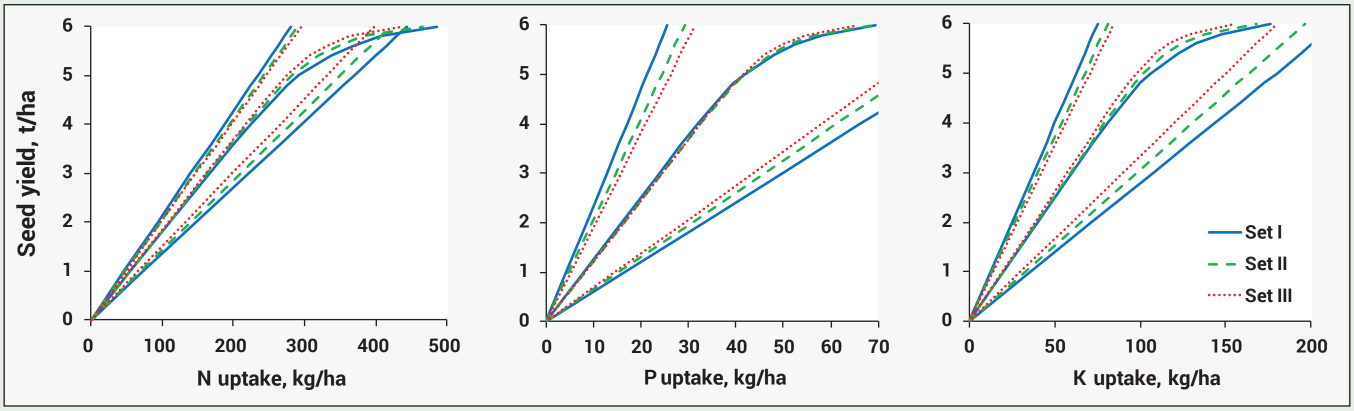

Figure 1. The relationship of seed yield and nutrient uptake of soybean at different sets of constants *a* and *d*. YD, YA, and YU represented the maximum dilution, maximum accumulation, and balanced uptake of N, P, or K in aboveground parts, respectively. The yield potential was set at 6.0 t/ha for the present study as an example.

index (HI), a term used to quantify the yield of a crop versus the total amount of biomass produced, was 0.46 kg/kg (range of 0.26 to 0.66 kg/kg) and more than 90% of the HI values were between 0.40 and 0.60 kg/kg. The average aboveground nutrient accumulation of N, P, and K was 132, 22, and 48 kg/ha, and ranged from 21 to 435, from 5.6 to 73, and from 8.2 to 194 kg/ha, respectively. This range in nutrient concentrations in grain and straw resulted in tremendous variation for HI values of P and K, which were 0.42 to 0.95 and 0.36 to 0.88 kg/kg, respectively. However, the HI of N was more consistent and ranged between 0.71 to 0.94 kg/kg (**Table 1**).

Table 1. Characters of yield and nutrient uptake of soybean (2001-2015) in China.

Parameter	*n*[a]	Mean	SD[b]	Minimum	Maximum
Seed yield (13.5% moisture), kg/ha	9,318	2,470	683	525	6,515
Harvest Index (HI), kg/kg	5,277	0.46	0.06	0.26	0.66
Shoot N, kg/ha	2,193	132	39	21	435
Shoot P, kg/ha	2,199	22	8.6	5.6	73
Shoot K, kg/ha	2,192	48	22	8.2	194
HI for N, kg/kg	1,570	0.84	0.04	0.71	0.94
HI for P, kg/kg	1,579	0.67	0.09	0.42	0.95
HI for K, kg/kg	1,576	0.58	0.08	0.36	0.88

[a] n = number of observations. [b] SD = standard deviation.

Estimating the Optimum Nutrient Requirement

The relationship between soybean yield and nutrient accumulation in the aboveground parts at maturity was estimated using the QUEFTS model under different potential yields (3.0 to 6.0 t/ha). The model predicted a linear increase in seed yield, until the yield reached about 60 to 70% of the yield potential, if the N, P, and K were taken up in a balanced manner. In other words, whatever the yield potential was, the optimal nutrient accumulation required to produce 1000 kg seed was the same when the yield reached about 60 to 70% of potential yield (**Figure 2**).

The QUEFTS model predicted a balanced nutrient accumulation of 55.4 kg N, 7.9 kg P, and 20.1 kg K per t of seed when the yield reached about 60 to 70% of the potential yield and an IE of 18.1 kg seed/kg N, 126.6 kg seed/kg P, and 49.8 kg seed/kg K for soybean in China. The optimal N: P: K ratio in the aboveground parts was about 7: 1: 2.5.

Seed nutrient removal could be also simulated by the QUEFTS model. The model indicated that the balanced N, P, and K removal required to produce 1000 kg seed was 48.3 kg N, 5.9 kg P, and 12.2 kg K when the targeted yield reached 60 to 70% of the potential yield. Compared to the total nutrient uptake in aboveground plant parts, approximately 87, 74 and 61% of N, P, and K accumulated in seed and was removed

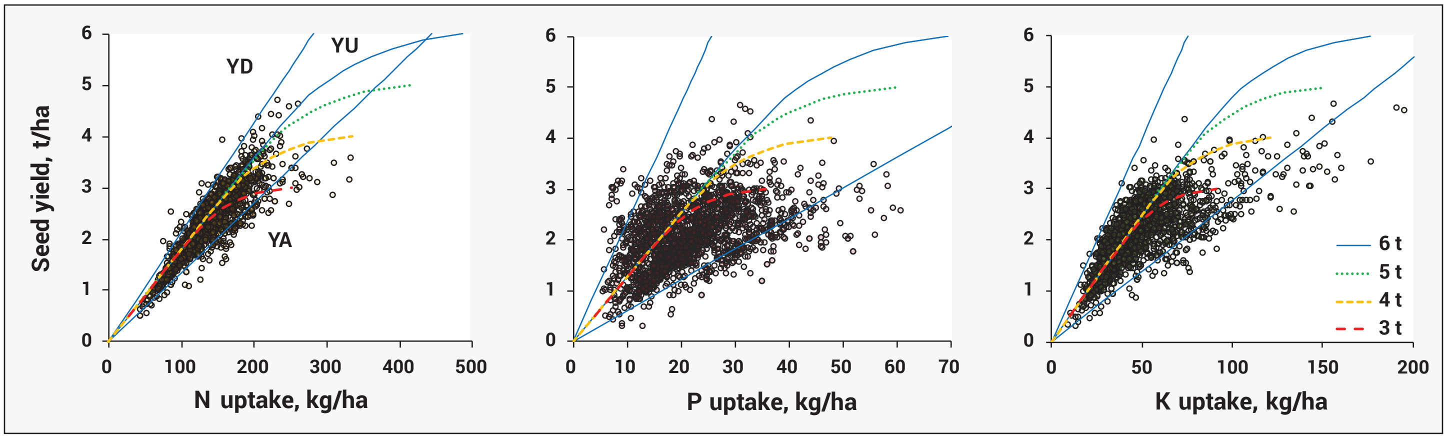

Figure 2. The relationship between seed yield and nutrient accumulation of N, P, and K in aboveground parts at different target yields simulated by the QUEFTS model for soybean in China. YD, YA, and YU represented the maximum dilution, maximum accumulation, and balanced uptake of N, P, or K in aboveground parts for a specific target yield, respectively. The range of yield potential for soybean was from 3.0 to 6.0 t/ha.

from the field with harvest. In addition, biological N_2 fixation should be also considered for N fertilizer recommendation, because soybean is partly relying on biological N_2 fixation.

Field Validation

The relationship between observed and simulated nutrient uptake was analyzed using field experiments conducted in 2014 and 2015 in Northeast China.

While there was some deviation for P and K, the observed and simulated N, P, and K uptake in the aboveground parts occurred near the 1: 1 line, suggesting that the measured values agreed well with the simulated nutrient uptake and there was no significant deviation between each other (**Figure 3**).

Summary

The large datasets from a variety of growing environments were used to estimate the balanced nutrient requirements for soybean using the QUEFTS model. The model predicted a linear increase in aboveground dry matter or seed yield if nutrients were taken up in balance until yield reached about 60 to 70% of the yield potential. To produce 1000 kg seed of soybean in China, 55.4 kg N, 7.9 kg P and 20.1 kg K (N: P: K=7.0: 1: 2.5) were required in the aboveground parts, and the corresponding IEs were 18.1, 126.6, and 49.8 kg seed per kg of N, P, and K, respectively. The QUEFTS model also simulated 48.3 kg N, 5.9 kg P, and 12.2 kg K nutrient in seed per 1000 kg seed, accounting for 87, 74, and 61% of the N, P, and K in total aboveground parts, respectively. The field validation indicated that the QUEFTS model can be used to estimate balanced nutrient requirement and help develop robust fertilizer recommendations for soybean. **BC**

Acknowledgement

This article is a summary of 2017 paper published by Yang, F. et al. 2017. PLoS ONE 12(5): e0177509. https://doi.org/10.1371/journal.pone.0177509. The work is an outcome of activities of IPNI China Program within the IPNI Working Group on Nutrient Decision Support for Soybean Systems.

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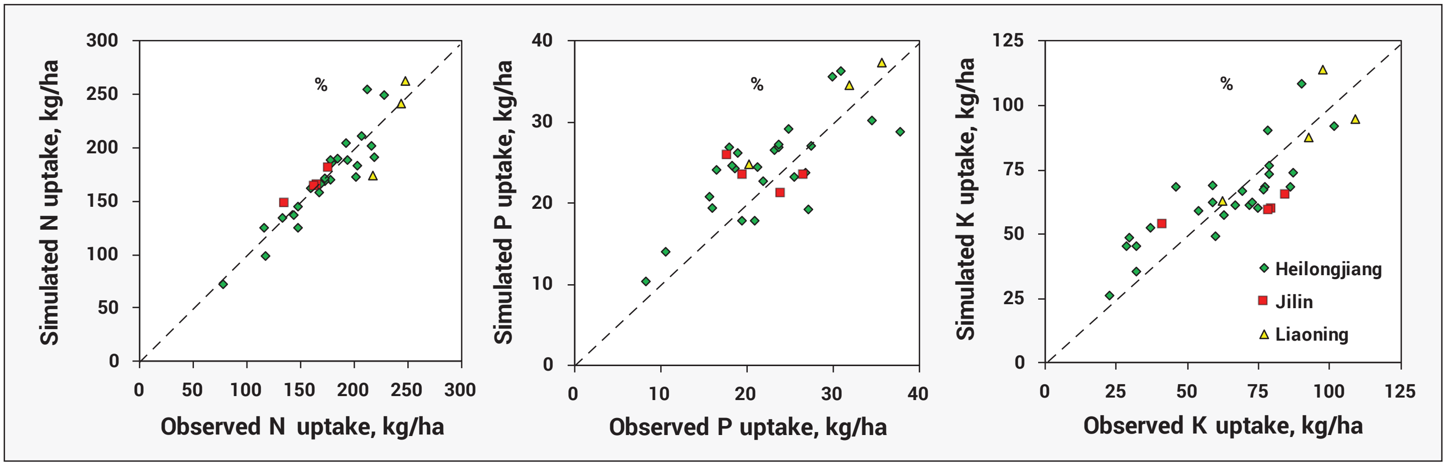

Figure 3. Comparisons of the simulated and observed N, P, and K uptake in soybean. The observed nutrient uptake was from field experiments, and the simulated data was from the QUEFTS model.

G. Barth Image

Nutrient Uptake Illustrated for Modern, High-Yielding Soybean

By Gabriel Barth, Eros Francisco, Juliana Tamie Suyama, and Fernando Garcia

Soybean has grown to be the major crop both in terms of land use and grain production in Brazil. In turn, soybean leads all crops in nutrient consumption. Fields growing high-yielding cultivars are capable of supporting grain yields that are twice the country's average, leading to questions about how these yields impact crop nutrient demand.

Uptake patterns find N and K in highest demand, with K having the fastest acquisition rate (63% of total K uptake occurs before pod filling). Remobilization from leaves, stems, and petioles provides a significant contribution to the total grain content of N, P, K, S, Cu, and Zn, while Mg, B, and Fe only remobilize from leaves.

KEYWORDS:
recommendations; high yields; accumulation; partitioning; removal

ABBREVIATIONS AND NOTES:
N = nitrogen; P = phosphorus; K = potassium; Ca = calcium; Mg = magnesium; S = sulfur; B = boron; Cu = copper; Fe = iron; Mn = manganese; Zn = zinc.

IPNI Project GBL-62

https://doi.org/10.24047/BC102111

Originally introduced to Brazil in 1882, soybean first became a significant grain crop in Rio Grande do Sul, Brazil's most southern state, during the first decade of the 1900s. Today, soybean dominates the country's agricultural landscape. The five-year average yield for soybean in Brazil is 3.0 t/ha, but farmers using modern varieties and best management practices are achieving 4.5 to 6.0 t/ha without irrigation. Genetic development and new technologies have created these popular, high-yielding soybean varieties with an indeterminate growth habit (i.e., vegetative growth continues through flowering). However, fertilizer recommendations are still traditionally based on older varieties with a determinate growth habit (i.e., vegetative growth ceases at flowering), which has led to a knowledge gap. In the study described below, researchers worked to quantify nutrient uptake, partitioning, and remobilization during the soybean growing season in order to collect the

Table 1. Nutrient accumulation associated with producing, on average, 6.6 t grain/ha with a modern soybean variety in the state of Paraná, Brazil.

Parameter	Total accumulation	Accumulation in grain	Harvest index[1]	Removal coefficient	Maximum accumulation rate[2]	Non-linear sigmoidal regression parameters a	X_0	b	Growth stage at max accumulation rate
	----- kg/ha -----		%	kg/t	kg/ha/d				
Biomass (DM[3])	12,554	5,841	47	-	162	13,391	75.1	21.4	R5.2
N	429	330	77	57	5.4	482	74.9	22.2	R5.2
P	34	29	84	4.9	0.49	37.6	75.0	19.1	R5.2
K	177	112	63	19	1.89	176	52.7	23.4	R1
Ca	100	19	19	3.3	1.36	109	67.7	20.1	R4
Mg	43	16	36	2.7	0.50	47.4	70.4	23.9	R5.2
S	19	12	65	2.1	0.27	20.2	65.3	18.5	R4
	----- g/ha -----		%	g/t	g/ha/d				
B	250	89	36	15	3.3	268	62.0	20.1	R3
Cu	100	62	63	11	1.4	102	61.1	18.7	R3
Fe	1,695	703	42	120	17	1,914	73.0	28.6	R5.2
Mn	793	140	18	24	11	836	72.7	19.2	R5.2
Zn	344	211	61	36	4.8	377	69.1	19.8	R5.2

[1] Harvest index: percentage of total nutrient accumulation that is present in the grain.
[2] Maximum accumulation rate was obtained using a non-linear sigmoidal regression: $y = \frac{a}{1+e^{-\frac{(X-Xo)}{b}}}$, where y is maximum accumulation rate, a and b are coefficients, and Xo is the date after planting with maximum accumulation rate.
[3] DM = dry matter.

data critical to assessing modern soybean crop requirements (amounts and timings) for nutrient application.

