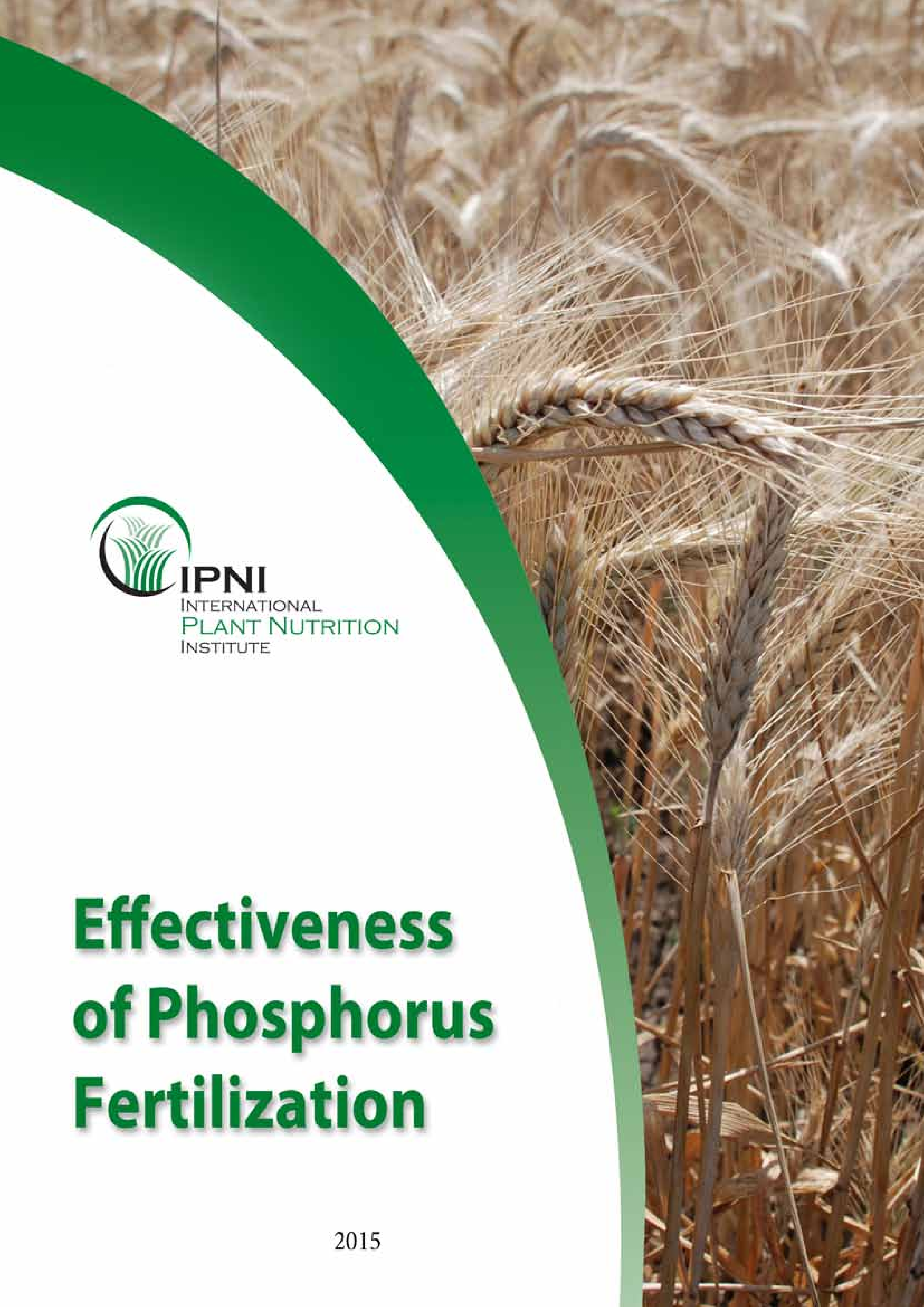

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Effectiveness of Phosphorus Fertilization

2015

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Concepts for Facilitating the Improvement of Crop Productivity and Nutrient Use Efficiency

By Paul E. Fixen

The global character of the demand for agricultural products and many of the most critical environmental issues creates a tight linkage between improving productivity and minimizing environmental impact. Merging these two objectives into one goal is likely the only strategic approach that will allow either objective to be accomplished. Sustainably meeting this challenging goal will require close cooperation and understanding among disciplines, across geographies, and between public and private sectors. Three concepts are offered that may facilitate this interaction.

- *The 4R Nutrient Stewardship Framework: Application of the right nutrient source, at the right rate, right time, and right place is a concept that when seen within a framework connecting practices to onfarm objectives and sustainability goals, along with critical performance indicators, can help keep individuals working on "parts" cognizant of the "whole".*
- *Mainstreaming of Simulation Models: Models recently developed can help identify unrealized yield potential and better manage the growing uncertainty of weather and climate.*
- *Global Data Networks: More extensive exploitation of electronic technology that facilitates global data collection, sharing, analysis, and use could expedite the acquisition and application of agronomic and plant nutrition knowledge.*

The Critical Role of Soil Fertility in Food and the Environment

Three underlying factors that encompass many of the major issues humankind will be facing for the next several decades are human nutrition, carbon (C), and land (**Figure 1**). Two of these factors, C and land, were recently discussed in an inspiring paper presented by Dr. Henry Janzen at the International Symposium on Soil Organic Matter Dynamics (Janzen, 2009). Carbon issues include climate change, cheap energy, and bioenergy. Land issues include land use, soil quality, water use and quality, and waste disposal. Dr. Janzen astutely pointed out that soil organic matter is the common ground between these two factors. The addition of human nutrition as a third factor brings into the picture the issues of food quantity, food quality, and food cost. Of critical importance in the discussion of nutrient management is that a significant component of the common ground of all three of these huge factors is soil fertility and how the management of plant nutrients affects our food supply, our land, and the C cycle.

Agricultural Productivity and Nutrient Use Efficiency (NUE) as One

Sustainable development is widely recognized as consisting of economic, social, and environmental elements. Sustainable nutrient management must support cropping systems that contribute to all three of these elements. Considering the increasing societal demand for food, fiber, and fuel, intense global financial stress, and growing concerns over impacts on water and air quality, simultaneous improvement of productivity and NUE is an essential goal for global agriculture. Striving to improve NUE without also improving productivity simply increases pressure to produce more on other lands that may be less suited to efficient production. Likewise, the squandering of resources to maximize productivity resulting in increased adverse environmental impact puts more pressure on other lands to reduce environmental impact while meeting productivity needs.

Soil fertility greatly impacts the productivity of our land and the carbon cycle.

Simultaneous pursuit of higher productivity and NUE requires caution in how NUE is being measured. Methods of NUE determination and their interpretation were recently reviewed by Dobermann (2007). He also

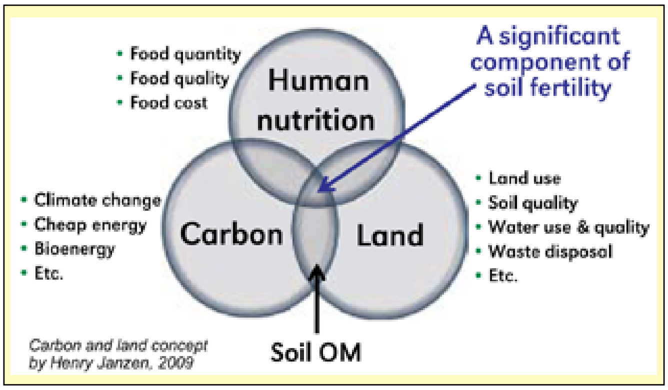


Figure 1. Underlying factors for the challenges of the coming decades.

summarized the current status of NUE for major crops around the world, pointing out that single-year average recovery efficiency for N in farmer fields is often less than 40%, but that the best managers operated at much higher efficiencies. Dobermann used a 6-year study in Nebraska on irrigated continuous maize managed at recommended and intensive levels of plant density and fertilization to illustrate how NUE expressions can be easily misinterpreted. In this study, comparing a higher yielding, intensively managed system to the recommended system for the region, the partial factor productivity (PFP or grain produced per unit of N applied) index indicated that the intensive system was considerably less N efficient than the recommended system. Because fertilizer N contributed to the buildup of soil organic matter in the intensive system, when the change in soil N was taken into account, the two systems had nearly the same system level N efficiency. Dobermann pointed out that over time, this increased soil N supply should eventually reduce the need for fertilizer N, resulting in an increase in PFP. Such effects are particularly noteworthy when striving to increase productivity with more intensive methods where new practices are being implemented that differ from the history for the research plot area or farm field. If cultural practice changes are such that soil organic matter is no longer in steady state, temporary net nutrient immobilization or mineralization can impact apparent NUE.

Some have estimated that the world will need twice as much food within 30 years (Glenn et al., 2008). That is equivalent to maintaining a proportional annual rate of increase of over 2.4% over that 30-year period. Others predict a 50% increase in food demand by 2030 which translates into a 1.8% annual increase (Evans, 2009). Sustainably meeting such demand is a huge challenge and will require close cooperation and understanding among disciplines, across geographies, and between public and private sectors. The magnitude of the challenge is appreciated when such a proportional rate of increase is compared to historical cereal yield trends which have been linear for nearly half a century with slopes equal to only 1.2 to 1.3% of 2007 yields (**Figure 2** and **Figure 3**). Three concepts are offered here that may facilitate cooperation among the groups needed to accomplish the required productivity and efficiency improvements.

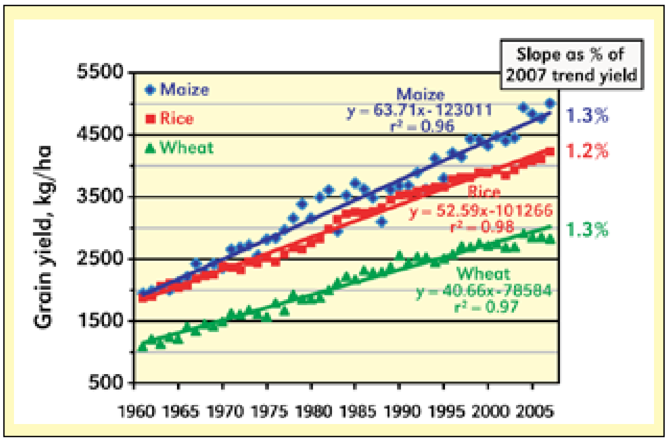


Figure 2. Global cereal yield trends.