The field study was conducted at the ABC Foundation Experimental Station in Ponta Grossa, Paraná, Brazil, on a typical Oxisol clay soil cultivated for 30 years under a no-till soybean-oat-maize-wheat rotation system. Soil at the site (0 to 20 cm) had pH($CaCl_2$) 5.1, $P_{(resin)}$ 47 mg/dm^3, $K_{(resin)}$ 97 mg/dm^3, base saturation 61%, and organic matter (OM) 3.6%. A modern, high-yielding soybean variety (NA 5909RG; 6.9 relative maturity) was planted with a 40-cm row spacing to achieve a final stand of approximately 350,000 plants/ha. Agronomic management at planting included seed inoculation and a N-P_2O_5-K_2O blend of 0-20-20 applied at 300 kg/ha. Dry matter production and accumulation of N, P, K, Ca, Mg, S, B, Cu, Fe, Mn, and Zn were determined at nine growth stages: V4 (fourth trifoliate), V7 (seventh trifoliate), R1 (beginning flowering), R4 (full pod), R5.2 (early seed filling), R5.4 (late seed filling), R6 (full seed), R7 (beginning maturity), and R8 (full maturity) (Ciampitti, 2017). Representative plants were separated into stem (stems and petioles), leaf (individual leaves), reproductive (flowers and pods), and grain tissue components.

Nutrient Uptake and Removal

Average grain yield at the site was 6.6 t/ha (13% moisture content), two times higher than Brazil's average yield. Crop nutrient uptake and removal, harvest index (HI), and maximum accumulation rate and growth stage of occurrence are provided in **Table 1**.

As described by Bender et al. (2015), grain nutrient HI values are relative indicators of nutrient partitioning to the grain. In this study, six nutrients had HI values above 50%: P (84), N (77), S (65), K (63), Cu (63), and Zn (61) (**Table 1**). These results are similar to previous research with the exception of K and Zn, which were notably higher in this study. High HI values should represent a concern for high-yielding fields where large removal of key nutrients may impact the sustainability of soybean production unless adequate fertilizer input is provided.

Timing and Rate of Nutrient Uptake

Nutrients with the most rapid time of acquisition were K, Cu, and B with 63%, 58%, and 57% of total uptake, respectively, occurring before the onset of the seed filling growth stage (R4) (**Figures 1 and 2**). The uptake of other nutrients was more evenly distributed during vegetative and seed-filling growth stages. Phosphorus, N, and Zn uptake was the slowest with 39%, 43%, and 43% of total uptake acquired at R4, respectively. Maximum accumulation rates occurred as follows: K at R1 (beginning flowering), B and Cu at R3 (beginning pod), Ca and S at R4 (full pod), and N, P, Mg, Fe, Mn, and Zn at R5.2 (early seed filling) (**Table 1**). As mentioned by Bender et al. (2015), the proportion of total nutrient accumulation acquired during seed filling in

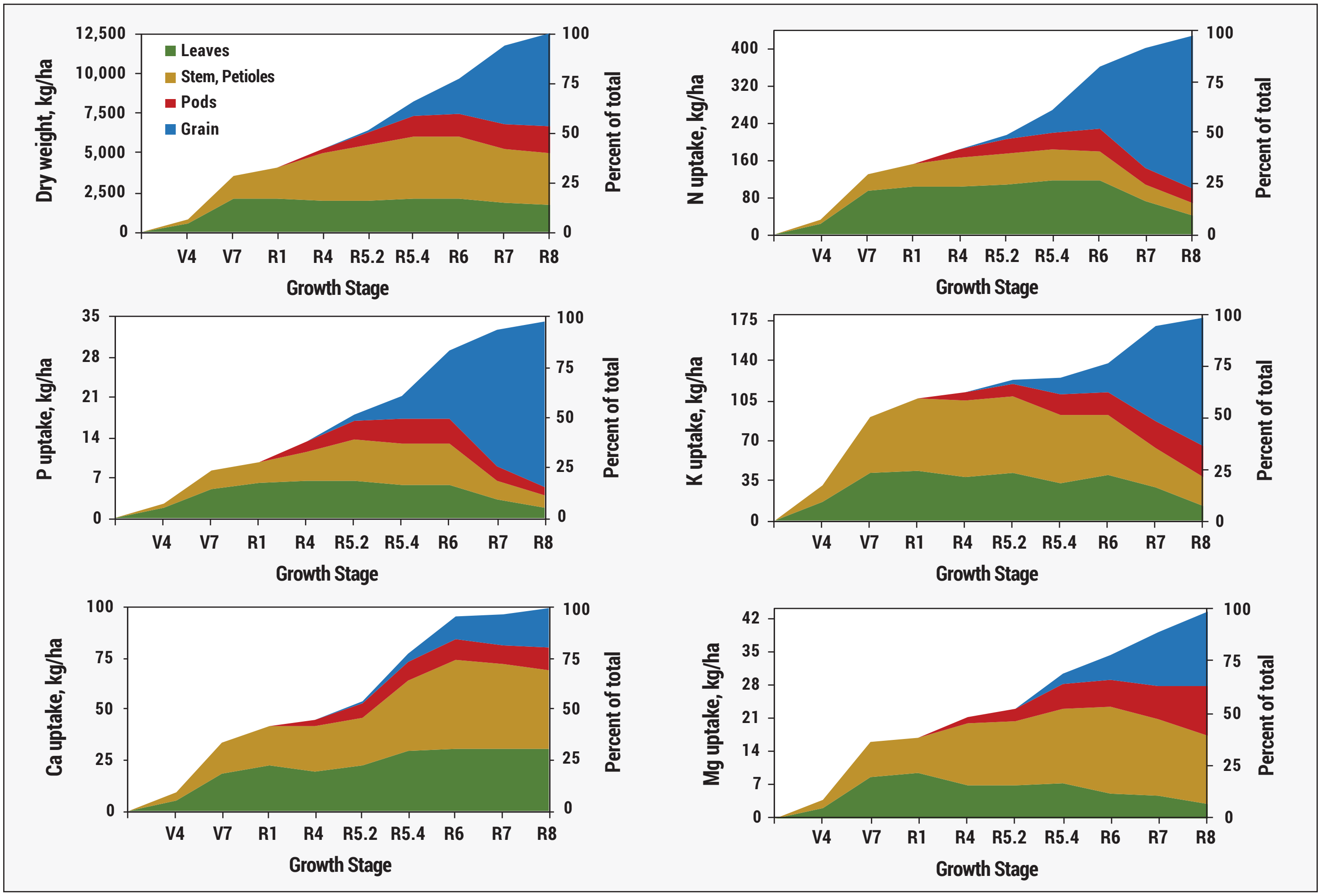

Figure 1. The seasonal accumulation and partitioning of dry matter, N, P, K, Ca, and Mg for an average yield level of 6.6 t grain/ha with a modern soybean cultivar.

modern cultivars has increased over time (**Table 2**), especially for N, P, Ca, and Mg, which have increased by an average of 42% compared to data from the 1970's. This means that higher-yielding cultivars have the potential to accumulate more nutrients.

Grain nutrients are acquired from direct uptake, partitioning, or remobilization from others parts. In the current study, remobilization from leaves, stem, and petioles was responsible for 33% of total grain content of N, P, S, and Cu, while K and Zn showed 61% and 17%, respectively. Some nutrients remobilized only from leaves Mg, B, and Fe. Calcium and Mn accumulated in all parts showed no remobilization.

Implications for Soybean Production

The high N demand in this study (over 400 kg per ha) was mostly met by biological N_2 fixation (BNF) since no mineral N was applied and high soil N supply is not expected from soil with less than 3.6% OM content. Therefore, seed inoculation with Bradyrhizobium is very important to obtain high yields in tropical soils. However,

Table 2. Percentage of total nutrient accumulation after the completion of R4, as compared to other nutrient accumulation studies. Days after planting (DAP) was used to estimate the length of time spent during specific phase of crop growth across studies.

Parameter	Hammond et al., 1951*	Hanway and Weber, 1971*	Bender et al., 2015	Current study
	------------- Growth season information -------------			
DAP to R4	80 d	75 d	70 d	68 d
DAP to R8	135 d	126 d	123 d	130 d
Approximate days during seed filling	55 d	51 d	53 d	62 d
	Percentage of total nutrient accumulation after the completion of R4			
Biomass	34	42	51	58
N	37	40	46	57
P	35	43	45	61
K	29	42	28	37
Ca	36	-	45	55
Mg	31	-	49	51
S	-	-	-	47
B	-	-	-	42
Cu	-	-	-	43
Fe	-	-	-	45
Mn	-	-	-	54
Zn	-	-	-	57

* Data adapted by Bender et al., 2015

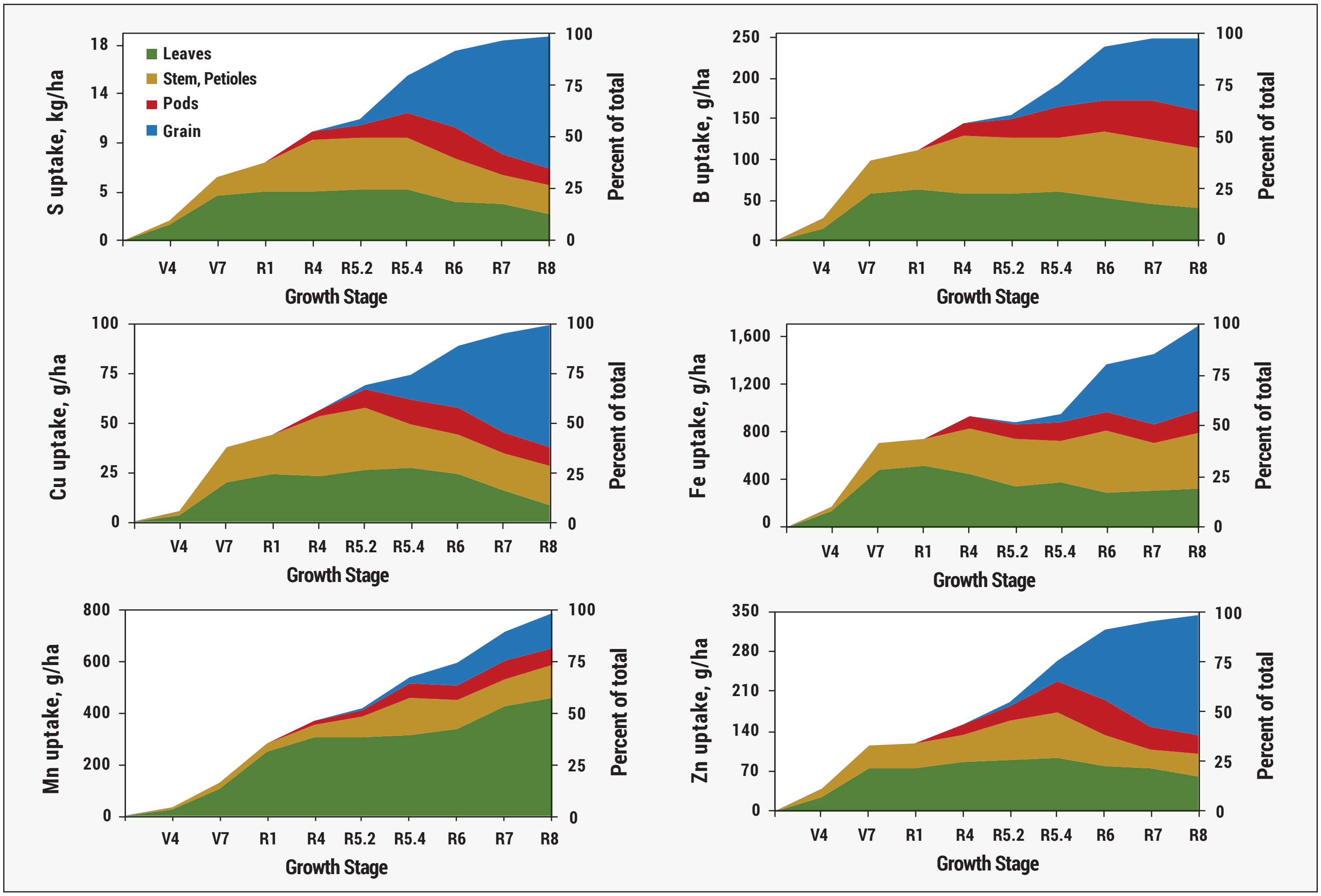

Figure 2. The seasonal accumulation and partitioning of S, B, Cu, Fe, Mn, and Zn for an average yield level of 6.6 t grain/ha with a modern soybean cultivar.

View Interactive Charts!

BNF efficiency is suppressed by soil conditions such as high acidity, poor aeration/compaction, and high temperature—all of which can be managed. Potassium uptake was noticeably high and rapid, which requires good soil K availability in the first half of the growing season. Potassium applications should occur near planting and rates recommended by soil testing. A split application of K further along in the season may be strategic to overcome any leaching losses in sandy soils. The high percentage of nutrient accumulation after the full pod stage indicates that good nutrient supply during seed filling stages are crucial to sustain high yields. In Brazil, soybean fields are heavily attacked by Asian rust and worms and bugs that can cause significant damage to parts of the plant. Maintaining good control over these diseases and pests is key to avoiding the loss of leaves and stems that are the source of remobilized nutrients.

Conclusions

The objective of this study was to quantify nutrient uptake, partitioning, and remobilization of a high yield soybean crop. The highest uptake by high-yielding soybean varieties is N, K, and Ca, and attention for the amount and timing of uptake involves N and K. In the current study, six nutrients presented HI values higher than 50%: P (84), N (77), S (65), K (63), Cu (63), and Zn (61). Therefore, soil management and agronomic practices must be adequate to ensure nutrient availability through early and late season growth stages to meet soybean needs for these nutrients. Current findings on high-yielding soybean nutrient uptake and partitioning may contribute to existing agronomic recommendations and help best management practices to be performed providing nutrient availability all season-long. **BC**

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Residual Effect of Potassium Fertilizer on Potato in Western Siberia

By Vladimir Yakimenko and Vladimir Nosov

This long-term field experiment revealed that the residual effect of K fertilization on potato yield may last 4 to 5 years depending on the prior application rates. During this period, the decline in exchangeable and non-exchangeable soil K was considerably larger than crop K removal.

KEYWORDS:
exchangeable K; non-exchangeable K; tuber yield; K balance; long-term experiments

ABBREVIATIONS AND NOTES:
N = nitrogen; P = phosphorus; K = potassium; ppm = parts per million.

https://doi.org/10.24047/BC102115

The optimization of crop K nutrition is an important area of research for the Siberian region where an increasing area is being exposed to soil K depletion. A long-term study, established by the Institute of Soil Science and Agrochemistry, Siberian Branch of Russian Academy of Sciences, in the forest steppe zone of Western Siberia, was specifically designed to identify the implications of omitting K fertilizer from the region's vegetable and potato-growing, grey forest soils.