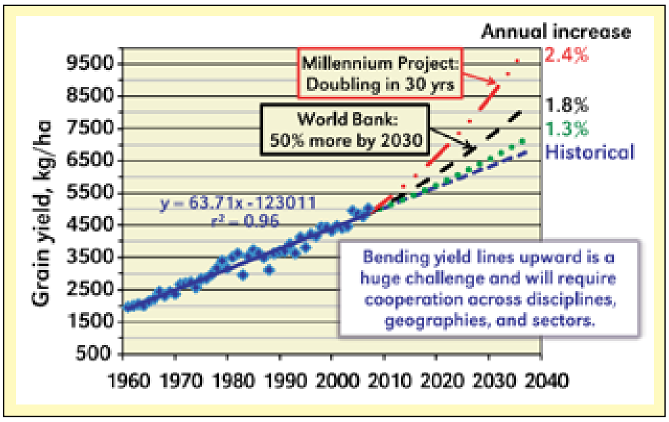


Figure 3. Future demand projections applied to maize yields.

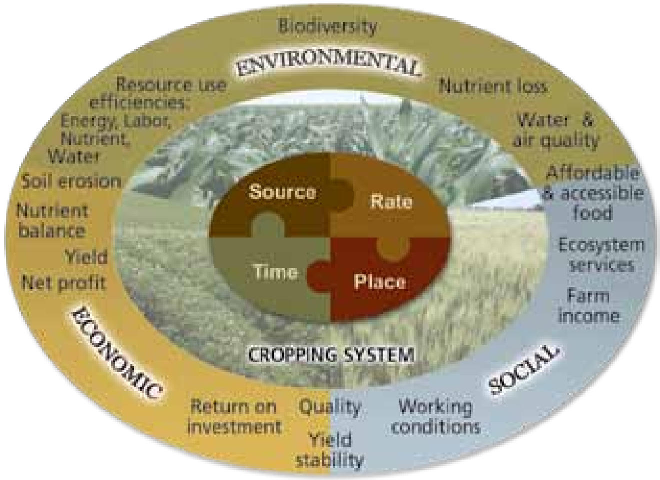


Figure 4. The 4R nutrient stewardship framework (after Bruulsema et. al., 2008).

The 4R Nutrient Stewardship Framework

For plant nutrition science to work well across disciplines, between public and private sectors, and across geographies, a common framework for viewing goals, practices, and performance is likely helpful. The seeds for such a framework were planted more than 20 years ago by Thorup and Stewart (1988) when they wrote: "This means using the right kind of fertilizer, in the right amount, in the right place, at the right time." **Figure 4** is a schematic representation of the 4R nutrient stewardship framework based on the concepts described by Thorup and Stewart (Bruulsema et al., 2008). At its core are the 4Rs – application of the right nutrient source at the right rate, right time, and right place. Best management practices are the infield manifestation of these 4Rs.

The 4Rs are shown within a cropping system circle because they integrate with agronomic BMPs selected to achieve crop management objectives. Those farm-level crop management objectives contribute toward the larger economic, social and environmental goals of sustainable development. Furthermore, the 4Rs cannot truly be realized if problems exist with other aspects of the cropping system. Darst and Murphy (1994) wrote about the lessons of the Dust Bowl in the USA in the 1930s coupled with a multitude of research studies showing the merits of proper fertilization and other new production

Table 1. A comparison of long-term average maize yields in an intensive management study to local average farmer yields (experimental data from Adviento-Borbe et al., 2007).

Average of 2000-2005	Continuous maize	Maize/ soybean
Lancaster County irrigated farmer average, t/ha	10.6	
University recommended treatment, t/ha	14.0	14.7
Intensive high yield management treatment, t/ha	15.0	15.6

technology, catalyzing the fusing of conservation and agronomic BMPs. Science and experience clearly show that the impact of a fertilizer BMP on crop yield, crop quality, profitability and nutrient loss to water or air is greatly influenced by other agronomic (plant population, cultivar, tillage, pest management, etc.) and conservation practices (terracing, strip cropping, residue management, riparian buffers, shelter belts, etc.). Practices defined with sufficient specificity to be useful in making on-farm fertilizer use decisions, often are "best" practices only when in the appropriate context of other agronomic and conservation BMPs. A fertilizer BMP can be totally ineffective if the cropping system in which it is employed has other serious inadequacies.

Around the outer circle of the 4R framework are examples of performance indicators. A balanced complement of these indicators can reflect the influence of nutrient BMPs on ac-complishment of the goals of sustainable development. The framework shows clearly that system sustainability involves more than yield and NUE, though these are critical indicators. Stakeholder input into performance indicators is an essential part of the process.

Mainstreaming of Simulation Models

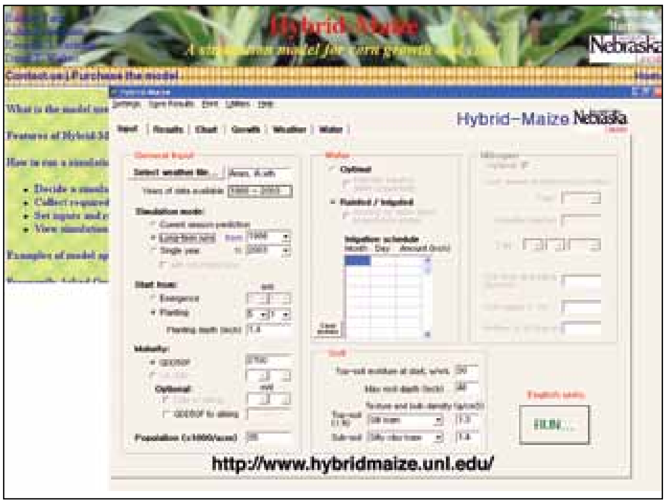
Defining the gap between current and potential yields is a useful step towards maximizing productivity and efficiency. FAO recently published a set of such estimates for six maize-producing countries (FAO, 2008). Their evaluation showed a yield gap varying from 4 or 5 t/ha in Mexico or India to zero for the USA. However, such existing general estimates should not be taken too literally relative to specific locations. For example, if one compares the Nebraska irrigated maize yields for the intensively managed treatments discussed earlier to the county average farmer yields for the same time-period, a difference of 4 to 5 t/ha is observed (**Table 1**), suggesting that a yield gap exists in at least some areas of the USA as well.

Crop simulation models can be useful tools for site-specific estimation of yield gaps. Significant progress has been made in user-friendly crop simulation models with the potential to assist with gap analysis and crop and nutrient management. One example is Hybrid Maize, developed by the University of Nebraska (Yang et al., 2006). Nutrient management functionality for the model is under development. Crop and nutrient management is complex in part because critical processes in plants and in soils are highly dependent on weather. In practice, managers have two options, either base decisions on climatic probabilities or on in-season, near real time information. Simulation models can assist with either ap-proach. Climate change adds another dimension to the utility of weather/climate driven models. A recent report by the National Research Council (2009) stated that the end of climate stationarity requires organized, data based decision support for climate-sensitive decisions. It would seem that crop and soil management would fall into that category of climate-sensitive decisions. Implications of climate change on plant nutrition were recently reviewed by Brouder and Volenec (2008). A thorough review of crop yield gaps with a focus on wheat, rice, and maize, including use of simulation models, was recently published by Lobell et al.(2009).

Global Data Networks

In its recent synthesis report, the International Assessment of Agricultural Knowledge, Science and Technology for Development stated that the main challenge for agricultural knowledge, science and technology (AKST) is to increase the productivity of agriculture in a sustainable manner (IAASTD, 2009). It proposed that one of six high priority natural resource management (NRM) options for action is to "Develop networks of AKST practitioners (farmer organizations, NGOs, government, private sector) to facilitate long-term NRM to enhance benefits from natural resources for the collective good. A second option was to "connect globalization and localization pathways that link locally generated NRM knowledge and in-novations to public and private AKST."

In her plenary lecture at the 2008 annual meeting of the American Association for the Advancement of Science, Dr. Nina Fedoroff, Administrator of USAID, said that the only alternative to higher food prices and progressive deforestation is to use contemporary science, including molecular modifica-tion, to increase



Hybrid-Maize is an example of a crop simulation model for site-specific estimation of the gap between current and potential corn yield.

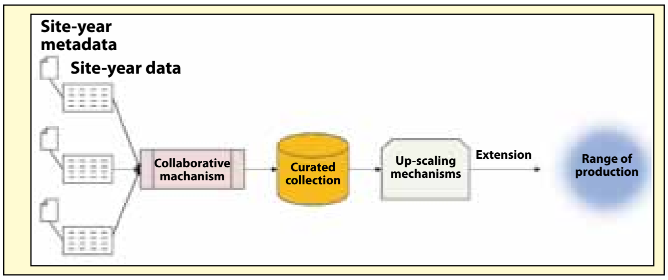


Рис. 5 A conceptual model of the process of developing and testing field data across large geographic scales (Murrell, 2008).

the productivity of the land we already farm and decrease its water demands (Fedoroff, 2008). She went on to say that our research universities and institutes, work-ing together with the business sector and using contemporary electronic resources, have a unique opportunity to accelerate global collaboration.

Can current communication and data management tech-nologies be put to better use in pursuing our productivity and NUE goals? The National Academy of Sciences (2009) now tells beginning scientists that researchers have a responsibility to devise ways to share their data in the best ways possible, mentioning repositories of astronomical images, protein se-quences, archaeological data, cell lines, reagents, and trans-genic animals as examples.

To address unmet communication needs of collaborating scientists, Purdue University researchers developed the Net-work for Computational Nanotechnology (NCN). An outcome of this network was nanoHUB (http://www.nanohub.org). This on-line community of over 90,000 annual users provides web access to the tools scientists need to collaborate on modeling, research, and educational efforts in nanotechnology. Is there need for a "Nutrohub", a global plant nutrition research and education community? Such a community could have numer-ous groups, each with its own focus, but sharing communica-tion and computing tools. Groups could develop integrated data management processes such as the one illustrated in **Figure 5**, developed for IPNI's Global Maize project (Murrell, 2008).