The study was established in 1988 on virgin (uncultivated) soil. Vegetable crops were grown in rotation at this site between 1988 and 2000, which were followed by monocropped potato (Yakimenko, 2003; 2006; Yakimenko and Nosov, 2013). Annual application rates of K began in 1988 and treatments ranged from 0 to 150 kg K_2O/ha.

In 2008, the field was divided into a split-plot design to examine the drawdown of soil K under annual potato cropping with no further K input. Exchangeable soil K was extracted with 1 M ammonium acetate solution (1:10), easily exchangeable K with 0.0025 M calcium chloride (1:2), and non-exchangeable K with 1 M nitric acid (1:10) following each potato harvest.

Easily Exchangeable K

Easily exchangeable K is rarely used to characterize the K fertility status of arable soils due to commonly low test values. Nevertheless, it offers diagnostic opportunities because of its sensitivity to soil K depletion and moreover this pool is less dependent on soil texture (Nosov et al., 1997; Yakimenko, 2003). A critical level of easily exchangeable K (i.e., when plants start to respond to K fertilizer application) was shown to be 10 ppm K_2O for soils of various texture (Yakimenko, 2003). For comparison, an increase in easily exchangeable soil K concentration to >30 ppm K_2O may result in a considerable increase in non-productive (luxury) crop K uptake, and possible risk of K leaching below the rooting zone.

The impact of omitting potassium (right) had immediate impacts on potato growth.

In Novosibirsk, easily exchangeable soil K rapidly fell below the critical concentration after K fertilizer was omitted (**Table 1**). This was observed in the first year with lower rates (<60 kg K_2O/ha) and in the second year under higher rates (<90 kg K_2O/ha). Easily exchangeable soil K decreased below critical levels after the fifth year with treatments that had provided either 120 or 150 kg K_2O/ha.

Table 1. Residual effect of K fertilizer on easily exchangeable soil K. Fertilizer K was applied for 20 years before stopping in 2008.

Prior treatment, kg K_2O/ha	2008	2009	2010	2011	2012
	- - - - - - - - - - - - -	- - - - - -	K_2O, ppm	- - - - - -	- - - - - - - - - - - - -
K_0	5	3	5	4	5
K_{30}	5	4	5	5	5
K_{60}	8	6	6	5	5
K_{90}	12	8	7	6	5
K_{120}	25	15	16	12	9
K_{150}	32	25	22	17	10
LSD (p = 0.05)	12	15	13	14	15

All treatments annually received 100 kg N/ha and 60 kg P_2O_5/ha. All K fertilizer was applied prior to 2008.

Exchangeable K

Exchangeable soil K in the zero K treatment decreased from 120 to 80 ppm over the first 4 to 5 years after the initial study began in 1988 (data not shown). The exchangeable K

Table 2. Residual effect of K fertilizer on exchangeable K.

Prior treatment, kg K_2O/ha	2008	2009	2010	2011	2012
	- - - - - - - - - - - -		K_2O, ppm	- - - - - - - - - - - -	
K_0	80	79	79	81	78
K_{30}	100	83	89	80	72
K_{60}	124	90	92	83	72
K_{90}	145	103	97	95	90
K_{120}	263	161	153	117	100
K_{150}	355	228	181	142	117
LSD (p = 0.05)	71	65	67	63	63

Table 3. Residual effect of K fertilizer on non-exchangeable K concentration.

Prior treatment, kg K_2O/ha	2008	2009	2010	2011	2012
	- - - - - - - - - - - -		K_2O, ppm	- - - - - - - - - - - -	
K_0	950	900	920	900	920
K_{30}	1,050	930	910	900	910
K_{60}	1,160	1,080	1,000	990	920
K_{90}	1,270	1,210	1,140	1,070	950
K_{120}	1,390	1,320	1,300	1,250	1,200
K_{150}	1,670	1,570	1,420	1,330	1,250
LSD (p = 0.05)	150	140	160	150	140

pool for this control remained at this minimum plateau concentration throughout the remainder of the study—including the period between 2008 and 2012 (**Table 2**). These minimum concentrations of exchangeable K depend on soil cation exchange capacity (CEC), which buffers against nutrient removal through crop harvest. In Western Siberia, this minimum is between 0.8 to 0.9% of the CEC for loam soils and 1.0 to 1.2% for sandy loam soils (Yakimenko, 2003). The minimum amount of exchangeable K is seemingly associated with K adsorbed on intramiccelar surfaces of the soil exchange complex (Yakimenko, 2015). Evidently, these exchangeable K surfaces are resistant to K depletion resulting from continuous potato cropping.

It is important to note that this apparent stability in exchangeable K is often wrongly interpreted as a positive situation while monitoring soil K fertility status. However, since this stabilization of exchangeable K occurs at a minimum concentration, many crops, and especially K-demanding crops like potato and vegetables, can suffer from K deficiency under this scenario.

Exchangeable soil K also declined in treatments that had received K fertilizer (**Table 2**). It decreased to the minimum concentration, or approached the minimum, in the second year for treatments that had previously received lower K rates (K_{30} and K_{60}). Treatments previously receiving 90 kg K_2O/ha saw a continual decline in exchangeable K concentrations in the years following K omission. Exchangeable K fell most noticeably in treatments that had the highest initial K concentrations (previously receiving 120 or 150 kg K_2O/ha). Exchangeable K concentrations declined rapidly in these treatments over the five years of cropping, with the greatest decrease occuring within the first two years after stopping K fertilization.

Non-exchangeable K

Non-exchangeable K is an estimate of the soil K reserve that can replenish the exchangeable soil K pool. Non-exchangeable K is commonly considered as K^+ ions situated within the interlayer positions of 2:1 type clay minerals. Non-exchangeable K concentrations stabilized in the zero K control in spite of the continual K removal through crop harvest (**Table 3**). Therefore, non-exchangeable K also appeared to reach a steady-state concentration near 900 ppm.

Omission of K fertilizer resulted in a decrease in non-exchangeable soil K. This decrease was most noticeable in treatments with higher K rates, which fell by between 300 and 600 ppm K_2O compared to concentrations measured in 2007 (data not shown).

The relatively stable measurements of non-exchangeable K during an extended period of negative K balance suggests that an even more slowly available K is helping to maintain the existing equilibrium between soil K pools. This slowly available K pool seems to be non-extractable with the acid solutions used in this study and may be originating from primary soil minerals such as micas and feldspars. Micaceous structures have been shown to be the basic minerals in 'physical clay' (soil particles <0.01 mm) mainly affecting the K fertility status of this soil (Yakimenko, 2003).

Potato Tuber Yield

Tuber yield was strongly dependent on the fluctuations in weather during the growing season (**Figure 1**). The summer seasons of 2008, 2010, and especially 2012 were dry, but 2009 and 2011 seasons were favorable in both tempera-

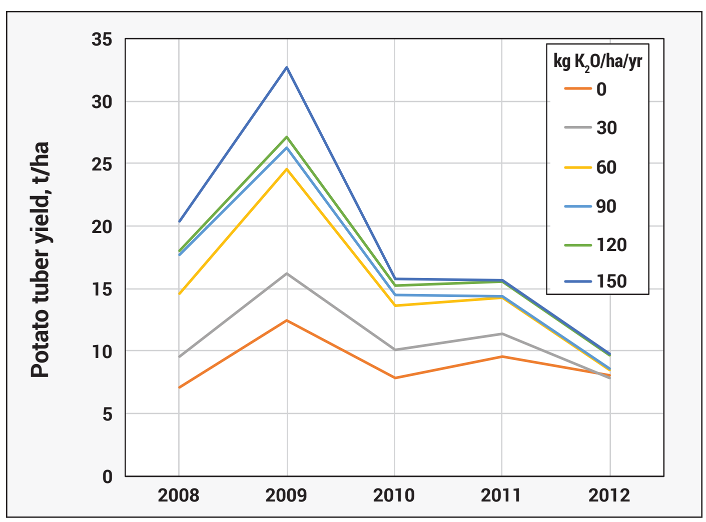

Figure 1. Residual effect of K fertilizer on potato yield. Prior to 2008, K fertilization ranged from 0 to 150 kg K_2O/ha/yr.

ture and water availability.

Potato productivity also followed the changes in soil K status noted above. Yields in treatments with more residual fertilizer K were considerably higher compared to yields from the continuous zero-K control. However, tuber yields equalized across treatments by 2012. The relative yield produced under the residual effect of K fertilizer in the last experimental year was only 60 to 65% of the yield obtained under continuous application of K fertilizer (data not shown, Yakimenko, 2015). Therefore, it appears that the residual effect of K application could no longer support high yields by the fifth year of cropping.

Some residual benefit of K fertilizer might be continued further in treatments that received the highest K rates, but may only be expected in a favorable growing season. The final soil K concentration was not sufficient for potato nutrition in a dry year, which was the case in 2011, the last experimental year of this study.

Potassium Balances

A K balance was calculated based on fertilizer K input and K removal in the tubers and vines of potato that were also removed (**Table 4**). Potassium uptake by potato including vines ranged from 27 kg K_2O/ha/yr in the zero-K control to 95 kg K_2O/ha/yr for the highest residual K treatment. Potassium removal was directly related to soil K fertility build up over the previous years of K fertilization. Plots with the highest K inputs had the most negative K balances.

Table 4. Total 5-year K balance for potatoes growing on plots with a prior 20-yr history of K fertilization.

Prior treatment, kg K_2O/ha	Crop removal, kg/ha	- - K_2O balance - - kg/ha	ppm*
K_0	135	-135	-68
K_{30}	176	-176	-88
K_{60}	263	-263	-132
K_{90}	318	-318	-159
K_{120}	360	-360	-180
K_{150}	477	-477	-239

*Estimated cumulative changes in soil K pools in the arable soil layer, 0 to 20 cm depth (assumed bulk density of 1.0 g/cm^3)

The major changes in soil K forms measured during this experiment have occurred in the 0 to 20-cm soil layer regardless of the K balance (Yakimenko, 2007). The extent of actual soil K depletion seems to considerably exceed the absolute values (ppm) of the negative K balances estimated in treatments that received K fertilizer in the past. Potassium removal with crop harvest alone does not explain the significant decrease in soil K forms observed over the years presented. Soil fixation of previously applied K may explain such findings. This fixed K is apparently not extracted with the acid solutions used in this study.

Summary

This study on the residual effects of accumulated soil K due to long-term application of K fertilizer indicates that the duration of residual K value for crop production depends on the K accumulation during the previous years. However, for these grey forest soils, any high quantities of K formed in the pools of varying plant availability over 20 years of K fertilization quickly revert (over 4 to 5 years) to the lower K concentrations inherent to uncultivated soils. **BC**

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Does Balanced Fertilization Improve Soil Health?

By Laura Ferreras, Gustavo Magra, Andres Saperdi, Silvia Toresani, Miguel Boxler, Santiago Gallo, Ricardo Pozzi, Adrian Correndo, and Fernando Garcia

Crop fertilization not only improves crop yields but also generates positive changes in soil health, which contributes to cropping system sustainability. Balanced fertilization during 12 consecutive years improved soil organic matter, soil microbial population and enzyme activity, and soil aggregate stability in fields with long annual cropping history and coarse soil texture. Similar effects were not found in fields with shorter annual cropping history and finer soil texture.

KEYWORDS:
long-term experiments; Pampas; crop rotation; C sequestration; cropping history.

ABBREVIATIONS AND NOTES:
N = nitrogen; P = phosphorus; S = sulfur; C = carbon; ppm = parts per million.

IPNI Project ARG-12

https://doi.org/10.24047/BC102118

The Argentine Pampas is dominated by fertile Mollisol soils that are broadly characterized as having deep soil profiles high in organic matter and agricultural suitability. Yet inadequate soil management creates erosion and promotes soil degradation processes. A lack of crop rotation schemes under soybean monoculture, and negative soil nutrient balances have caused up to 50% reductions in soil organic matter (SOM) compared to original values, and have negatively affected crop yields (Álvarez, 2001; Sainz Rozas et al., 2011).

Sustainable agriculture should be based on getting better crop production efficiencies per resource unit. But strategies are needed to preserve the natural resources needed to meet global food demands (Masera et al., 2000). In order to generate information about crop nutrition management for the central Pampas, the Southern Santa Fe Region of CREA (*Consorcios Regionales de Experimentación Agrícola*), IPNI Latin America Southern Cone Program, and *Agroservicios Pampeanos* (ASP, Agrium Inc.) established an on-farm experimental network to evaluate the effects of long-term fertilization on crop yields, nutrient use efficiency, economics, and soil health (García et al., 2010). This CREA Southern Santa Fe Crop Nutrition Network (CSSFNN) is still active in five out of the initial eleven on-farm experiments that were initiated in 2000. This report provides an analysis of soil physical and biological properties after a 12-year period of contrasting crop nutrient management.

Five sites within the CSSFNN were included in this study (**Table 1**). Plot size was 25 to 30-m wide and 65 to 70-m long. Three treatments included: i) soils with no agricultural history (Reference) that were adjacent to the experimental plots, ii) agricultural soils that have not been fertilized (Unfertilized) between 2000 and 2012, and iii) agricultural soils that have been fertilized with N, P, and S (fertilized) during this same 12-year period. Nitrogen, P, and S are the most deficient nutrients for this region. Nitrogen was applied at optimum rates for high-yielding crops according to local research in maize and wheat, but N was not added to soybean crops. Phosphorus and S rates were decided each season before planting according to the expected crop yield and P and S removal. All nutrients were applied before or at planting using fertilizer blends. The sources of N, P, and S were urea (46-0-0), mono-ammonium phosphate (12-52-0), and calcium sulfate (0-0-0-19S), respectively. Each site included only one rotation at a time so not all of the crop phases were present every year.

In 2012, soil physical and biological properties were examined under each treatment. Soil variables included: soil organic carbon (SOC) due to its role on nutrient supply and soil structure; microbial biomass carbon (MBC) and total enzyme activity (FDA - fluorescein diacetate) due to their roles within soil organic matter (SOM) and nutrient release dynamics; soil bulk density (SBD) which is related to soil porosity; and lastly ag-

Table 1. Soil taxonomy, cropping history, and soil texture for the five study sites. Two sites has a corn-double-cropped wheat/soybean (C-W/S) rotation while three had a corn-soybean-double-cropped wheat/soybean (C-S-W/S) rotation.

	----- C-W/S Rotation -----		------------ C-S-W/S Rotation ------------		
Properties	Balducci	San Alfredo	La Blanca	La Hansa	Lambaré
Soil classification	Typic Hapludoll	Typic Argiudoll	Typic Hapludoll	Aquic Argiudoll	Typic Argiudoll
Years of continuous row cropping*	+60	8	6	+20	12
Textural class (surface layer)	Silt loam	Silt loam	Silt loam	Silt loam	Silt loam
Clay, %	12	18	16	18	20
Silt, %	53	62	56	79	77
Sand, %	35	20	28	3	3

*years after the last pasture season.

gregate stability (AS) due to its relationship with SOC, soil water content, and soil aeration.