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Towards a 4R-consistent fertiliser industry

T. Bruulsema

The concept of 4R Nutrient Stewardship has been embraced by a wide segment of the fertilizer industry, and many of its associated partners in agriculture, government, and the environmental movement. The 4Rs communicate the essentials of responsible management of plant nutrition to a wide range of stakeholders, technical and non-technical. The specific nutrient application practices being encouraged vary from one region to another, because the implementation of 4R Nutrient Stewardship is site-specific. The core concept is that the right source of plant nutrient be applied at the right rate, right time, and right place to obtain improved sustainability outcomes. Industry needs to support an adaptive management approach at all levels. Segments of the industry including agri-service providers, retail, wholesale, manufacturing, and investors, working together, can ensure that producers are empowered and enabled to make the right choices to improve the performance of their cropping systems.

About 25 years ago, the United Nation's World Commission on Environment and Development produced a report titled "Our Common Future". This report provided the basis for the concept of sustainable development, and in particular, sustainable agriculture. Over the past few years, sustainability has become an important topic for corporations, including those in the agriculture and food sectors. Major food retailers are developing programs to assess and improve their own performance, along with that of their supply chain, extending all the way to the farm level and to the inputs used by farmers. These food retailers are engaging agri-business by participating in organizations like the Sustainability Consortium and the Keystone Alliance.

The 4Rs connect to sustainability

4R Nutrient Stewardship encourages more sustainable choices for the source, rate, time and place of application of crop nutrients. The Keystone Alliance, for example, has developed a "Fieldprint Calculator" which includes elements of 4R Nutrient Stewardship in its greenhouse gas component, and a Water Quality Index currently under development is likely to be linked to 4R Nutrient Stewardship as well.

Definitions of sustainable agriculture abound, but most emphasize a need to accommodate growing demands for production without compromising natural resources. This entails a balance among economic, social and environmental impacts of management choices.

The fertilizer rights – source, rate, time, and place – are connected to the goals of sustainable agriculture through the cropping system, as shown in **Figure 1**. Fertilizer management, to be considered "right," must support stakeholders' goals for how that cropping system performs, how it produces, how it affects the air they breathe, the water they drink, etc.

Scientific principles apply to the 4Rs

The sciences of physics, chemistry, and biology provide fundamental principles for the mineral nutrition of plants growing in soils. The application of these sciences to practical management of plant nutrition has led to the development of the scientific disciplines of soil fertility and plant nutrition. The management components source, rate, time and place each have unique science which describes the processes related to plant nutrition, and can be condensed into principles (**Table 1**). Understanding the sciences underpinning these key principles is critical for those advising crop producers on plant nutrition.

SOURCE, RATE, TIME, AND PLACE are completely interconnected in the management of plant nutrition. None of the four can be right when any one of them is wrong. It is possible that for a given situation there is more than one right combination, but when one of the four changes the others may as well. The 4Rs must work in synchrony with each other and with the cropping system and management environment. 4R Nutrient Stewardship emphasizes the impact of these combinations of management choices on outcomes, or performance, toward improved sustainability. For example, when potassium limits yield, application of potash fertilizer improves recovery and use efficiency of nitrogen and phosphorus.

Adaptive Management

Adaptive management for plant nutrition includes cycles of decision, implementation and evaluation (**Figure 2**). These cycles operate at several levels, including the farm, the regional and the policy levels. There is a role for industry at each level.

Agri-service providers—including retail dealers—

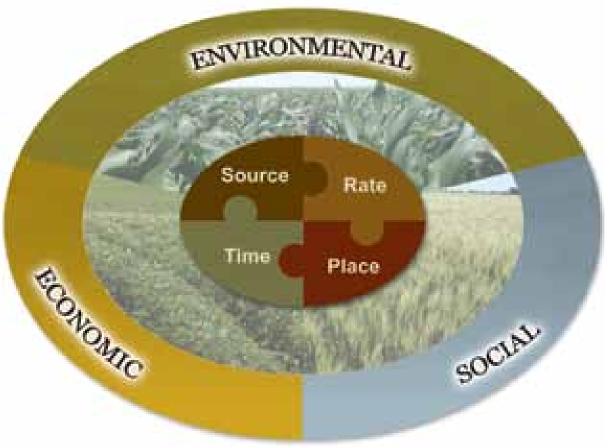

Figure 1. The 4R Nutrient Stewardship concept considers the right source, rate, time, and place for fertiliser application capable of producing the stakeholders' desired economic, social, and environmental outcomes for the ecosystem.

Table 1. Key scientifc principles associated with the 4Rs (IPNI, 2012).			
Source	**Rate**	**Time**	**Place**
Provide essential elements	Assess plant demand	Assess timing of uptake	Consider where roots grow
Supply plant-available forms	Assess soil supply	Identify sensitive growth stages	Consider soil chemical reactions
Suit soil properties	Use all available sources	Assess dynamics of soil supply	Suit the tillage system
Recognise synergisms	Predict uptake efficiency	Recognise dynamics of losses from soil	Manage variability among felds
Respect blend compatibility	Maintain soil fertility	Evaluate logistics of feld operations	Manage variability within felds
Recognize associated elements	Consider economics		

often advise producers at the farm level. Producers review options for each crop, choosing recommendations for source, rate, time, and place of application which suit their local site factors. These site-specific factors start with soil and landscape and extend to a wide range of considerations including local regulations and land tenure.

At the regional level, agri-service providers make decisions on the nutrient sources (products) they will offer and on the logistics of how they can be delivered at the right time to the farm or to the field. Industry agronomists interact with producers and crop advisers to implement and interpret on-farm trials that aid in the evaluation of selected practices.

At the policy level (often a national or global level), manufacturers, investors and governments make decisions on product development, and investments in production facilities and transportation infrastructure. These decisions influence the range of source and time options available to producers.

All three levels need to be consistent in the goals against which they evaluate outcome. Source, rate, time and place are central to all, but it's the full framework that we mean when we talk about 4R Nutrient Stewardship, or the 4Rs.

Accountability

Systems for sustainability improvement and certification generally require accountability. Accountability at the farm level often requires a nutrient management plan. The general principles that make a 4R Nutrient Stewardship plan distinct from a regulatory nutrient management plan are: 1) asking the producer to state sustainability goals and performance indicators for the farm, 2) allowing producers

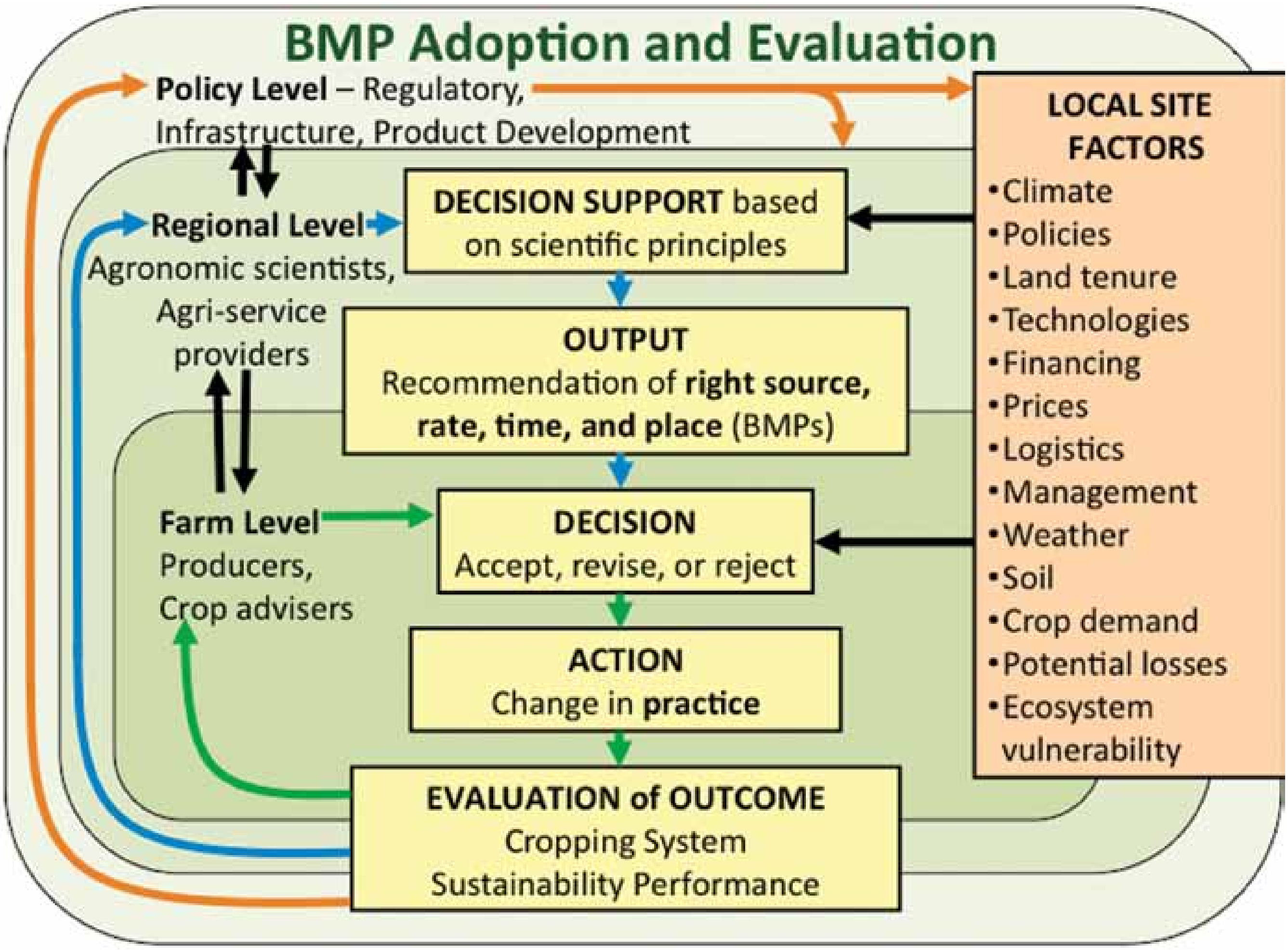

Figure 2. The 4Rs are included in adaptive management to take into account local site-specific factors in cycles of continuous improvement at farm, regional and policy levels.

flexibility to implement adaptive management by ensuring that the details of practices implemented for each crop and in each field are documented but kept private, and 3) publicly reporting progress in using indicators or measures of performance reflecting the economic, social and environmental pillars of sustainability. These principles are at the core of a management system consistent with international principles of accountability for sustainability performance.

Example – Managing Phosphorus Fertilizer in the Lake Erie Watershed

Phosphorus (P) is an essential nutrient for growing crops. But in the wrong place – in excess concentration in streams, rivers, and lakes – it can lead to algal blooms. In the Lake Erie watershed region in and around the state of Ohio, USA, levels of dissolved P in rivers and algal blooms in lakes have been trending upward from 1995 to 2011. Fertilizers applied to the predominant corn-soybean cropping system are not the only cause, but are one possible cause among many.

Research data show that when fertilizer P is broadcast and left on the surface, runoff resulting from rainstorms within a few days of application is enriched in dissolved P to levels far above those known to stimulate algal blooms, even though the losses amount to less than 5 to 10 percent of the fertilizer P applied. To mitigate these losses, 4R Nutrient Stewardship implemented in this region focuses on applying fertilizer at the "right time" and in the "right place." Wherever possible, fertilizer P is recommended to be placed below the soil surface, by injecting, banding, or by incorporating after broadcasting. Where incorporation is difficult, for example in no-till systems, producers are advised to pay close attention to the weather forecast, and avoid broadcasting P fertilizer when there is more than 50% chance of intense rain within the next few days.

A group of agri-business partners, government agencies and environmental organizations is working together to provide educational programs and raise awareness of how nutrient stewardship can contribute to reducing losses of dissolved P. This group includes The Nature Conservancy, the Ohio Agri-Business Association, the Ohio government departments of agriculture and natural resources, Ohio State University Extension, and several agri-retailers and crop producers. Further work is ongoing to develop better validated criteria for selecting practices, based on research monitoring actual edge-of-field losses. Further information on the program is available from The Nature Conservancy. By supporting management that is adaptive and addressed at economic and environmental goals at the same time, 4R Nutrient Stewardship assures continued progress in advancing crop yield s in this highly productive watershed.

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Learning from Long-term Experiments – What Do They Teach Us?

By Rob Norton, Roger Perris, and Roger Armstrong

Established in 1916, the Longerenong long-term rotation provides a platform for evaluating long-term trends in farming systems and soil health over a period of many years. Longerenong rotation 1 (LR1) gives us essentially the same message as other long-term agronomic experiments. The message is that rotations can be sustained and productive provided the challenges of diseases, weeds, soil structure, and nutrient replacement are met.

Long-term agronomic experiments (LTAE) reflect new ideas and practices in farming systems. The longest running experiments were established at Rothamsted in the United Kingdom (UK) in 1843, and seven are still running today (Rassmussen et al., 1998). There are only 10 others of these classical (more than 50 years) experiments across the globe, including

LR1 in Australia.LR1 is Australia's longest running annual cropping system experiment, established in 1916 on a self-mulching, alkaline Grey Vertosol near Horsham in southeastern Australia. Average annual rainfall is about 420 mm. LR1 sought to identify what crop sequences would provide improved yields and over time it has became a platform for other research such as on the use of superphosphate. The experiment compares seven cropping rotations and although not spatially replicated, each cropping phase is present every year. The rotations are continuous wheat (WWW), wheat/fallow (WF), wheat/oats grazed/fallow (WOgF), wheat/barley/peas (WBP), wheat/oats/peas (WOP), wheat/oats grazed/fallow (WOgF) and wheat/oats/oats grazed/fallow (WOOgF). The crops receive no fertilizer N, 10 kg P/ha on cereals, and 5 kg P/ha on other harvested crops. Crop establishment, weed control, and crop protection activities follow district practice. In the soil, N and P are present in a range of forms that have different availabilities to plants. Most of the soil N is present in organic forms which are mineralised to nitrate which is the form that plants can take up. Applied P is partitioned into a range of soil pools with different plant availability, due to differences in desorbtion, dissolution, and mineralisation rates that contribute to plant P nutrition.

Soil tests can distinguish the more available P (e.g. resin, bicar-bonate, and sodium hydroxide extractable) forms in the soil (Hedley et al., 1982). Understanding the fate of this applied P helps us predict future P strategies.

The 90+ years of this experiment have given several lessons about grain yields, nutrient removals, and sustainability.

Lesson 1 – Yields can be sustained over long periods

The mean wheat yields over the period of the experiment are shown in **Figure 1**. There are phases in these trends and the most recent recovery, starting in 1975, is co-incident with the use of herbicides on this experiment (Hannah and O'Leary 1995). Over the past 10 years, the rotation experiment has been challenged by the root nematode Pratylenchus and infes-tations of the weed bromegrass, but the downward trend seen in **Figure 1** since about 2000 is a result of low rainfall over that time. The only rotation that did not trend downwards is the WWW, which was already low yielding.

The highest producing rotation (WBP) from LR1 produced two and a half times the energy equivalence of the WWW rotation (2.22 t/ha/y glucose equivalence versus 0.87 t/ha/y glucose equivalence). Glucose equivalence is the energy content of the grain and provides a way to compare yields of different crops with different energy densities. Over the past 90 years, the WBP has produced 1.52 t/ha of wheat, 1.53 t/ha peas, and 1.57 t/ha barley in its 3-year cycle. At current grain prices, this is the most profitable rotation. Although damag-ing to soil structure, the inclusion of a fallow phase into the rotations gave lower yield variability than continually cropped rotations, especially in these years of low rainfall over the past decade (**Table 1**).

Weed and disease control strategies both require biological diversity in the farming system. Crop rotation is fundamental to ensure sustainable production systems with each phase acting as a tool to support and enhance the following crops by providing disease breaks, opportunities for alternative weed control strategies, and/or improving soil conditions.

Lesson 2 – Nutrient balances need to be addressed

Long-term production does come at a cost, though. **Table 1** shows the N and P balance for LR1 over the past 25 years. This period was chosen because the experiment was altered a little in 1984 and since then south-eastern Australia has experienced a long period of below average rainfall.

Table 1. Apparent mass balances for N and P for the seven rotations of LR1 (1986-2008).

Rotation treatment 1986-2006	Average wheat yield, t/ha	P balance, Δ kg P/ha/y	N balance, Δ kg N/ha/y
Continuous wheat	0.64±0.52	7.3	-7.3
Wheat:fallow	1.50±0.76	0.9	-11.8
Wheat:grazed oats:fallow	2.05±0.97	-0.3	-10.6
Wheat:barley:peas	1.46±1.31	3.2	2.9
Wheat:oats:peas	1.39±1.24	1.2	1.8
Wheat:oats:fallow	1.86±0.95	3.0	-13.9
Wheat:oats:grazed oats:fallow	2.11±0.96	-0.1	-12.1

LR1 has a history of providing lessons to farmers and scientists. This photograph was taken at the annual field day in 1930.

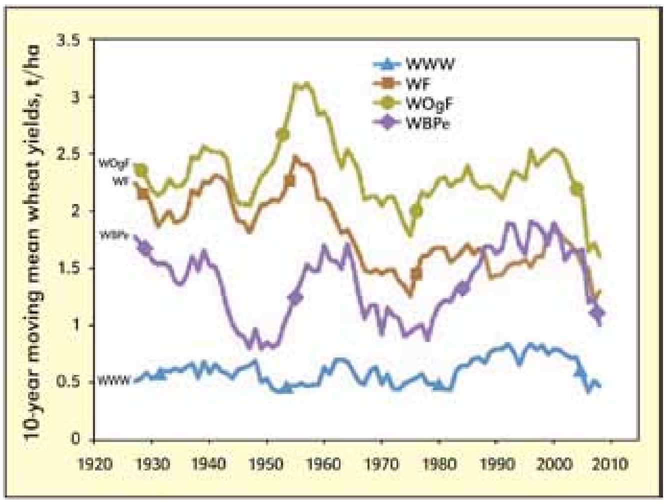

Figure 1. Grain yields of four of the seven rotations from LR1. Data presented are the 10-year moving means for the wheat phases of the rotations for the period 1916 to 2008.

Grain yield has been recorded each year and grain protein (N) in recent years. However, seed P content has not been measured, but estimated from other experiments. To develop a nutrient balance for this experiment, the apparent balance of N or P was calculated on an annual basis as:

N balance = N applied as fertilizer + N fixed by legumes – N removed in grain

or **P balance** = P applied as fertilizer - P removed in grain

No estimates were made for free living N fixation, non-biological N inputs, N leaching, N volatilization, or N lost in soil erosion. The N2 fixation for the pea phases were estimated using the peak biomass for peas from the pea grain yield, as suming a harvest index of 0.3, then converting this peak biomass to N fixed by using the conversion of 25 kg N/tonne of biomass (Peoples et al. 2001). Grain N removal was estimated by the grain N content multiplied by the yield of peas, barley, or wheat.

Longerenong College open day in 1930, putting new cultivars in front of farmers.

Longerenong College was one of the first places in southeastern Australia to trial superphosphate for grain production.

Roger Perris (left) in LR1 plots with second year agronomy students from The University of Melbourne.

Both the grazed oats and the crop stubbles were retained within the plots. Grain P content was estimated from grain P contents taken in 2005, but the actual grain P contents may differ in response to different soil P levels.

Table 1 shows an average N removal of 12 kg N/ha/y from 1984 where no pulse was included and a slightly positive N balance where the rotation included peas.

There was no baseline soil archived when the experiment was established 90 years ago, and so a "fence-line" sample was taken in an uncultivated area adjacent to the site. The soil N and C values (top 10 cm) measured then are in general agreement with the estimated N decline from the mass balances. While it is not possible to fully analyze these data due to the nature of the experimental design, there is an indication that C:N ratios are higher for rotations that have fallows, reflecting the gradual decline in the amount and nature of the organic matter present.

Table 1 also shows the P balance for the various rotations at LR1. Tang et al. (2006) reported P fractionation of the soils from this experiment and a summary of some of these results is given in **Table 2**. All rotations show a positive P balance except for the two grazed oat rotations.