Soil Organic Carbon

At all sites, lower SOC was observed for both unfertilized and fertilized treatments when compared with adjacent reference soils (**Figure 1**). The Balducci and La Hansa sites

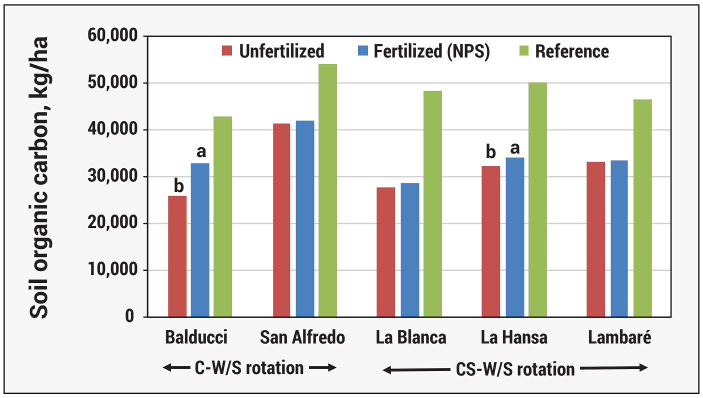

Figure 1. Soil organic carbon (0 to 15 cm) for unfertilized, fertilized, and reference plots. Different letters indicate significant differences between treatments after 12 years of study ($p \leq 0.05$).

had the longest annual cropping histories and showed significant differences in SOC between fertilized and unfertilized plots (i.e., 7,010 and 1,782 kg SOC/ha, respectively). Balanced NPS fertilization increased both crop biomass and grain yield, which produced large inputs of C for the soil.

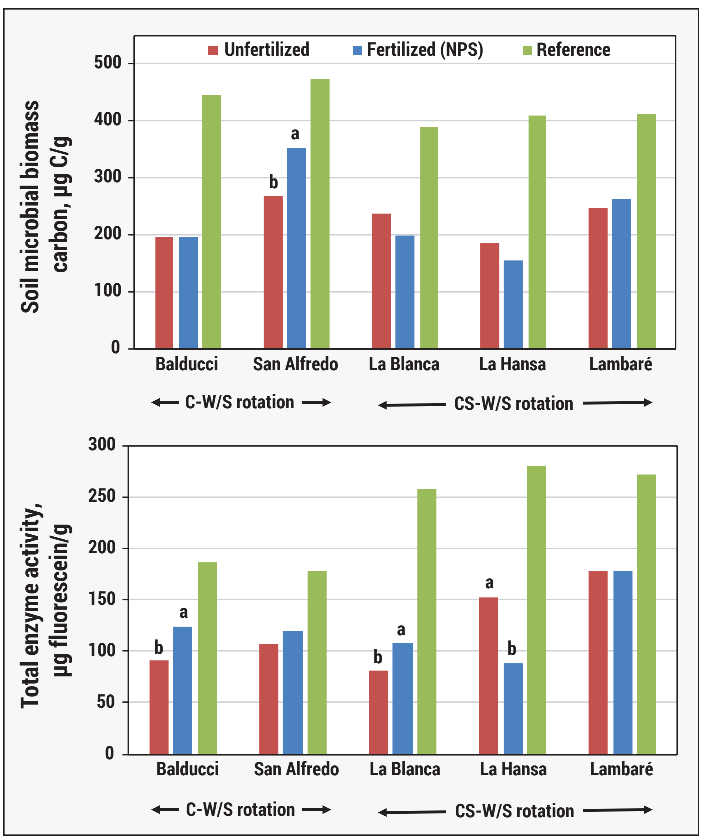

Figure 2. Soil microbial biomass carbon (top) and total enzyme activity (FDA; Bottom) for unfertilized, fertilized, and reference plots. Different letters indicate significant differences between treatments after 12 years of study ($p \leq 0.05$).

Soil cover under fertilized (top) and unfertilized (bottom) plots at the La Hansa site during the 2012-13 cropping season.

The sites at La Blanca, San Alfredo, and Lambaré all had shorter cropping histories and showed no significant differences in SOC amongst treatments.

Microbial Biomass and Enzyme Activity

Reference soils always had the highest MBC and FDA indices. Soil MBC was higher in the fertilized plots compared to the unfertilized plots in San Alfredo, but no other sites showed this difference (**Figure 2a**). The FDA indicator revealed higher enzyme activity with fertilization at La Blanca and Balducci; however, lower enzyme activity was also detected within fertilized plots at La Hansa (**Figure 2b**).

Enzymes determined by FDA hydrolysis are estearases, proteases, and lipases, which are involved in the decomposition of different types of residues. Normally they are exocellular and exist in a free-form in soil. Input of residues and increased SOC might promote soil microbial populations and enzymatic activity. Long-term building of SOM under balanced fertilization may contribute to the retention and

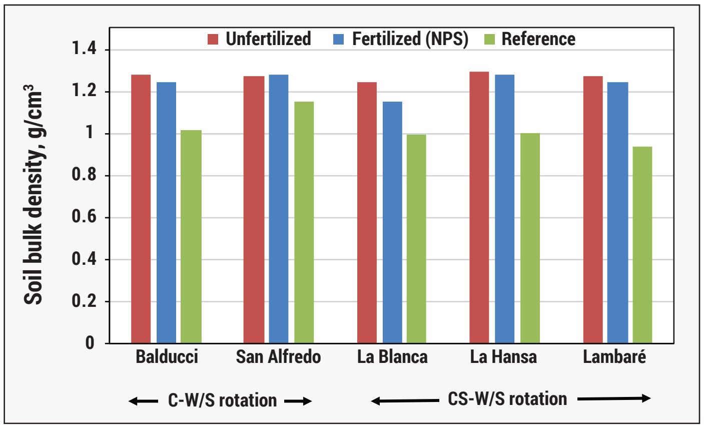

Figure 3. Soil bulk density (SBD) at the soil surface for unfertilized, fertilized, and reference plots after 12 years of study.

protection of these exocellular enzymes.

Bulk Density

Soil bulk density measurements produced no significant differences between unfertilized and fertilized plots (**Figure 3**). The lowest bulk densities were consistently observed in the reference soils due to their lack of disturbance. Root growth tends to be restricted in soils with bulk densities of 1.6 g/cm^3 or higher.

Aggregate Stability

High SOM and clay content allows for greater soil cohesion and AS. Good AS is critical for the storage and transmission of water, nutrients, and air, which in turn promote the growth and development of crops and soil organisms. Reference soils always had higher AS compared to unfertilized or fertilized plots. The Hapludoll sites (Balducci and La Blanca) had the lowest AS due to lower clay and SOC at the soil surface (**Figure 4**). Argiudolls (San Alfredo, La Hansa and Lambaré) showed higher levels of AS. After 12 years, fertilized plots showed higher AS compared to unfertilized plots at the sites with coarser-textured soils (Balducci and La Blanca) while no differences were detected among the sites with finer-textured soils.

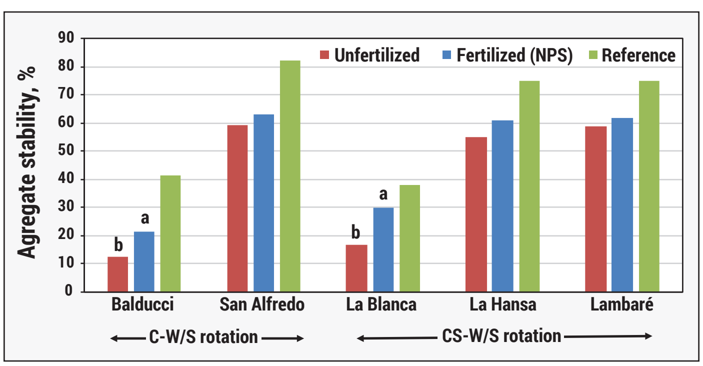

Figure 4. Soil aggregates stability at the soil surface (0 to 20 cm) for unfertilized, fertilized, and reference plots. Different letters indicate significant differences between fertilization management situations after 12 years of study ($p \leq 0.05$).

Summary

The five study sites showed different responses to balanced NPS fertilization, which were dependent on crop rotation, cropping history, and soil texture. For the short crop rotation (C-W/S), with larger C inputs from residues, fertilization resulted in higher SOC, FDA, and AS in the site with coarser soil texture and longer cropping history (i.e., Balducci). Fertilization only increased MBC at the finer-textured site with shorter cropping history (i.e., San Alfredo). In the long crop rotation (C-S-W/S), the most significant changes were observed in the site with the coarser texture (La Blanca) where there were increases in FDA and AS. At La Hansa (finer texture but longer cropping history), there were only changes in SOC and FDA. The Lambare site, with the shortest cropping history and fine soil texture, did not show any impact of fertilization on the selected soil properties after 12 years.

There are important long-term effects of balanced crop nutrition management on soil health. The improvement of soil health is one of the most relevant issues that agronomists face in order to get the best performance from farming systems within the Pampas. Better crop nutrition translated into higher yields in these experiments (+27% to +120% depending on the site). Directly or indirectly, and through a positive feedback process that supports soil C sequestration, soil improvement, and crop growth, balanced fertilization can improve soil structure, soil water dynamics, soil biological activity, as well as soil nutrient supply.

Conditions and results of this study would replicate in many areas of the central Pampas of Argentina. The Southern Santa Fe Region of CREA includes 160 farmers who crop approximately half a million ha under similar cropping systems found in this study. **BC**

Acknowledgement

The Nutrition Network CREA Southern Santa Fe is a joint project of CREA Southern Santa Fe, IPNI, and ASP, more information on this network is available at http://research.ipni.net/project/IPNI-2000-ARG-12.

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Phosphorus Placement for Annual Crops in the Tropics

By Luís Prochnow, Álvaro Resende, Adilson Junior, Eros Francisco, Valter Casarin, and Paulo Pavinato

Phosphorus interactions are complex in tropical soils. Many intense reactions take place that can prevent plant-available phosphate ions (HPO_4^{2-}, $H_2PO_4^-$) from reaching the crop. For example, ionic P can precipitate with Ca, Fe, and Al, be absorbed by microorganisms, or be adsorbed by soil colloids. Although generally taken up in lower amounts than other macronutrients (particularly N and K), more P needs to be added to soils of the tropics than any other nutrient. Agriculture in tropical soils of low fertility have very limited chance of success without adequate use of P inputs.

Agronomic research has established recommendations for improving P fertilization in the tropics. For example, highly soluble P fertilizers such as SSP, TSP, MAP, and DAP perform better when applied in-furrow as granules to soils with pH values ranging between 6.0 to 6.5. Reactive phosphate rock works best in a more powdered form, well mixed with soils having pH values less than 5.4.

Recently, while looking for better operational efficiency, Brazilian farmers with large areas have been challenging the above recommendation for highly water soluble P sources and they are increasingly broadcasting these fertilizers on the soil surface before seeding. Equipment has been replaced, employees trained, and other operations adjusted with this goal in mind. Now a common question from farmers in Brazil is “Should I broadcast P?” or “Should I continue to broadcast P?” Often this question is asked with the hope for a positive reply. In reality, the answers to the questions farmers ask on this issue are more complicated than a simple “yes” or “no”.

In fact, this matter can often bring intense debate between those in favor or against broadcasting P as both sides present data proving their points. In the short-term point of view of many, noticeably farmers, applying broadcast P may be more favorable. However, a more ample and long-term view may indicate that the widespread use of this practice can lead to environmental problems. Such a broad view is not often the focus of those making field-level decisions, but it should be present in the minds of those responsible for planning agriculture at country level, guiding environmental stewardship, and even maintaining open channels to international markets.

This article discusses principles for optimizing the placement of P in soils of the tropics—looking towards better agronomic, economic, environmental, and social outcomes. General guidelines are offered for short and long-term sustainability.

KEYWORDS:
broadcast; no-till; P placement; soluble P; runoff

ABBREVIATIONS AND NOTES:
N = nitrogen; P = phosphorus; K = potassium; Ca – calcium; Fe = iron; Al = aluminum; SSP = single superphosphate; TSP = triple superphosphate; MAP = monoammonium phosphate; DAP = diammonium phosphate; ppm = parts per million.

https://doi.org/10.24047/BC102121

Agronomic Aspects About the Placement of Phosphorus

Recommendations for the placement of soluble sources of P in tropical soils have always tried to minimize the contact of the fertilizer granule with the surface of soil particles as a means to improve efficiency. The low solubility of P compounds in the soil favors the recommendation to apply this P in close proximity to plant roots.

Two main strategies have been developed for P fertilization. The first, named *corrective fertilization*, has the goal to increase the soil P concentrations to near or above the critical value. This strategy can be very expensive for soils having high P fixation capacity because high rates of P fertilizer are required. The second more common approach is *maintenance fertilization*, which has the goal of nourishing each annual crop cycle. This approach uses lower rates applied in-furrow, is less expensive, but needs to be repeated each crop season. A third possibility involves a combination of both strategies by applying larger rates than required for maintenance fertilization, which increases the soil P concentration over time. In Brazil, there has never been a strategy recommending the surface broadcasting of soluble P at rates similar to a maintenance strategy. This ad-hoc approach has been created in the field specifically to optimize the operation of P application and facilitate more rapid planting of crops.

There is no general rule on how to place soluble sources of P in the soil. It is possible to obtain identical responses to either broadcast or in-furrow P. For farmers, or decision-makers at the field level, the first essential step is to understand the available P status throughout the whole soil profile. Gains due to more efficient farm field operations are always welcome, but they should not come at the expense of failing to consider a best practice for high yields and environmental protection. A good distribution of available P within the soil profile is important for such stability. As an example, **Table 1** summarizes data for available soil P concentrations at different soil depths within three soil management scenarios (A = natural ecosystem, B = surface broad-

Table 1. Availability of P in three soil management scenarios (A = natural ecosystem, B = P fertilizer applied on the soil surface, C = P fertilizer applied in-furrow in a well-managed, no-till cropping system).

	Management		
	A	B	C
Soil depth, cm	- - - - - - Soil P concentration, ppm* - - - - - -		
0 to 5	3	65	48
5 to 10	2	6	25
10 to 20	1	2	19
20 to 40	1	1	15
40 to 60	1	1	2

*Resin soil test P categories: very low = 0 to 6, low = 7 to 15, medium = 16 to 40, high = 41 to 80, very high ≥ 80.

cast P, C = in-furrow P in a well-managed, no-till system). The better distribution of P observed in scenario C gives a better chance for the growth and development of plant roots compared to scenario A with very low soil P status, and scenario B with P concentrated at the soil surface. Scenarios A and B are also susceptible to periods of low water supply that dries the soil surface first. Thus, continuous broadcast application of P may also lead to water stress in dry years as roots mainly develop within the top soil layers.

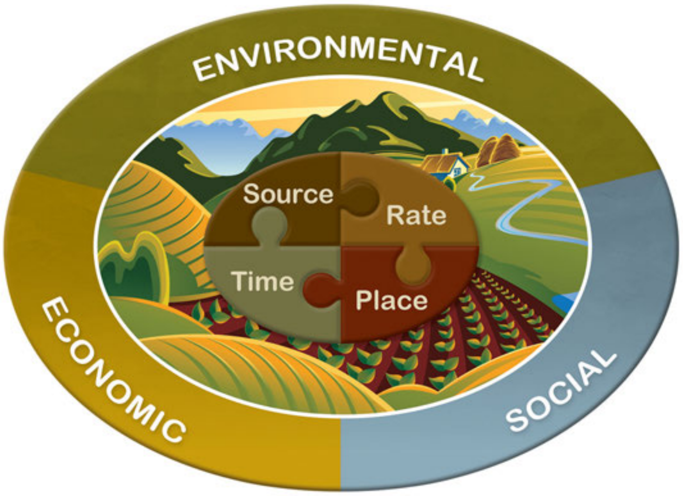
Environmental Aspects Related to the Placement of Phosphorus

Agriculture in general and P fertilization in particular are among the factors influencing the eutrophication of waters, a concern for both environmentalists and society. Eutrophication of water happens by different means, with one important mode being field runoff of water containing some portion of applied P (inorganic or organic). Water eutrophication can also be sourced to the discharge of P-containing sewage sludge from urban areas. Organic sources like manure or compost are another main source of P entering streams and water bodies, especially in areas close to intensive livestock production. These areas can accumulate a lot of manure and farmers tend to apply it at high rates within a short radius of their origin.

If P fertilizers are broadcast, soluble and particulate P will accumulate at the soil surface leaving a larger portion susceptible to reaching water reservoirs through runoff—even in the Oxisols of the tropics. When applying P fertilizer in-furrow, the chance of P movement with runoff decreases significantly because it is incorporated deeper into the soil. Local research is always necessary to establish the potential risks of the different methods of P placement to runoff.

E. Francisco/IPNI Image

Runoff happens – even in the well-drained Oxisols of the tropics.



Phosphorus fertilization, as well as that of any other nutrient, should be based on the principles of 4R Nutrient Stewardship that can identify the right combination of source, rate, time, and place for each specific field (IPNI, 2016).

Guidelines for the Placement of Phosphorus

In the absence of local research that can help farmers establish best practice, some general guidelines on the placement of fertilizer P are provided below.

New areas - When opening new areas (still common in the tropics), if financial resources are available, farmers can choose to correct low soil P and raise it above the critical concentration. Fertilizer should be broadcasted and then incorporated into the soil. Although this strategy has a higher initial cost, it will create conditions suited for better crop establishment for a new no-till area due to deeper root distribution in the soil profile. In many cases this strategy is used initially, but it does not prevent the need for the maintenance rates of P application.

Increasing soil P with time - If the goal is to correct soil P concentrations gradually from very low or low to medium or high, farmers should apply P fertilizer at rates that are higher than crop removal. It is recommended to avoid broadcast applications and apply P fertilizer in-furrow. Farmers should soil test regularly in order to monitor the increase in the soil P concentration and understand when to decrease their application rates.

Soil topography - Soils with sloping topography have a higher potential for P loss by runoff so fertilizer should be applied in-furrow and not broadcasted.

Soil profiles with P stratification - In soils with moderate P concentrations at the surface (0 to 10 cm) and very low or low soil P at 10 to 20 cm, other factors such as soil topography and the possibility for water stress should be considered. Generally, the higher the risk for water stress and the more sloping the field landscape, the greater the requirement is to apply P fertilizer in-furrow and avoid broadcast applications.

Soil profiles without P stratification and with sufficient available P - In soils with moderate to high P concentrations to at least the 20-cm depth, and a field landscape that offers a low risk for runoff, P fertilizer may be broadcast on the soil surface if faster fertilization and seeding operations are desired.

Alternate the placement - Varying the P placement strategy over time can be a good way to combine the advantages of the different systems available.

Plan for in-furrow P placement - Modern, satellite-guided planting equipment is able to ensure optimal seed placement relative to where bands of fertilizer P are applied. When time allows, farmers should rely on this benefit and apply P in-furrow before seeding (i.e., the slower operation) and switch to faster options when time pressures change.

Pay close attention to spatial variability of P - Phosphorus is a nutrient with high variability in the soil and soil P concentrations can vary greatly within short distances. Fields that have received P fertilizer for a number of years can have higher variability due to low P mobility in the soil and the resulting residual effect. Farmers should adjust application equipment so P distribution is uniform for both broadcast and more precise in-furrow systems. Correct adjustment of equipment may be even more important for broadcast fertilizer distribution due to differences in particle size amongst and within fertilizer products. Failure to account for this can create even higher variability in soil P concentrations.

Do no-till right - Cropping systems that have diverse crop rotations and which promote the accumulation of organic matter offer better conditions for water infiltration (Calonego et al., 2011; Moraes et al., 2016), which leads to protection against erosion and runoff. In Brazil, for example, about 50% of the area cultivated is done so under no-till. Unfortunately, many fields still lack both adequate crop rotation and surface residue on the soil surface. If managed well, a variety of crops (and crop roots) under no-till favors P distribution throughout the soil profile through biological incorporation. Certain grasses have robust root systems that help to absorb P. One example of this effect is shown in

TAKE IT TO THE FIELD

1. Farmers should promote practices that increase the soil P concentration throughout the profile and not just the surface.
2. In years with good water availability and P supply, expect little agronomic difference between broadcast or more localized P placements. Differences may only happen when the water supply is inadequate.

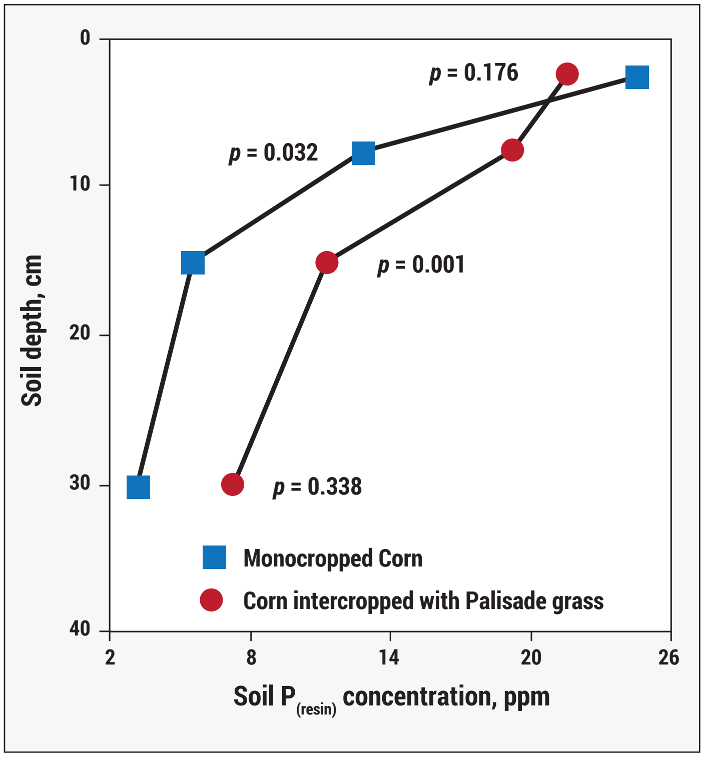


Figure 1. Farming systems including grasses may increase the soil P through the soil profile in well-managed no-till systems. Source: Crusciol et al. 2015.

Figure 1 where available P increased between 5 to 40 cm when corn was intercropped with palisade grass (*Urochloa brizantha*), as opposed to monocropped corn (Crusciol et al., 2015). If poorly managed, no-till generally favors the stratification of P in the soil profile, which leads to much higher P concentrations at the soil surface.

Monitor the spatial distribution of soil fertility - Evaluation of soil fertility at different soil depths (i.e., 0 to 10 cm and 10 to 20 cm) helps to determine the best way to nourish crops. Phosphorus concentration and soil acidity are essential to monitor within the profile in order to decide which strategy for P placement should be used.

Conclusions

The 4R Nutrient Stewardship concept of applying the right source of fertilizer, at the right rate, time, and place is fundamental for optimizing yields, profit, and for protecting the environment. These general concepts should be adapted to each and every farm field. The right placement of P depends on several factors, as described in this article. Generalized approaches to P fertilization should be avoided on the farm. Decisions on whether P fertilizer placement should be in-furrow, more localized, broadcast at the soil surface, or a combination of these practices should be defined locally and according to principles described in this article. **BC**

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Watershed-Scale Phosphorus Balances to Establish Reasonable Water Quality Expectations

By Heidi Peterson and Lawrence Baker

Addressing a watershed's nutrient impairment by reducing losses is an economical and long-term best management approach. When conservation practices designed to trap sediment are implemented to reduce agricultural P water quality impacts, nutrients are retained on the landscape. If improperly managed, this accumulated P can eventually leak out of the system through erosion or desorption from the soil, resulting in long-term losses of P to the stream, referred to as legacy P. Compiling a watershed-scale nutrient balance enables watershed managers to identify production areas where P use efficiency strategies could be incorporated into conventional conservation planning. This produces a more holistic approach to understanding nutrient cycling across the landscape, thereby enhancing prospects for meeting P loss reduction goals for water quality improvement.

Lisa Gjersvik Photo

Aerial view of farmland surrounding a creek within the Albert Lea Lake watershed in southern Minnesota.

Agricultural System Phosphorus Balance and Use Efficiency

A watershed's P mass balance for agriculture could be calculated on an annual basis using the general equation:

Δ P (Storage) = P Inputs - Deliberate P Outputs - Stream P Exports; where Δ P is the annual change of P stored in the watershed.

Inputs to consider would include any feed, livestock, manure, or fertilizers brought into the watershed. Deliberate outputs may include meat or dairy products, harvested crops not consumed as livestock feed, and livestock mortalities that are exported out of the watershed to landfills or rendering plants. Manure may be considered a deliberate output if it is not all applied to crops within the watershed. Stream exports are the P losses out of the watershed through waterways. When P inputs into the watershed are greater than deliberate P outputs, either Δ P increases and the soil P within the watershed is increasing, or P is running off the landscape and into the watershed's waterways.

Another way to look at this system balance using deliberate P outputs and inputs is by calculating the P use efficiency (PUE).

$$\text{Agricultural System PUE} = \frac{\text{Deliberate P Outputs}}{\text{P Inputs}}$$

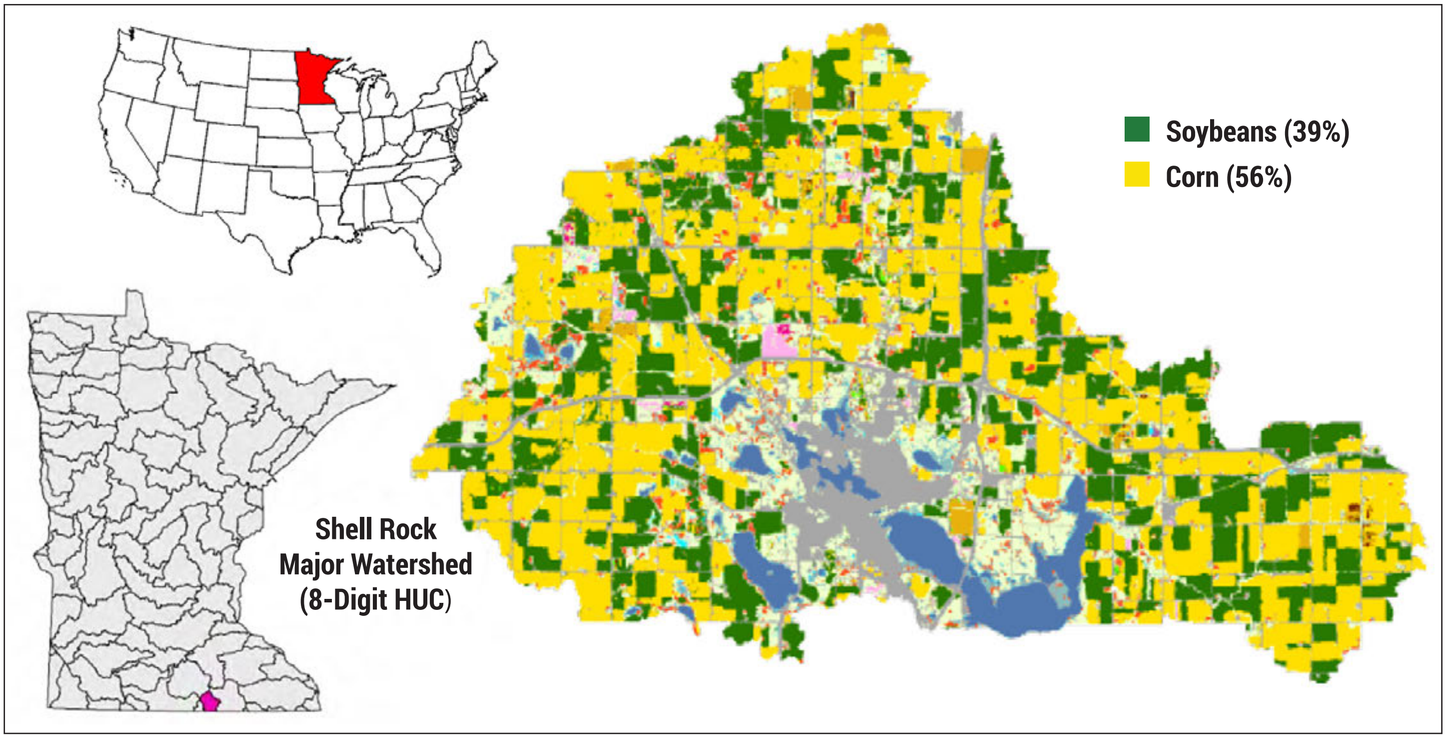
An agricultural system with high PUE results when deliberate P outputs exceed P inputs and PUE > 1.0. When this occurs, assuming all other management practices remain the same, watershed Δ P and STP should decrease with time, eventually leading to declines in stream P exports due to reduced contributions from surface P runoff. If more P is brought into the watershed than exported, the agricultural system PUE < 1, resulting in increased P storage and STP concentrations, which could lead to increased stream P concentrations. When the system is in balance and P inputs are equivalent to P outputs, PUE = 1.0. Depending on the purpose of the calculation results, the defined inputs and outputs will vary. When looking at efficiency from a water quality perspective, the outputs should include any P that is removed from the watershed, whether it is a product, reusable by-product, or waste material. For a producer's purpose

Integrating watershed P balances into conventional conservation planning provides a holistic approach to understanding the nutrient cycling across the landscape, critical for meeting load reduction goals for water quality improvement. To maintain high P use efficiency while ensuring successful crop yields, soil sampling should be encouraged to utilize the available P in areas where additional inputs are not necessary, while ensuring that STP remains above the crop's critical concentration.

KEYWORDS:
phosphorus balance; phosphorus use efficiency; watershed; Minnesota

ABBREVIATIONS AND NOTES:
P = phosphorus; STP = soil test phosphorus; ppm = parts per million.

https://doi.org/10.24047/BC102125



Albert Lea Lake watershed in Freeborn County, Minnesota (USDA, 2011) drains south into the Cedar River, a tributary of the Iowa River, which flows to the Mississippi River.

of determining how efficient a specific cropping or livestock system is at utilizing P through growth and development, into a finished or value-added product, the P outputs would not include any landfilled waste.