The total amount of P and the less available acid-soluble P fraction increased in all rotations, especially in the continuous wheat which also had the highest P balance. The regular P applications used as part of the cropping practices in this experiment increased the total P content of the soil, while the relative proportion of P in the "plant available" pools decreased.

Where is the N coming from? Unfortunately, LR1 had no soil samples archived from the beginning, but we can look at fenceline soils as a measure of "native" soil levels. **Table 2** shows the soil N and C levels. It is possible to estimate the annual decline in soil N from these data, if we assume the starting point was the fenceline soil. These values are largely consistent with the mass balance estimates and indicate that the decline in N is basically derived from the mineralization of organic matter. The conclusion then is that to access N in rotations, soil organic matter needs to be oxidized, and N from the soil comes at a cost to soil C. We need to consider the converse of this statement, which is that if we wish to sequester C in soils, N (and P) will need to be supplied.

Where is the P going? It is clear that the long-term P applications have raised the total amount of soil P, basically in accord with input and outputs presented in **Table 1**. The soil P fractions differ in their availability to crops and these results show that almost all the applied P is now in the low availability pool (Residual and Acid P). Tang et al. (2006) took soil from these rotations and tested the crop response to P in a glasshouse. This showed a positive response to additional P which is not what would be expected from the Olsen soil P test values. The conclusion is that on these alkaline soils, the fixation processes are rapid and current commercial soil tests are not very reliable indicators of potential P response, and indeed the responses differed among a range of crops used to test response. Those authors also concluded that the key to improving P use efficiency is to match P fertilizer applications to crop P removal on these soils.

Table 2. Soil N, C, bicarbonate extractable P (Olsen P), total P, and selected P fractions as a percentage of total P for rotations of LR1 and the adjacent uncropped fenceline, when sampled in 2005.

	WWW	WF	WOgF	WBP	WOP	WOF	WOOgF	Fenceline
Total soil N %	0.070	0.056	0.063	0.085	0.087	0.061	0.066	0.162
C: N ratio	13.3	16.2	14.9	13.0	12.9	13.9	13.8	13.1
Total P, mg/kg	486	367	307	341	329	330	322	295
Bicarbonate Ext. P, mg/kg	69	52	40	40	47	66	50	18
% HCl P	39	25	18	25	22	23	19	7
% Residual P	35	43	47	49	52	50	61	75

Soil C levels The effect of mineralizing N is to reduce C so that soil C levels have declined. With the current interest in C sequestration, LTAEs such as LR1 can provide unique real world data on soil C stocks under different farming systems. In 1916, when the experiment was established, such a ques-tion would not have been thought of and now as part of a new research project, this site will be used to measure soil C stocks to depth and accounting for soil bulk density.

Conclusion

At the most fundamental level, LTAEs provide us with reassurance that cropping and pasture systems can operate for many decades and depending on the strategies adopted, continue to produce food and fibre with resource protection. While cropping and pasture systems computer simulation models can help refine information, they do require real world data to calibrate against. Conclusions based on 10 to 20 years of experimental data can be quite different to those based on 50 years of data. Long-term agronomic experiments have pro-vided us with understanding about the trends in productivity associated with different crop sequences and tillage operations. Since their inception, we now use LTAE's to help identify fac-tors affecting sustainability and environmental quality as well as species impacts in response to change.

While we know a lot about the effect of systems on soil health ("knowns"), there are things we have not yet param-eterised ("known unknowns", such as soil C). There are other things we have not even considered. Dealing with "unknown unknowns" is difficult to cost and plan for, but having well planned and suitably resourced long-term experiments can play a vital role in such studies. As Rassmussen et al. (1998) indicated, "We need continuity with the past to better predict the future."

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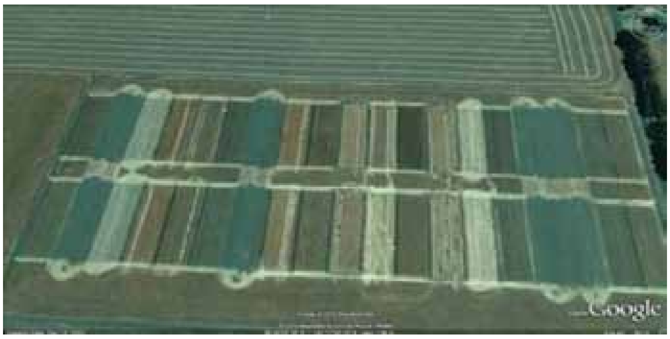

Google Earth/DigitalGlobe view of LR1 showing the plot layout. All plots were originally one acre each. In 1986, they were split, with the southern half using the latest cultivars while the northern half retained the traditional variety Ghurkha wheat.

Acknowledgments

The nutrient balances constructed here were supported by the Grains Research and Development Corporation through the project UM00023. The authors acknowledge the foresight of those who established these long-term experiments, as well as the generations of staff involved in managing them since their inception.

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The Essential Role of Soil Organic Matter in Crop Production and the Efficient use of Nitrogen and Phosphorus

By Johnny Johnston

The role of soil organic matter (SOM) in supporting the nutrient requirements of high crop yields is fundamental, especially as crop yield potential continues to improve. Lessons on N and P interactions with SOM and its support of high crop yields are well illustrated here through examples gleaned from long-term research conducted at Rothamsted.

A first example of the contribution of SOM towards en-hancing crop productivity is provided here through use of data from the Hoosf eld Continuous Barley experi-ment at Rothamsted. Started in 1852 on a silty clay loam soil, the Hoosf eld site received annual application of NPK fertil-izers, or farmyard manure (FYM) at 35 t/ha, which produced soils that now have 1.74 and 6.16% SOM, respectively. Each year since 1968, four amounts of fertilizer N (0, 48, 96, and 144 kg N/ha) are applied to these soils. Beginning in the mid 1970s, **Figure 1** plots changes in grain yield of three succes-sive cultivars of spring barley, each with higher yield potential than its predecessor. On the soil with lower SOM, the crop responds to N and there is little difference in maximum yield of the three cultivars in the three periods. On soil with more SOM, the crop responds only a little to fertilizer N, but as the yield potential of the crop has increased, the maximum yield on this soil has increased—as has the benef t from having more SOM. The difference in maximum grain yield on the two soils is now more than 2.5 t/ha.

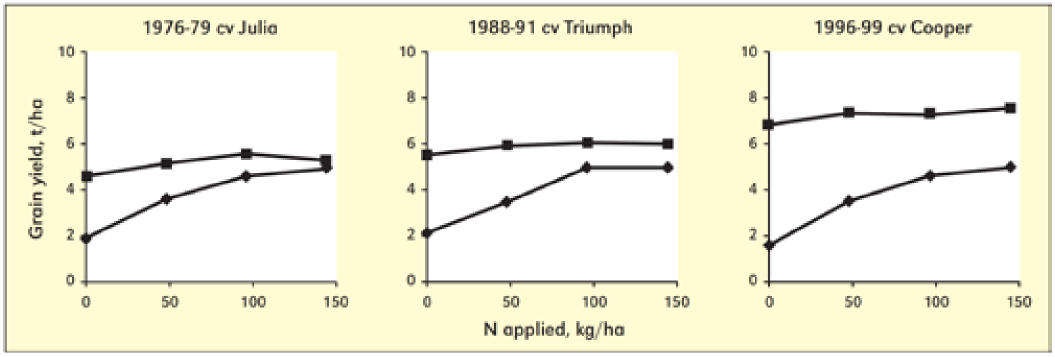

Figure 1. O Grain yield response to applied N from three spring barley cultivars with increasing yield potential (left to right) grown on two soils with 1.74◆) or 6.16 ■ % SOM, Hoosfield Continuous Barley experiment, Rothamsted.

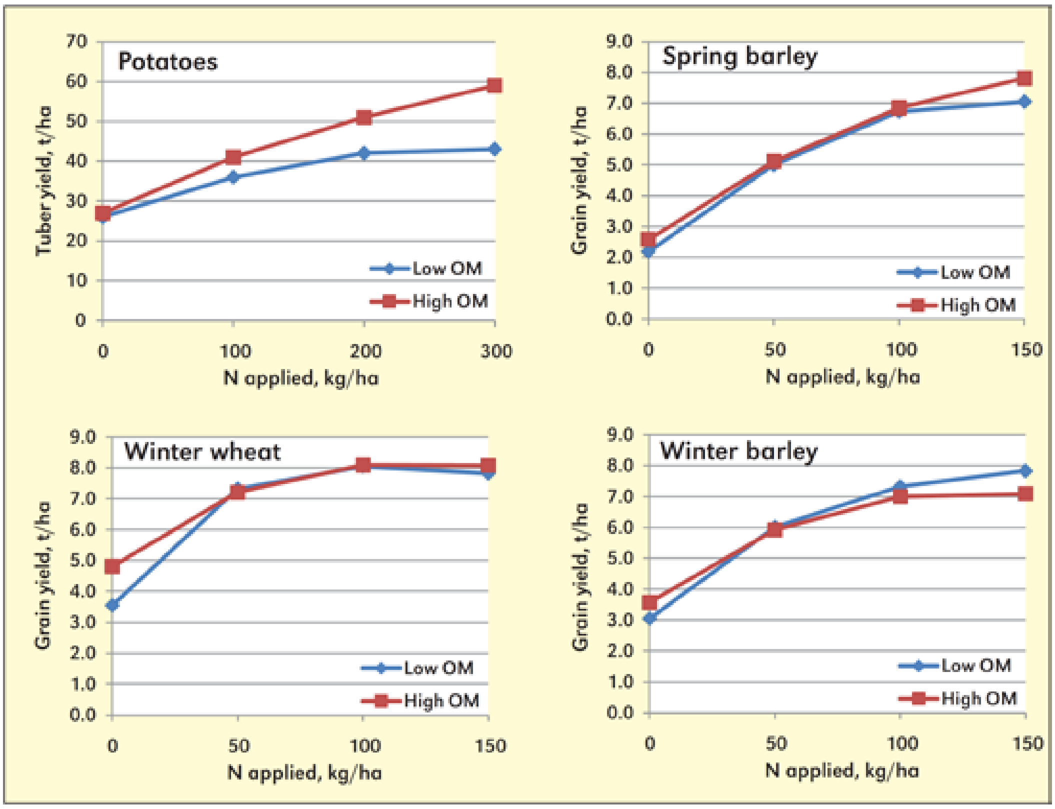

Figure 2. Yield response to applied N by spring and winter crops grown on a sandy loam soil with two levels of SOM, 1.3 and 3.4%, respectively.