For example, IPNI's NuGIS database (IPNI, 2012) provides regional PUE estimates using fertilizer and manure as the P input, and the P removed by the harvested crop is the P output. This calculation allows a producer to quantify how much P is being taken out of the system in relation to the amount applied and can be useful over the long-term when compared to STP. Data from NuGIS indicates increasing crop PUE for the U.S. Corn Belt states from 0.81 in 1987 to 1.13 in 2010, likely attributed to increased crop P removal from higher yields with reduced P fertilizer inputs. When PUE > 1.0 and crop P uptake is greater than the quantity applied, STP concentrations will decline, as crops utilize the available P (Fixen et al., 2010). This has been demonstrated across the Corn Belt states, where median STP concentrations declined from 29 ppm in 2005 to 23 ppm in 2015 (IPNI, 2015). Research has demonstrated that as STP concentrations decline, there is also a consistent relationship in reduced dissolved P runoff losses (Vadas et al., 2005).

Table 1. Albert Lea Lake watershed 2010 crop P use efficiency (PUE) data.

	Calculated total crop removal of P	Calculated total applied P	Crop PUE
	--------- lb/yr ---------		
Alfalfa	18,916	646	29.3
Barley	692	739	0.9
Corn	1,085,265	852,534	1.3
Corn-*Sweet*	56,851	20,884	2.7
Grasses-*Hay*	10,651	9,458	1.1
Oats	273	243	1.1
Rye	9	15	0.6
Soybeans	445,435	23,415	19.0
Wheat	223	401	0.6
Total	1,618,312	908,333	1.8

Phosphorus Balance Case Study from a Minnesota Watershed

Albert Lea Lake watershed is a highly productive agricultural watershed in south-central Minnesota, at the headwaters of the nutrient impaired Shell Rock River watershed. Local stream monitoring has indicated that a high proportion of the total P load is soluble P, originating from subsurface drainage systems; however, watershed planning has focused primarily on implementing practices that re-

Table 2. Phosphorus use efficiency (PUE) of livestock systems within the Albert Lea Lake watershed.

	P input[1]	Product P output[2]	PUE
	----- tons (U.S.)/yr -----		
Beef	18.1	5.1	0.28
Pork	90.2	49.9	0.55
Dairy	3.6	1.3	0.37
Turkey	22.7	12.3	0.54

[1]P inputs included young animals, feed and supplements.
[2]P outputs included livestock products, manure and rendered mortalities.

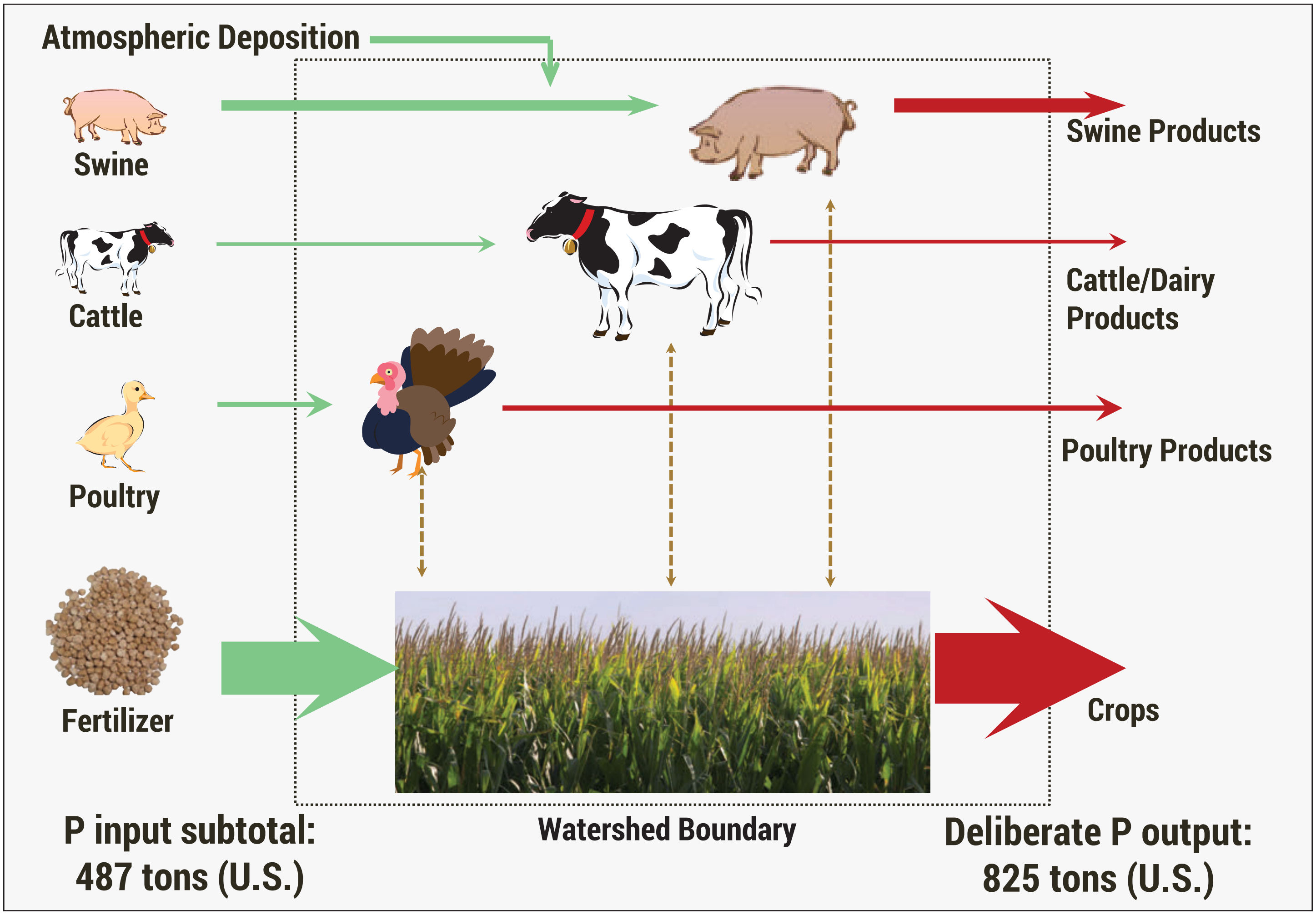


Figure 1. Annual agricultural P inputs to, outputs from, and transfers within the Albert Lea Lake watershed, resulting in a watershed P balance of 1.7. Arrow size represents the relative proportion of watershed inputs or outputs.

duce particulate P rather than improving agricultural nutrient management (MPCA, 2012).

A comprehensive agricultural system P balance was computed for the approximately 93,160-acre watershed using site-specific crop and livestock management data acquired through personal interviews, surveys, feedlot permits, and site visits together with published resources (Peterson et al., 2017). The data was computed using the Agricultural P Balance Calculator developed by Peterson and Baker (2014). Total crop PUE was 1.8 (**Table 1**), which is consistent with the 1.1 to 2.0 watershed range estimated by IPNI for 2010 (IPNI, 2012).

Most of the agricultural fields in the watershed operate under a corn and soybean rotation, applying P only during a corn planting year. Phosphorus removal by the crops increased faster than P inputs, resulting in improved efficiency. The agricultural system PUE was 1.7, indicating that more P was exported from the watershed as agricultural products than brought in as fertilizer, implying that crops were utilizing available P from watershed soils (**Figure 1**; Peterson et al., 2017). The watershed has low livestock density (0.08 animal units/A), allowing farmers to spread manure based on STP concentrations (**Table 2**).

Although the agricultural system PUE was > 1, stream P export was 5% of the annual watershed P input, exceeding the target P load for lakes within the watershed. Since deliberate P outputs are greater than P inputs within the watershed, this suggests that the root of the problem is likely something other than a general P input surplus. Inefficient P application practices with a combination of improper timing and placement could be resulting in high runoff losses. It could also be an indication that areas within the watershed with disproportionately high STP concentrations from legacy P are contributing P losses through erosion or desorption. Bray P results from southern Minnesota soil samples indicate that over 60% of the samples analyzed exceeded optimum STP concentrations, with approximately 40% of sam-

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Soil P testing allows producers to maintain optimum STP concentrations while reducing their water quality impacts without jeopardizing crop yield.

ples twice the critical concentration. To maintain high PUE while ensuring successful crop yields, soil sampling should be encouraged to utilize the available P in areas where additional inputs are not necessary, while ensuring that STP remains above the crop's critical concentration. This will ensure that crop PUE > 1 until the STP is reduced to the optimum range. In other areas of the watershed where manure or fertilizer P is applied, producers could adopt management practices which have been shown to reduce soluble P losses, such as the incorporation of manure through light tillage or variable rate application technology.

If the Albert Lea Lake watershed continues to operate in a P balance deficit, STP concentrations should decline, resulting in decreases in runoff P, especially when integrated with the adoption of conservation practices. Quantifying how quickly this reduction in stream P export occurs would require ongoing annual watershed P balance studies with long-term soil and water quality monitoring. The availability of soil P is dynamic and through mineralization of organic matter and desorption from soluble minerals, the soil solution can maintain equilibrium and continue to supply plant available P depending on soil characteristics and management including microbiology, tillage, and moisture levels.

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Summary

Incorporating a P balance approach as a first step in watershed planning provides watershed managers with a holistic perspective into the agricultural system to determine the efficiency of livestock and cropping systems. Producers within the watershed could improve the watershed agricultural system PUE by optimizing their crop or livestock PUE. This could be done by keeping the crop PUE > 1 where STP concentrations exceed the recommended optimum range, keeping the crop PUE < 1 where STP concentrations are below the recommended optimum range, or maintaining crop PUE = 1 where STP is at the recommended optimum range. If cropping and livestock PUEs are optimized by producers, then watershed and conservation organizations could target the implementation of conservation practices in areas where erosion losses dominate the P input. **BC**

Acknowledgement

This article is adapted from Peterson, H.M. et al. 2017. Agricultural Phosphorus Balance Calculator: A tool for watershed planning. J. Soil Water Cons. 72:395-404. http://doi:10.2489/jswc.72.4.395

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Maize trial site in Zimbabwe illustrating the effects of moisture stress and low soil fertility on crop growth.

Managing Nutrients for Climatic Resilience in African Smallholder Maize Production

By Jairos Rurinda, Mark T. van Wijk, Paul Mapfumo, and Ken E. Giller

Soil nutrient management proves critical to increase maize yield under both current and projected climatic conditions. The yield benefits from nutrient management are further enhanced given an early maize planting date.

KEYWORDS:
climate change; APSIM; planting date; simulation modelling; *Zea mays*

ABBREVIATIONS AND NOTES:
N = nitrogen; P = phosphorus;
K = potassium.

https://doi.org/10.24047/BC102129

A combination of climate change and declining soil fertility are major causes of low crop productivity in sub-Saharan Africa (SSA) (Mapfumo et al., 2013). Productivity of maize, the main cereal crop in the region, is predicted to decline by 30 to 60% by the end of 21st century due to rising temperatures and changing rainfall patterns (Rurinda et al., 2015; Traoré et al., 2017). Yet the demand for food is anticipated to rise as the population in Africa increases. There is a great concern that food deficits will worsen in SSA; thus, there is a growing need for crop and nutrient management technologies that are adapted for the region.

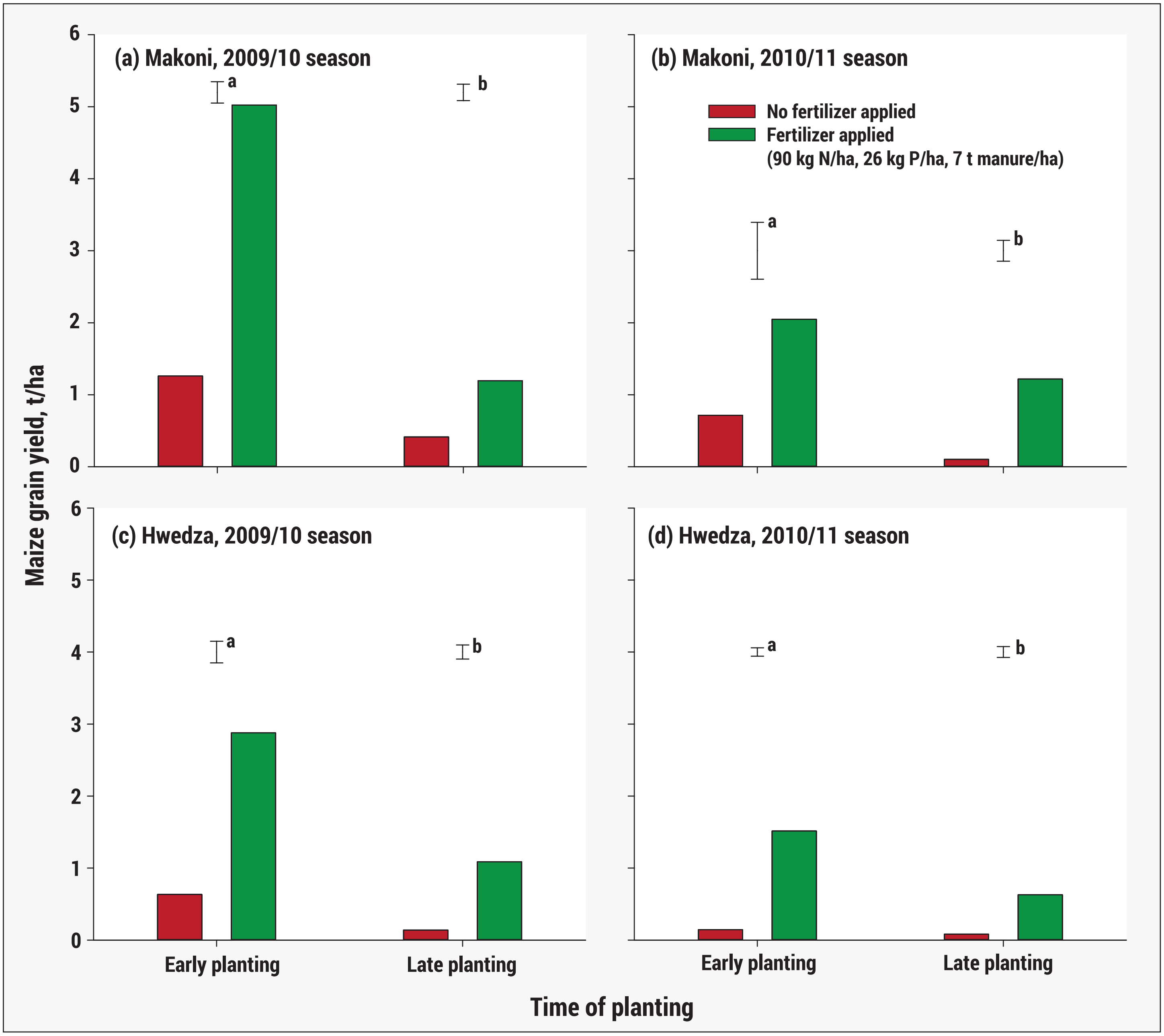

Figure 1. Maize grain yield in response to fertilizer use and planting date for two cropping seasons in Makoni and Hwedza districts, Zimbabwe. Error bars represent the standard error of the difference (SED) for a = time of planting, b = nutrient management.

A study in Zimbabwe made use of both on-farm trials and simulation modelling to quantify the yield response of maize to current and projected climatic conditions. Field experiments were conducted in eastern Zimbabwe within both sub-humid (Makoni District) and semi-arid (Hwedza) climatic zones. The study evaluated the effect of management practices such as cultivar choice, planting date, and fertilizer use. The long-term impact of these management options was assessed through crop simulation modelling using the Agricultural Production Systems Simulator (APSIM) (Keating et al., 2003). Three maize cultivars were sown in each of the early and late planting windows defined by stakeholders. Each of the three cultivar-planting date combinations received N, P, K, and manure combinations at either zero (no fertilizer applied), low (35 kg N/ha, 14 kg P/ha, 3 t manure/ha), or moderate (90 kg N/ha, 26 kg P/ha, 7 t manure/ha) fertilization rates. Three climate periods were selected to cover both near and long-term climatic conditions (i.e., 2010 to 2039; 2040 to 2069; 2070 to 2099) against a baseline period of 1976 to 2005. Future climate data for a Representative Concentration Pathway (RCP) was generated from an ensemble of five global circulation models. RCP 8.5 is a high concentration pathway with the highest greenhouse gas emissions for which radiative forcing reaches >8.5 watts/m^2 by the year 2100. RCP 8.5 combines assumptions about high population and relatively slow income growth with modest rates of technological change and energy intensity improvements, leading in the long-term to

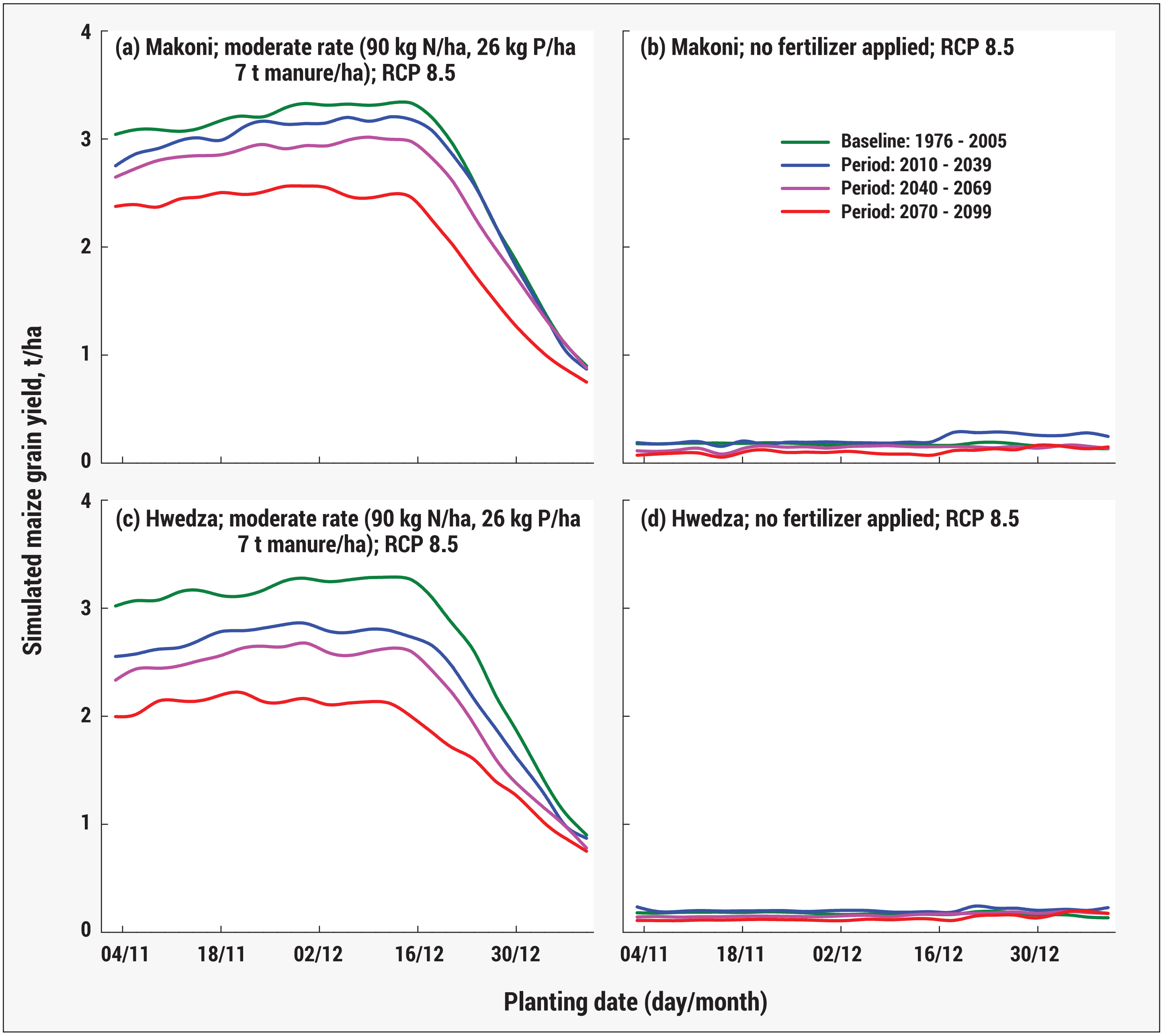

Figure 2. Simulated average seasonal maize yield distribution with planting date (cultivar SC401) under two fertilization rates. RCP 8.5 = Representative Concentration Pathway (8.5 watts/m^2).

high energy demand and greenhouse gas emissions in absence of climate change policies.

Nutrients, Climate Resilience, and Sustainable Cropping

Fertilizer and manure application increased maize grain yields threefold compared with the control (no nutrient application) under the current sub-humid (**Figure 1a** and **1b**) and semi-arid (**Figure 1c** and **1d**) climatic conditions. Likewise, results from the simulation modelling showed significant increases in grain yields with nutrient application under both current and projected climates (**Figure 2**). The similar results obtained between the on-farm experiments and the simulation modelling reinforces the continued importance of nutrient management for improved crop productivity in SSA, even under a changing climate.

Supporting Research Examples

In Sudano-Sahelian zone of West Africa, Traoré et al. (2014) reported that use of fertilizers at recommended rates could buffer losses in maize yield by up to 50% of the baseline yield under a changing climate. The study also concluded that fertilizer use on millet could offset the predicted yield losses and contribute to yield increases in the face of climate change and variability. In another large-scale study in SSA, Folberth et al. (2013) highlighted that increasing nutrient supply to rates commonly applied in high-input systems would allow for a tripling of maize yields from the current 1.4 t/ha to 4.5 t/ha.

Yield benefits from nutrient management further increased when maize was planted early (**Figure 1** and **2**).

Regardless of the amount of fertilizer applied, yield declined drastically when the planting of maize was delayed past mid-December, four weeks after the start of the rainy season. Across SSA, numerous studies have demonstrated that early planting is important for achieving optimal yields (Shumba et al., 1992). For this study, the differences in yield between cultivars were negligible under current and projected climates (data not shown). The range in time to maturity of the cultivars available on the market was too small to respond differently to the rainfall trends experienced.

Conclusion

Fertilizer and manure use increased maize yield under both current and projected changes in climatic conditions. The yield benefits of nutrient management were further increased when maize was planted within three weeks of the start of the rainy season. The results highlight the critical contribution of soil nutrient management and planting time to improved maize productivity and resilience to climate change in Zimbabwe and in similar maize-growing environments in SSA. **BC**

Acknowledgement

The article is adapted from Rurinda, J. et al. 2015. Climate change and maize yields in southern Africa: what can farm management do? Global Change Biology 3:65-78.

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International Conference: The Future of Long-Term Experiments in Agricultural Science

Rothamsted Conference Centre,
Rothamsted Research, Harpenden, Hertfordshire, UK
21-23 May 2018

Long-term research plays a major role in designing future agricultural systems and understanding the consequences of new practices and technologies. Worldwide, numerous long-term experiments (LTE) or other long-term research platforms have been established, following a tradition that started with the first classical long-term trials planted in 1843 at Rothamsted in the UK.

2018 marks the 175th anniversary of these trials and of Rothamsted as an agricultural research institution. On that occasion, Rothamsted Research will host an international conference to celebrate the unique role of long-term experiments in agricultural science, review lessons learned from similar studies worldwide, identify new questions to ask, and discuss new ways of doing such long-term research in the future.

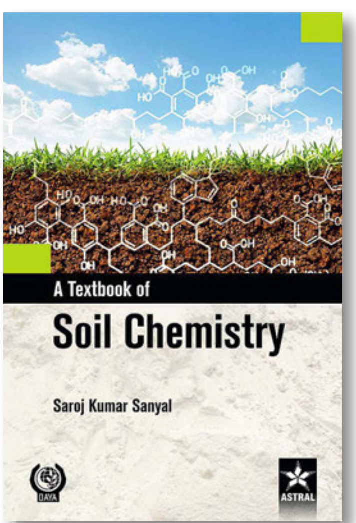
Planned sessions

- The unique contributions of LTEs to agricultural science
- New designs, methods, and tools for LTEs
- The mathematics and statistics of LTEs including mathematical modelling and databases
- Progress and future viability of a Global Long-Term Experiments Network

The conference will be forward-looking, focusing on how long-term experiments can contribute best to the worldwide quest for a sustainable intensification of agriculture. Besides scientific presentations and debates, it will include live streaming of key sessions to a global audience, flash talks, visits to the long-term experiments and sample archive, and other activities.

More about this conference at:
https://www.rothamsted.ac.uk/events/future-long-term-experiments-agricultural-science

Recommended Reading: A Textbook of Soil Chemistry by Dr. Saroj Kumar Sanyal



The book entitled "A Textbook of Soil Chemistry", written by Prof. (Dr.) Saroj Kumar Sanyal, is a significant contribution to aid modern soil science education and research. This book has dealt with the chemistry of soil which involves application of the basic concepts and principles of chemistry to the heterogeneous, complex, and living soil system. The book has made a concerted effort to unravel the basic processes in soil, accompanying several important transformations, with direct bearing to its use for agricultural production. Professor Sanyal is particularly successful in relating the principles of basic chemistry to the intricate processes in soil, thereby leading to an in-depth understanding of the soil processes.

This comprehensive textbook provides a thorough knowledge base for new students as well as advanced learners. As a legacy of Prof. Sanyal's outstanding teaching and research contributions in the field of soil chemistry, the text will certainly cater to the needs of post-graduates, and will serve as teaching material for teachers and agricultural scientists.

Dr. K. Majumdar
Vice President, Asia and Africa Programs, International Plant Nutrition Institute (IPNI)
Gurgaon, Haryana, India

2017 PHOTO CONTEST WINNERS

Congratulations to this year's crop of winning photo submissions! In addition to their cash award, each will receive our most recent USB flash drive collection featuring hundreds of images. More details on our image collection are available at: http://ipni.info/nutrientimagecollection.

With the close of last year's contest, we are already preparing the 2018 edition. Look for more information in the near future. You can also check back with the contest's website www.ipni.net/photocontest for details on how to make a submission.

Thanks to all for supporting our contest! **BC**

4R Nutrient Stewardship Category

See Image Slide Show!

FIRST PLACE:

Localized Placement of Urea to Maize

Ms. Ruth Atchoglo, Agricultural Experimental Station in Lomé, Southern Togo.

Urea is placed in a localized nests beside maize plants 1 month after planting at a rate of 60 kg N/ha. These fertilizer nests should be covered to avoid losses from N volatilization. This placement helps to reduce nutrient losses and improve crop N uptake.

SECOND PLACE:

Direct Seeding on the Canadian Prairies

Mr. Lyle Cowell, Northeast Saskatchewan, Canada

Seed, starter fertilizer, and banded anhydrous ammonia (NH_3) combine to efficiently apply fertilizer with minimal soil disturbance. This is the view from on top of a seed cart while a farmer is getting ready to direct seed and fertilize his canola crop in a single pass.

Primary Nutrient Category

FIRST PLACE:

Phosphorus Deficiency in Cotton

Dr. Srinivasan Subbiah, Kovilpatti, Tamil Nadu, India.

Rain-fed cotton plant in flowering stage that is growing on black calcareous soil. The leaf nearest to flower has developed interveinal purple pigmentation. The soil test (Olsen-P) revealed a very low (<1.4 mg/kg) P concentration. Leaf tissue analysis was 0.11%.

SECOND PLACE:

Potassium Deficiency in Cashew

Mr. Rahul Kulkarni, Usgaon, Ponda, Goa, India

Symptom first appear on the older leaves as yellowing of margins progress towards the midrib. Soils in this region are acidic (pH 6.2), highly weathered, and are deficient in the available potassium.

Secondary Nutrient Category

FIRST PLACE:

Magnesium Deficiency in Avocado

Dr. Jaume Cots Ibiza, Oliva, Valencia, Spain.

Leaves show interveinal chlorosis which progressed from the margins of the leaves. This farm has a sandy soil with low soil organic matter and a pH of 7.4. Tissue was low in magnesium (0.32% Mg). Application of Mg fertilizer source at the beginning of sprouting corrected the problem for the remainder of the season.

SECOND PLACE:

Magnesium Deficiency in Tomato

Ms. Cristina Pulido Gilabert,
Torre Pacheco (Murcia), Spain.

Interveinal chlorosis is visible on mature leaves. Main leaf veins remained green. The site had loamy textured soil (pH 7.4) with low organic matter (0.86%) and high carbonate concentrations (52%). Soil testing indicated 0.23 meq Mg/100g soil. The site had no history of Mg fertilization, but plants improved and the symptoms disappeared with an in-season application of magnesium sulfate.

Micronutrient Category

FIRST PLACE:

Boron Deficiency in Mango

Mr. Sandesh Nayak,
Farmer Field Near Krishna Ganj,
District Sirohi, Rajasthan, India.

Severe fruit cracking symptom attributed to boron deficiency. The deficiency becomes more prominent in summer months when temperatures can reach 44 to 46°C (110 to 115°F) and water availability becomes poor. Soil status was 0.1 mg/kg and plant concentration was 4.5 mg/kg.

SECOND PLACE:

Iron Deficiency in Avocado

Dr. Jaume Cots Ibiza, Altea, Alicante, Spain.

Extreme iron chlorosis where the leaves are losing their green appearance. The soil is low in organic matter and has a high concentration of active calcium carbonate (12.5%) and a pH of 7.8. Iron-based fertilizers have not been applied here for a long time. Foliar analysis found an extremely low Fe concentration of 23 ppm. This problem tends to decrease progressively after the application of a EDDHA chelate source of iron.

An Interview with 2017 IPNI Science Award Winner - Dr. Abdul Rashid

Dr. Abdul Rashid, Fellow & Editor-in-Chief with the Pakistan Academy of Sciences, was recently named as the recipient of the International Plant Nutrition Institute (IPNI) Science Award for 2017. The IPNI Science Award recognizes outstanding achievements in research, extension, or education—focusing on efficient management of plant nutrients and their positive interaction in fully integrated cropping systems that enhance yield potential.