Similarly, on the Broadbalk winter wheat experiment, soils treated with fertilizers or FYM (35 t/ha each year) since 1843 now contain 1.93 and 4.87% SOM, respectively. Different amounts of N have always been tested with PK fertilizers and the resulting yields have compared with those given by FYM alone. In many years before 1967, grain yields with FYM were slightly better than with fertilizers (Garner and Dyke, 1969), but the yield increase due to FYM for winter wheat was not as large as that with spring barley, probably because winter wheat has a longer growing season in which to make a root system. Since 1968, when short-strawed cultivars were intro-duced with improved grain-to-straw ratios and higher yield potentials, yields have only been larger on FYM-treated soil if an additional 96 kg N/ha is given as fertilizer. Interestingly, when cv. Hereward began to be grown at Broadbalk in 1996, the addition of 96 kg N/ha with FYM no longer gave a larger yield than the optimum NPK fertilizer application (Johnston et al., 2009). Since 2005 it has been necessary to add 144 kg N/ha with FYM to give slightly larger yields than with fertilizers. It would seem that the available N from 35 t/ha FYM, and that mineralized from the accumulated SOM, is not suff cient to give maximum yields of a cultivar of winter wheat with a large yield potential. It would be interesting to speculate why this is so.

Soil Organic Matter and Nitrogen Interactions

At the present time there is considerable interest in the ef-f cient use of N in agriculture. This arises not only because the different forms and pathways by which N can be lost from soil can have adverse environmental impact, but also because such losses are a direct cost to growers. There is much evidence to show that N is used more eff ciently on soils with more organic matter, and presumably a better structure, so that roots explore the soil more effectively to f nd nutrients.

On a sandy loam soil with two levels of SOM, potatoes, spring barley, winter wheat, and winter barley have been grown in different years, each crop given four appropriate amounts of N (**Figure 2**).

Yields of the spring sown crops, potatoes and barley, were always larger on the soil with more SOM irrespective of the amount of N applied, and the recovery of the applied N was greater where the yields were larger. A better soil structure with more SOM allowed for quicker root development and bet-ter exploration of the soil mass for nutrients. At each amount of applied N, the yields of the winter sown cereals, with a longer growing period than a spring-sown crop, were largely independent of

SOM, probably because these autumn-sown crops had time to develop an adequate root system on the soil with less SOM.

In another experiment on a sandy loam soil, the effects of various organic amendments on SOM and yields of arable crops have been tested since 1964 with two periods of organic additions (the "treatment" period) and two periods of arable "test" cropping (Johnston et al., 2009). Annual organic treat-ments that were common to both periods of addition included incorporating straw (7.5 t/ha dry matter), applying FYM (50 t/ha fresh material) and growing and then incorporating a grass/clover ley (temporary pasture) before growing arable "test" crops to measure the effects of any additional SOM built up during the two "treatment" periods.

In 1986, C in the top 23 cm was 0.65% without organic addition—about the equilibrium level for this soil and treat-ment. The organic additions increased it to 0.85% with added straw, 1.06% with FYM, and 0.90% following the incorporation of an 8-year grass/clover ley. The yields of potatoes (in 1988 and 1989) and winter wheat (in 1987 and 1988), each testing six amounts of N, are compared with those on soils without extra organic matter addition in **Figure 3**. Yields were always smallest on soil with least SOM and generally largest on soils ploughed out from the grass/clover ley. In all comparisons, less N was needed to achieve optimum yield on soil with more SOM.

There are two interesting features in these results. First, in **Figure 3a**, the largest winter wheat response to the maximum amount of N tested was on the FYM treatment—an effect similar to that on the Broadbalk experiment discussed earlier, and perhaps explained for the same reason. Second, following the ploughed-in grass/clover ley, the largest yields were with the second increment of N tested, suggesting that there could have been some benef cial effect late in the growing season from N mineralized from the N-rich ley residues ploughed-in the previous autumn. If this mineralized N is lower down in the soil prof le, where roots are actively taking up nutrients, then such a benef cial effect would be diff cult to mimic with fertilizer N applied on the soil surface.

Two further comments about these results; first, although best yields followed the grass/clover ley, having a ley for 3 years must be economically vi-able within the whole farm budget. Second, there was continued benef cial effects from straw incor-poration, one of the few methods available to many farmers for slightly increasing or maintaining SOM, and perhaps preventing SOM decline.

Soil Organic Matter and Phosphorus Interactions

In addition to important interactions between SOM and the response to N, there are equally important interactions between SOM and plant-available P in soil. In an experiment on a silty clay loam soil, known to be diff cult to cultivate, especially in spring, plots were established over a 12-year period with two levels of SOM, 1.5% (the arable plots) and 2.4% (the grass plots), and 24 levels of Olsen-P at each level of SOM. After the 12-year preparatory period, potatoes, sugar beet, and spring barley were each grown twice in rotation in 3 years. The

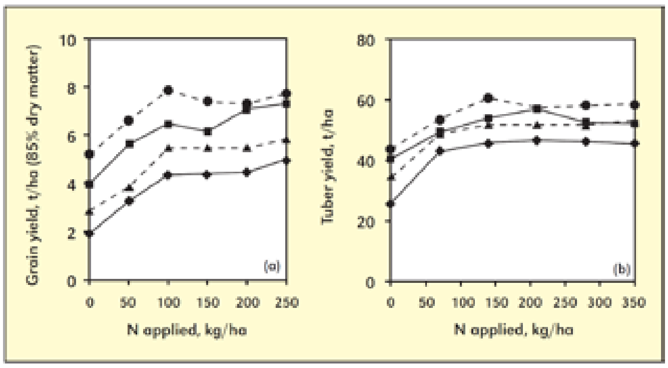

Figure 3. Yield response to N rate for winter wheat in 1987/88 (a) and potatoes in 1988/89 (b) after periods of various organic treatments (see text). Treatment and % SOM: No organic amendment, 0.65% SOM ( ); incorporating straw, 0.85% SOM ( ); adding FYM, 1.06% SOM ( ); incorporating a grass/clover ley, 0.90% SOM ( ).

2-year average yield of each crop was plotted against Olsen-P, and the response curve f tted statistically to determine maximum yield and Olsen-P associated with 95% of the maximum yield (**Table 1**).

The 95% yield of spring barley was appreciably smaller on soil with low SOM compared to that on soil with high SOM, but potatoes and sugar beet gave similar yields on both soils because better seedbeds could be prepared for these two crops sown later than spring barley. Of great importance, however, the level of Olsen-P associated with the 95% yield was much lower on soil with more SOM. The effect of SOM was to improve soil structure so that roots could grow more freely and explore the soil more thoroughly to f nd plant-available P.

Subsequently, soil samples from all 48 plots (two levels of SOM x 24 levels Olsen-P) were cropped with ryegrass under uniform conditions in the glasshouse. The cumulative yields from four harvests were plotted against Olsen-P and the response curves on soil with the two levels of SOM were not visually different. The 95% yields were virtu-ally the same as were the Olsen-P levels associated with these yields (Table 1) strongly suggesting that soil structure in the f eld was the explanation for the large differences in Olsen-P associated with the 95% yields.

Table 1. Crop yield and Olsen-P associated with 95% of the maximum yield determined by plotting the 2-year average crop yields against Olsen-P.

Crop yield	Soil organic matter, %	Yield at 95% maximum, t/ha	Olsen-P associated with 95% yield,mg/kg	R^2
Field experiment				
Spring barley grain, t/ha	2.4	5.00	16	8.83
	1.5	4.45	45	0.46
Potatoes tubers, t/ha	2.4	44.7	17	0.89
	1.5	44.1	61	0.72
Sugar beet sugar, t/ha	2.4	6.58	18	0.87
	1.5	6.56	32	0.61
Pot experiment				
Grass dry matter, g/pot	2.4	6.46	23	0.96
	1.5	6.51	25	0.82

Summary

It is not easy to increase SOM in many arable cropping systems unless it is possible to add large amounts of organic materials. However, every attempt should be made to conserve and increase SOM wherever possible because it improves soil structure and thus the ability of plant roots to grow through the soil to f nd the nutrients required to optimize growth and yield. This is especially so in relation to the acquisition of N and P and thus their eff cient use in agriculture.

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Improvement of Diagnosis Accuracy of Phosphate Status for Ukrainian Soils

By Anatoly Khristenko and Svetlana Ivanova

Through an analysis of the effect of soil properties on the accuracy of the Olsen P soil test, a refined method and interpretive scale for available soil P supply was developed for use in alkaline soils.

Studies performed at the Institute for Soil Science and Agrochemistry Research named after O.N. Sokolovsky, National Academy of Agrarian Science, Ukraine, show that some chemical methods used for the determination of plant available elements involve large errors. In particular, the error for determining available soil P or K based on former Soviet Union soil testing standards can reach 100 to 200% or more. Most methods include the use of strong acid solutions that can underestimate results for all coarse (sandy and loamy sandy) soils, as well as for strongly acid (pH_{KCl} < 4.5) soils of different textures, and can overestimate results for soils with high contents of primary P-containing apatite minerals.

Presently eight national soil test standards and five standard drafts have been developed for Ukraine's 32 million ha of arable land. The process began with the identification of Ukrainian regions and soil types for which specific chemical methods of determining plant available N, P, and K are most advisable. The potential effects of soil composition and physical properties on the results of chemical analyses were taken into consideration. New scales of soil supply for available P or exchangeable K were developed for some methods that together specify methods for determining plant available N, P, and K for all soils of the country.

The use of State standards, including the Olsen, Machigin, Chirikov, Kirsanov, and Karpinskii–Zamyatina methods (described below), has generally meant that available P status of arable soils under extensive agricultural use fall within the low-to-medium supply levels, while available K status is generally considered medium. This agrees with well-known empirical data that demonstrates high efficiency of mineral fertilizers, especially P fertilizers, on all types of arable soils of Ukraine, including its chernozems. New regulatory soil tests explained below, demonstrate an increase in accuracy of the diagnosis of soil fertility. The subsequent correction of fertilizer application rates, and more rational distribution of fertilizers among fields and crops, can increase use efficiency by an average of 30%.

Errors in soil testing theory and methodology create overestimation (or underestimation) of results for not only individual fields, but also entire regions. An illusion of rich chernozems on loessial rocks is related to the increased content of P-bearing apatites and K-bearing feldspars in these soils. However, P or K present in these minerals are not directly available to plants. At the same

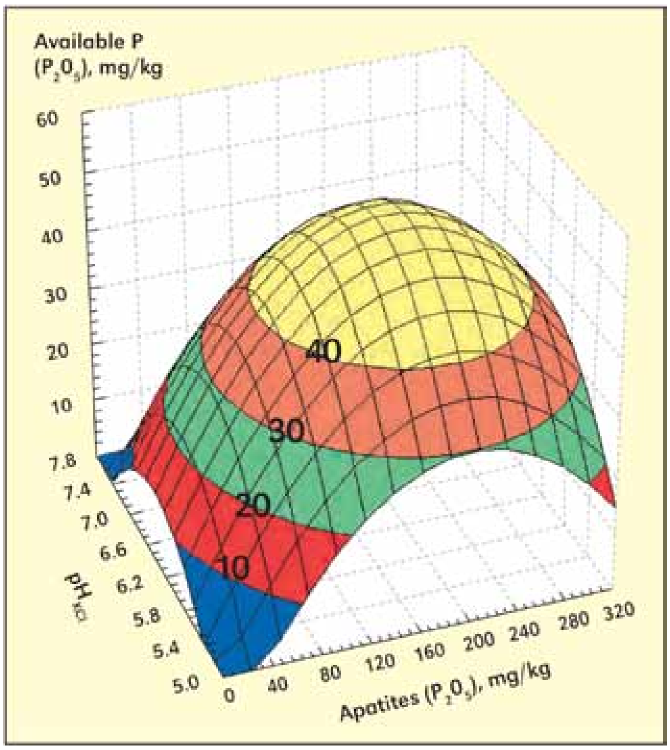

Figure 1. Determination of P in 21 soil samples representing common soil types of Ukraine and Russia by the Egner–Riehm method depending on soil pH and apatite content (Ca–P fraction).

Table 1. The content of plant available P in the main arable soils of Ukraine from the acid, alkaline, and salt methods depending on soil pH and apatite content.

Soil type*	Content of particles <0.01mm, %	pH_{KCl}	P_2O_5, mg/kg		
			Chang–Jackson, Ca–P fraction	Chirikov, pH 2.5	Olsen, pH 8.5
Albeluvisols Umbric	9	4.5	34	34.0	19.6
Albeluvisols Umbric	18	4.9	75	35.0	19.8
Cambisols Eutric	32	3.8	45	1.9	20.7
Phaeozems Albic	48	3.8	104	2.1	20.9
Chernozems Luvic	32	5.4	118	10.0	19.8
Chernozems Calcic	56	6.8	201	79.9	19.5
Chernozems Calcic	54	6.7	244	80.0	20.0
Chernozems Chernic	48	6.0	273	132.0	25.2
Chernozems Chernic	55	6.4	297	161.0	25.6
Chernozems Calcic	60	6.9	326	170.1	24.5
Mollic Gleysols	27	6.6	806	345.1	30.3

* according to the World Reference Base for Soil Resources (WRB) nomenclature

Table 2. Assessment of P supply in Chernic Chernozem soil with chemical and biological methods used in a pot study.

Soil texture	Field experimental treatment*	P_2O_5, mg/kg			P_2O_5 inoat biomass, %
		Ion-exchange chromatography	Olsen	Karpinskii–Zamyatina (DSTU† 4729)	
Clay loam	Control	20.0	19.1	0.31	0.52±0.09
	P_{1200}**	58.9	52.9	1.75	0.70±0.09
Loam	Control	31.0	24.0	0.44	0.58±0.11
	$N_{400}P_{400}K_{480}$***	119.1	124.9	5.84	0.81±0.11

*Fertilizer treatment for the field from which soil was collected for use in the greenhouse pot study; subscripts indicate kg/ha on oxide basis.
**A single application of P with no cropping prior to sample collection.
***A long-term study where the indicated rates were the average application for one 5-year rotation with the experiment conducted for 11 rotations (total fertilizer applied was 11 times the rates shown).
†Denotes National Soil Test Standard

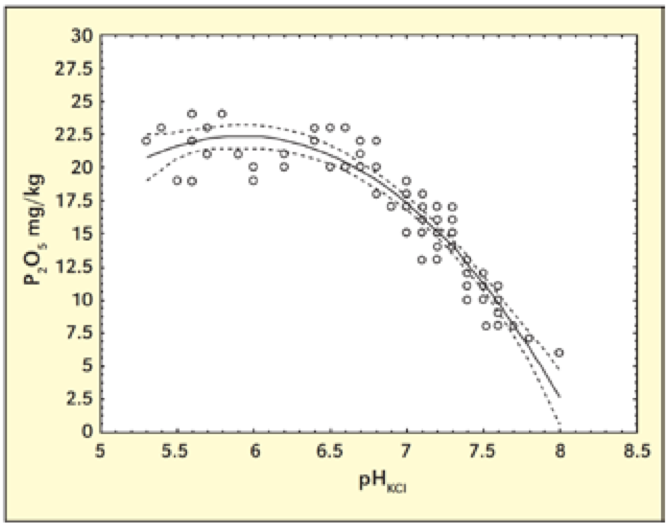

Figure 2. Results of the determination of available P by the Olsen method depending on soil pH.

time, these elements are partially extracted by strong acid solutions, including 0.02 N HCl (pH 1.0, Kirsanov method) and 0.5 N CH_3COOH (pH 2.5, Chirikov method). Reported data shows that the unbiased assessment of soil fertility and available forms of macro- and micronutrient is a global challenge.

Shortcomings of the methods based on the use of acid solutions are largely typical for all methods using extractant solutions with pH below 4.5: Bray–Kurtz 2 (pH 1.0), Mehlich 1 (pH 1.2), Arrhenius (pH 2.0), Mehlich 3 (pH 2.5), Mehlich 2 (pH 2.6), Van Lierop (Kelowna, pH 2.7), Egner–Riehm (pH 3.6), Bray–Kurtz 1 (pH 3.5), Egner–Riehm–Domingo (pH 4.2), etc. For example, we found that the determination of P by the Egner–Riehm method in soils with strongly acid or alkaline reaction entails the underestimation of the results (**Figure 1**). An increase in the content of apatite in the soil, on the contrary, overestimates the results. The content of apatite is reflected in the Ca–P fraction (i.e. Chang–Jackson method).

The tendency toward a "decrease" in the content of P in soils with the very high content of apatite (prevalent in the Ukrainian steppes) is related to their alkaline reaction. The authors evaluated this through a combination of methods based on different principles: chemical methods, ion-exchange chromatography, and pot studies. A statistical analysis of data from an automated information data bank (more than 1,500 soil samples) was also performed. On the basis of these studies, a conclusion was drawn about the advisability of the wide use of socalled "mild" methods (based on the use of salt and weakly alkaline extractant solutions). A 30-year-long comparative study of different methods showed the superiority of the method based on the use of a sodium bicarbonate solution (Olsen et al., 1954). It was found that the particle-size distribution and other soil properties (e.g. presence of apatite, acid reaction) had almost no effect on the Olsen method's results. The coefficient of correlation was $r < 0.33$.

The content of available P in the Ukraine's unfertilized and under-fertilized soils, as determined by the acid method, can vary from very low to very high values of P supply (**Table 1**). According to the Olsen method, Ukrainian soils always are within the low-to-medium P supply range. Data obtained by the Olsen method for acid and neutral soils always agree with the soil fertility estimated using other mild methods. The adequacy of the P status estimation was also confirmed by pot study (**Table 2**).

The Olsen-P method has wide applicability across Ukrainian soils: from acid Cambisols Gleyic and Albeluvisols Umbric to Chernozems Calcic and Kastanozems Haplic. In comparison, the scope of the Chirikov method is significantly smaller–only recommended for podzolized soils (Albeluvisols Umbric, Phaeozems Albic, Chernozem Luvic). Although the Olsen method is primarily designed for the analysis of alkaline soils, its use for these soils could result in the underestimation of P supply. The higher the soil alkalinity, the lower the result (**Figure 2**). As a result, the general

Table 3. Soil supply with plant available phosphorus as determined by the Olsen method.

Phosphorus sufficiency ranges	Soil test P_2O_5, mg/kg		Proposed ranges
	Yanishevskii, 1996	Agrochemical methodsof Soil Examination, 1975	
Low	< 11	< 25	< 18
Medium	11-23	25-50	19-34
Increased	23-41	50-90	35-50
High	> 41	> 90	51-66
Very high	-	-	> 67

opinion is that alkaline soils are poorly supplied with available P. The parallel use of salt solutions (Karpinskii–Zamyatina, 0.03 N K_2SO_4 with pH 5.8; Schofield) shows that no actual decrease in available P occurs in alkaline soils. Thus, the disappearance of P is an illusion related to a limitation of the method as an alkaline extract loses its extraction capacity under alkaline conditions. The maximum underestimation is about 18 mg P_2O_5/kg—a value equivalent to the effect of a single application of at least 600 kg P_2O_5/ha in a heavy soil.

Rigorous application of soil test protocols lose their value given a lack of official nutrient sufficiency ranges in terms of plant available P supply. The P status of soil cannot be impartially assessed without adequate nutrient sufficiency ranges. Available literature data are contradictory (**Table 3**). Studies performed at the Institute for Soil Science and Agrochemistry Research reveal that the P sufficiency ranges estimated by the Olsen method in accordance with the P sufficiency ranges developed earlier (Yanishevskii, 1996; Agrochemical methods of soil examination, 1975) do not usually agree with the values obtained by other alkaline and salt methods.