Dr. Abdul Rashid

During his formative years in research (1973-79), Dr. Rashid contributed towards identification, establishment, and mechanisms of zinc deficiency in rice, wheat, and corn. In 1979, he became coordinator of *Micronutrients Project* in Pakistan. Then, he obtained Ph.D. from the University of Hawaii by determining crop zinc requirement in acid soils of Hawaii and calcareous soils of Colorado. Abdul returned to Pakistan in 1986 and led a well-conceived soil fertility and crop nutrition program at the National Agricultural Research Center. Dr. Rashid's farmer-friendly fertilizer use technologies have been formally recommended and widely adopted throughout Pakistan.

Can you take us back to the mid 1980s ...coming out of graduate school and establishing a new national research program...any unique challenges or obstacles faced at that time?

For my doctoral research at University of Hawaii, USA, under able guidance of Professor Robert Fox, I purposely worked on a micronutrient problem of importance to my country (zinc deficiency in crops). Once I returned to National Agricultural Research Center in Islamabad in 1986, I was well prepared to embark upon a comprehensive soil fertility and plant nutrition research program. When I look back, the major challenges of that time included meager research funding and a socio-economic environment within Pakistan that was not conducive for scientific research. I think the major credit for eventual success of my research group's consistent efforts goes to my employer (Pakistan Agricultural Research Council) and my colleague scientists within the research group.

Can you describe the story behind the discovery of extensive boron deficiencies in Pakistan?

Our identification and establishment of boron deficiency in many crops, in the face of a general perception of high boron availability in calcareous soils, was not a matter of chance. I was conscious that in Pakistan the first-ever crop yield increase with boron fertilization was observed as early as in 1970, but R&D on boron did not receive enough attention due to inadequate facilities and expertise for laboratory analysis of boron. Therefore, initially, we acquired competence in soil and plant boron analysis. Then, by systematic nutrient indexing, my research group diagnosed macro- and micronutrient deficiencies in farmer-grown crops. Identification of boron deficiency in various crops was verified in greenhouse studies. Thereafter, remedial measures were developed and demonstrated in extensive farmer field trials in the major crop growing areas—including 3 million (M) ha cotton during the 1990s and over 2 M ha of flooded rice during the 2000s.

Since 2008, Dr. Rashid has addressed micronutrient malnutrition by enriching staple cereals with zinc and iodine. This multi-country research under the *HarvestZinc Project* has established that wheat and rice grains can be enriched by foliar feeding, that foliar zinc fertilizer can be mixed safely with pesticide spray solutions, and that high-zinc wheat grains used as seed result in denser crop stand and higher yield. He is co-author of papers on agronomic biofortification of staple cereals with zinc, and the first-ever paper reporting wheat grain enrichment with iodine by fertilization.

His extensive field research demonstrated that balanced nutrient management leads to carbon sequestration. His advocacy for soil-plant analysis-based fertilizer use has helped avoid overuse of nitrogen and phosphorus in high-input cotton, potato, corn, and vegetables, has enhanced crop use efficiency of fertilizer nutrients, and has reduced the risk of nutrient losses to the environment. His *Soil-Plant Advisory Service* backstopped crop production as well as environmental concerns, like heavy metal contamination.

Can you describe your general philosophy to research? What works best? What should be one's focus?

Right from the beginning, I believed that the developing country soil fertility and plant nutrition research must aim at developing farmer-friendly nutrient management technologies for enhancing crop productivity and sustaining soil productivity in a cost-effective manner. In countries like ours, the research program must encompass diagnosis/prognosis *of nutrient disorders, field verification of the disorders, development of its cost-effective and practically feasible corrective measures, extensive field demonstration of the developed technologies, and, finally, formal recommendation for adoption of the technologies by growers.*

Any thought on the future challenges for soil fertility/crop nutrition research? Specific challenges faced for Pakistani Ag?

Though more prominent plant nutrition challenges in calcareous soils are of low use efficiency of nitrogen and phosphorus fertilizers and the dilemma of potassium nutrition, my R&D emphasis – throughout – has been on integrated nutrient management, inclusive of micronutrients. Though micronutrients are recognized as 'mighty', these eight equally essential nutrients have received lesser than required R&D attention – around the globe. In the presence of any micronutrient deficiency, optimum crop productivity can't be realized even with adequate catering of all other nutrients. However, micronutrient fertilizer use is much less than required. For instance, my recently prepared status report "Micronutrient Fertilizer Use in Pakistan: Historical Perspective and 4R Nutrient Stewardship" reveals that potential fertilizer requirement for boron is 22-times and for zinc 5-times of their current use levels in the country. Also, optimizing micronutrient nutrition of crops has gained much greater importance with relatively recent realization of their alarming malnutrition in vast segments of the resource-poor across the world. Thus, the apparent future challenges in calcareous soils of the world appear to be optimizing use of nitrogen, phosphorus and potassium fertilizers and enhancing micronutrient fertilizer use in the context of 4Rs.

Dr. Rashid has publicized his research effectively, locally and globally, through journal papers, books, conferences, advisory materials, and field demonstrations—addressing researchers, educators, extension service, farmers, and policy makers. He has lectured extensively in Pakistan and around the world.

Can you describe your passions or commitments now after your "retirement"?

My group's consistent R&D and effective advocacy, since mid-1980s, resulted in creating a 'pull force' for micronutrient fertilizers in Pakistan. Though I retired from formal service in 2011, my passion and commitment for micronutrient R&D continues. Since 2008, I am involved in HarvestPlus-sponsored R&D to address micronutrient malnutrition ('hidden hunger') by enriching staple cereals with zinc and iodine. This multi-country research, under the leadership of Professor Ismail Cakmak, has established that wheat and rice grains can be enriched with zinc and iodine by foliar feeding, and that foliar zinc fertilizer can be mixed safely with pesticide spray solutions. And high-zinc wheat grains used as seed result in denser crop stand and higher yield. It is a pleasure in being able to contribute for such a noble cause.

Dr. Rashid is an IFA Norman Borlaug Laureate, Pakistan's Dr. Norman Borlaug Laureate, East-West Center Distinguished Alumnus, Fellow of Indian Society of Soil Science, Fellow of Soil Science Society of Pakistan, PARC Silver Jubilee Laureate, Pakistan Scientist of the Year, National Book Foundation Awardee, and J. Benton Jones Laureate. **BC**

Nutri-Net Project Looks to Quantify the Impact of 4R Nutrient Stewardship Practices

Nutri-Net Team Members (pictured left to right) **Dr. Dan Jaynes,** Soil Scientist, USDA-ARS, **Dr. Laura Christianson,** Assistant Professor, University of Illinois, **Dr. Heidi Peterson,** Director, International Plant Nutrition Institute, **Dr. Alison Eagle,** Scientist, Environmental Defense Fund, **Dr. Jeffrey Volenec,** Professor, Purdue University, **Dr. Craig Drury,** Research Scientist, Agriculture and Agri-Food Canada, **Dr. John Kovar,** Soil Scientist, USDA-ARS, **Dr. Fabian Fernandez,** Associate Professor, University of Minnesota, **Dr. Sylvie Brouder,** Professor, Purdue University, **Dr. Matt Helmers,** Professor, Iowa State University, **Dr. Kelly Nelson,** Professor, University of Missouri, **Dr. Cameron Pittelkow,** Assistant Professor, University of Illinois, **Mr. Lowell Gentry,** Research Scientist, University of Illinois, **Dr. John Sawyer,** Professor, Iowa State University, **Dr. Cindy Cambardella,** Soil Scientist, USDA-ARS (not in picture), **Dr. Tom Moorman,** Microbiologist, USDA-ARS (not in picture).

There is a lack of research data linking agronomic and environmental performance across a wide variety of management conditions. This critical research gap is leading to high uncertainty regarding the efficiency of 4R practices for farmers, program managers, and policy- or decision-makers. Industry, universities, and state and federal action agencies have displayed a concerted effort to promote the 4R (Right Source, Right Rate, Right Time, and Right Place) on-farm nutrient management approach to using commercial fertilizer and organic materials (e.g., http://www.nutrientstewardship.com). However, our ability to quantify and track the impacts of 4R management on crop yield, P, K and nitrate loss to water, N loss to the atmosphere, and changes in soil health under a range of practices needs further improvement.

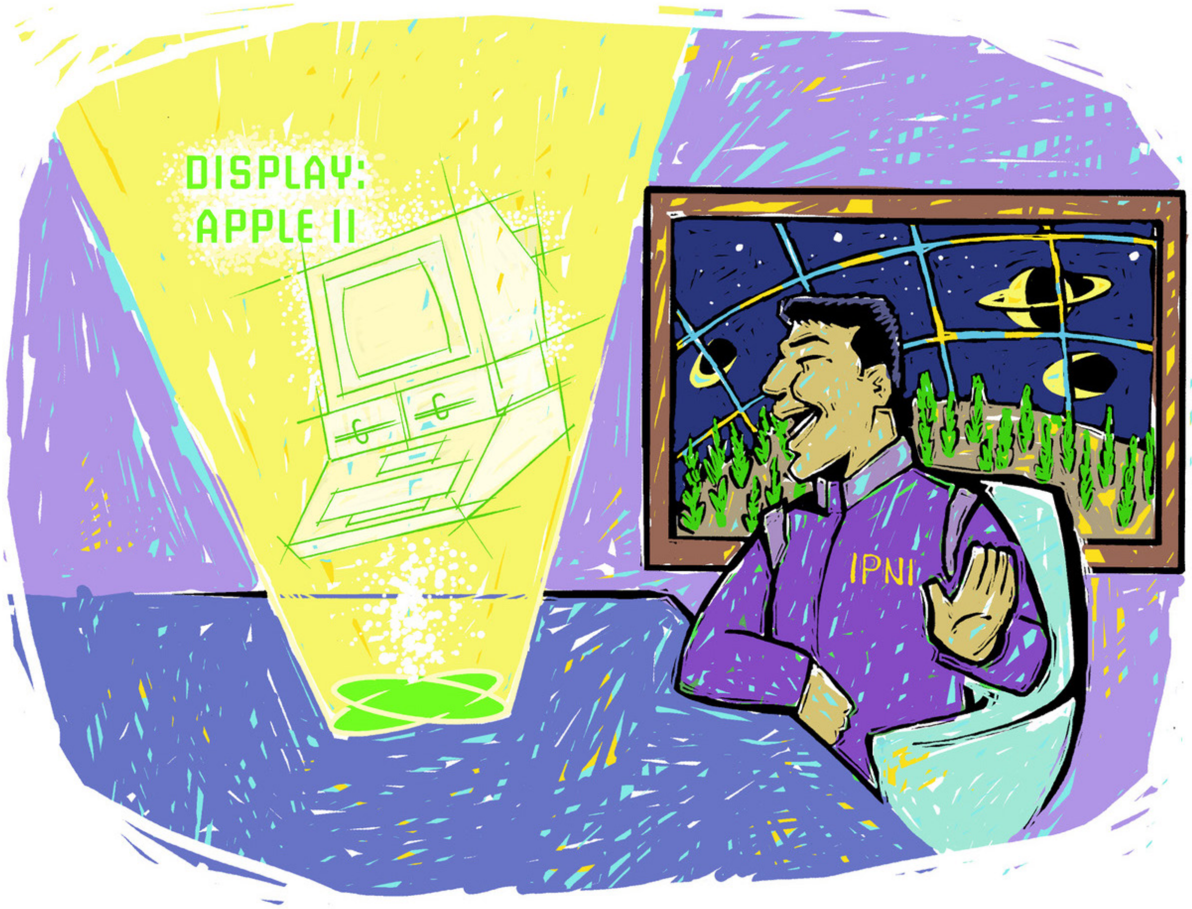
The Foundation for Agronomic Research (FAR) was selected this past summer to receive a US$1 million research grant from the Foundation for Food and Agriculture (FFAR) to study the impact of 4R Nutrient Stewardship practices on the movement of nutrients in corn and soybean cropping systems in Canada and the US. This grant was matched with US$1 million in funds from the North American fertilizer industry's 4R Research Fund. FAR will support 16 researchers in Illinois, Indiana, Iowa, Minnesota, Missouri, and Ontario. Their work will quantify the impact of 4R-based practices on crop yield, soil health, nutrient use efficiency, nutrient loss via leaching, and gaseous N loss across eight coordinated field sites. The project has been named the *Coordinated Site Network for Studying the Impacts of 4R Nutrient Management on Crop Production and Nutrient Loss*, or *Nutri-Net*.

Although Nutri-Net sites will focus on N management, the consistent comparison across all sites will include, partial nutrient balances for N, P, and K. All field sites are capable of capturing nutrient leaching losses in subsurface tile drains. Locally relevant, current nutrient management practices will be compared to more advanced 4R management systems. In addition, several sites will investigate specific 4R variations including timing of N application and N placement by side-dress application.

The novelty of this networked approach is that existing investment in agronomic/drainage research sites across the corn-belt can be leveraged to answer additional questions about the effectiveness of 4R practices. Data generated in this three-year project will combined into a centralized database that will grow over time. Future studies on N management will allow for continued improvement of knowledge that supports our management and policy recommendations. This effort will extend to help answer key questions about the impacts of nutrient management in corn-based cropping systems on water quality in the Mississippi River Basin and eutrophication in the Gulf of Mexico.

Current cooperating institutions include: Iowa State University, University of Illinois, Purdue University, University of Minnesota, National Laboratory for Agriculture and the Environment–Agricultural Research Service, Agriculture and Agri-Food Canada, and the Environmental Defense Fund. **BC**

Follow the Nutri-Net project at
http://research.ipni.net/project/IPNI-2017-USA-4RF01



Change Happens

I've seen a lot of technology changes in my 30+ year career. I wrote my PhD dissertation on an Apple II that used a 5.25" floppy disk for storage and a lo-res monitor. I printed it on a dot matrix printer, but had to re-type it on a typewriter to meet the print university standards for binding the thesis. I analyzed my data on a main frame computer. Data shown in figures were hand-drawn on graph paper and then reproduced by the university graphics department. The graphics department would also make our slides for presentations on blue diazo. I thought it was all pretty high tech.

In those days, we communicated by letter or telex and phoned on land lines. Fax machines replaced letters, e-mail replaced fax machines, and mobile phones replaced land lines. Today, it's SMS, facetime, and emoji's, and my cell phone has more power and memory than the main frames that analyzed my data.

Computerization brought us into the Information or Digital Age. It has transformed our lives. Look at the revolution technology has brought to agriculture … GPS, GIS, yield monitors, grid sampling, variable rate application, remote sensing, drones, autosteer, and much more. Big data is the new thing. They say human knowledge is doubling about every 12 months, but soon will be doubling every 12 hours. I'm not sure how that is determined, but it is indisputable that human knowledge is advancing at an extraordinary pace.

Better Crops, like everything else, is also changing. In 2016, we produced our 100th volume. Over the years our flagship publication has evolved. In the last couple of decades we merged *Better Crops International* with *Better Crops*, created *Better Crops India* and *China*, and have changed the size and format. We are now making another change; with this edition, we have transitioned Better Crops into a digital-only format …a central platform that can take advantage of what the digital age has to offer. What has not changed is the content. We will still bring you useful, applied agronomic information from around the world, but going electronic will expand our ability to deliver that information to you. And, if you prefer hardcopy, you can always download the pdf and print it.

We hope you will enjoy your new, electronic read.

Terry L. Roberts
IPNI President

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