The authors propose refined P sufficiency ranges, as determined by the Olsen method, which now coincide with estimates of soil P supply from other mild chemical methods (Machigin, pH 9.0; Chang–Jackson, Al–P fraction, pH 8.5; Karpinskii–Zamyatina, pH 5.8). A category of very high supply was also added in hopes of further contributing to the more rational use of the resources available. Optimum plant available P for stable, high crop yields lies within the range corresponding to high P supply. An increase above the optimum level results in an abrupt decrease in crop response to P fertilizer. Liberal application of P fertilizers to highly alkaline soils is also unadvisable as high alkalinity (pH_{KCl} 8.0 or pHwater 8.5 and higher) is frequently due not only to the presence of calcium carbonates, but also to the presence of Na. The latter compound is detrimental to the growth and development of many agricultural crops, which abruptly decreases the efficiency of fertilizers applied.

Mathematical models and the corresponding software were developed by the authors for the determination of the actual supply of alkaline soils with available P depending on the pH_{KCl} or pHwater values (Khristenko, 2009). The use of these mathematical models or software, as well as the improved scale for soil P supply, will contribute to the optimization of fertilizing systems and, hence, expenditures per ha of fertilized area. For example, finding that the supply of soil P is 25 mg P_2O_5/kg (medium P supply) rather than 5 mg P_2O_5/kg (low P supply), the farmer can significantly reduce fertilizer application without fear of crop yield reductions.

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A New Approach to Assessing Phosphorus Use Efficiency in Agriculture

By A.E. (Johnny) Johnston and J. Keith Syers

It is frequently stated that P is used inefficiently in agriculture, with percent recovery of P applied in fertilizers usually between 10 and 20%. We argue that such low efficiencies are primarily an artifact of the method used to calculate efficiency. When efficiency is measured by the "Balance Method" – P removed in crop expressed as a percentage of P applied – and when soil P levels are being maintained near the critical level, the efficiency of fertilizer P use frequently exceeds 90%.

In a recent comprehensive review of world literature on P use efficiency for a wide range of cropping systems, soil types, and climates, Syers et al. (2008) showed that the recovery (efficiency) of applied fertilizer P plus residual soil P frequently ranged from about 50 to 90% when measured by a suitable method and over an appropriate time scale. This article shows how the concepts in the review can be developed further.

Percent recovery of an applied plant nutrient, X, is frequently calculated by the difference method:

Rothamsted Research has plots with various P treatments going back to 1856.

$$\text{Percent recovery} = \frac{\text{uptake by crop given X minus uptake by crop without X}}{\text{Amount of X}} \times 100$$

While this method is generally appropriate for N fertilizers, it has more limited value for P and K. Why? Nitrogen applied as an inorganic fertilizer containing urea, ammonium, or ni-trate and not used by the crop rarely remains as a residue of inorganic N in the soil. Nitrate left in the soil after crop harvest can be lost by leaching or denitrification and ammonium by volatilization. Thus, percent recovery of applied fertilizer N is best determined by the difference method which allows for any N taken up by a crop in the absence of applied N. However, only a very small amount, if any, of the residue from applied P and K fertilizer is lost from the soil. In most soils, any residue accumulates as a reserve of these two nutrients.

The direct method – using the isotope 32P – can be used to measure percent recovery of P applied in a fertilizer. However, percent recovery (efficiency) rarely exceeds 25%. But stop and consider. If only 25% of the P in a crop has come from the freshly applied fertilizer, the remaining 75% must have come from soil reserves of P. If soil P fertility is to be maintained, any P from the soil reserves must be replaced. So it is reasonable to consider that the total P in a crop, part from the fertilizer, part from soil reserves (which are maintained by fertilizer P addition), represents the long-term recovery of fertilizer P. Johnston and Poulton (1977) proposed this approach to mea-suring P use efficiency and it was developed further by Syers et al. (2008) who called it the "Balance Method" in which percent recovery of added P is calculated as:

$$\text{Percent recovery} = \frac{\text{P removal by crop}}{\text{P applied}} \times 100$$

This method has the advantage that the recovery of P from soil reserves is allowed for and there is no need for a control or check plot.

The second aspect of P use efficiency is related to recent developments in understanding the behavior of P in soil. In relation to the availability of soil P for uptake by plant roots, Johnston (2001) suggested that soil P could be considered to exist in four pools. This concept was further developed by Syers et al. (2008). Besides considering that the four pools of soil P were characterized by the availability of the P for uptake by plant roots, the latter authors related the four pools to the extractability of P by chemical reagents. In this way, a laboratory measure of "available" P can be related to soil P "availability" as seen by the growing crop in the field.

The overall concept can be shown diagrammatically as in **Figure 1**.

The amount of P in each of the four pools is related to differences in bonding energy for P between sites both on the surfaces and within soil constituents able to retain P and varia-tions in the proportion of such sites within the soil matrix. For P in the less readily available pool, it is further envisaged that there can be other reactions of P with soil constituents (Syers et al., 2008).

Phosphorus is taken up by plant roots as orthophosphate ions, principally $H_2PO_4^-$ and to a lesser extent HPO_4^{2-}. Earlier ideas about the fate of applied fertilizer P considered that if not used by a crop, the P became "fixed" in soil in forms that no longer supplied these ions to the soil solution and, therefore, this P was no longer available for uptake by roots. However, by the 1950s there were indications from field experiments which showed that where sufficiently large P reserves had accumulated in soil from past applications of fertilizer and organic manure, these reserves could provide sufficient P to increase crop yields.

The most important feature shown in **Figure 1** is the reversible transfer of P between the soil solution, the readily plant-available P pool, and the less-readily plant-available pool. Examples of supporting data from field experiments are given by Syers et al. (2008). Routine soil analysis for plant-available P measures the P in the soil solution and the readily plant-available pool. Because this is an operationally-defined fraction of soil P, the method of analysis used is not important.What is essential is that the data obtained accurately charac-terize a soil in terms of the response of a crop either to soil P or to an application of P fertilizer.

The reversible transfer of P between the first three pools implies an equilibrium between the P in these pools. Data for the increase in both Olsen P and total P in the top 23 cm of soil are available for a number of long-term experiments on the silty clay loam soil at Rothamsted, the sandy loam at Woburn, and a sandy clay loam soil at Saxmundham. For all three soil types there is a common linear relationship between the increase in Olsen P and the increase in total P (**Figure 2**).

Similarly, in an experiment in North Carolina, McCollum (1991) showed that after adding P for 9 years at rates up to 1,128 kg P/ha, only about 20% was extracted by the Mehlich-1 method.

A number of important practical questions arise from this concept of the behavior of soil and fertilizer P.

The first question is: "How much P should there be in the readily available pool to ensure optimum yield?"

When crop yield is related to readily available soil P measured by a reliable method for routine soil analysis, yield increases rapidly at first and then more slowly until it reaches a plateau – the asymptotic yield (**Figure 3**). The available soil P level at which the asymptotic yield is reached can be considered the critical level for that crop. Below the critical level, lack of available P results in a loss of yield. Applying P to soil with more than the critical level of available P would be done only to maintain soil P at a non-limiting level where no direct yield response is expected.

Examples of yield/Olsen P response curves from

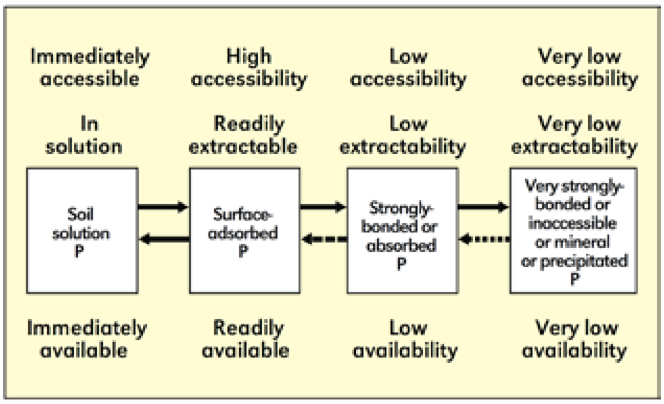

Figure 1. Efficiency of soil and fertilizer P..

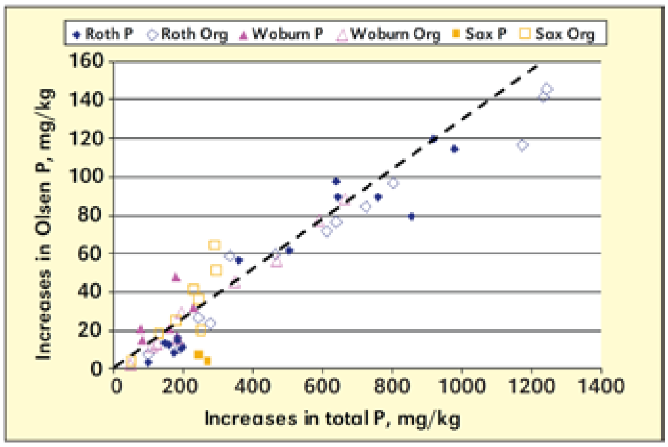

Figure 2. Relationship between total P and Olsen P.(Dashed line represents 13% of added P remaining as Olsen P.)

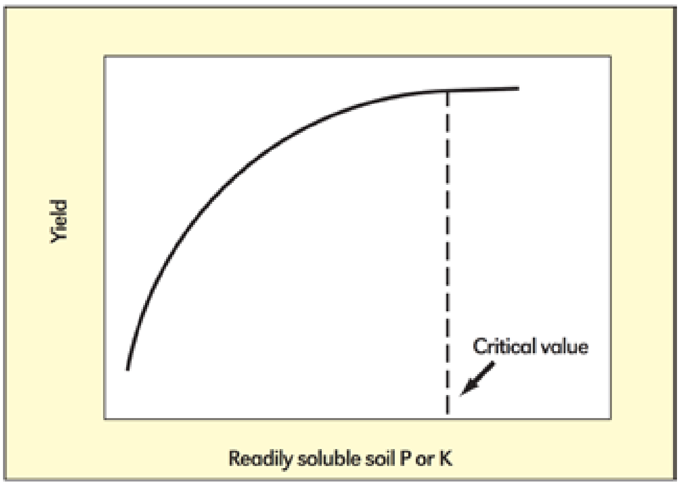

Figure 3. How much P should there be in the readily available pool?

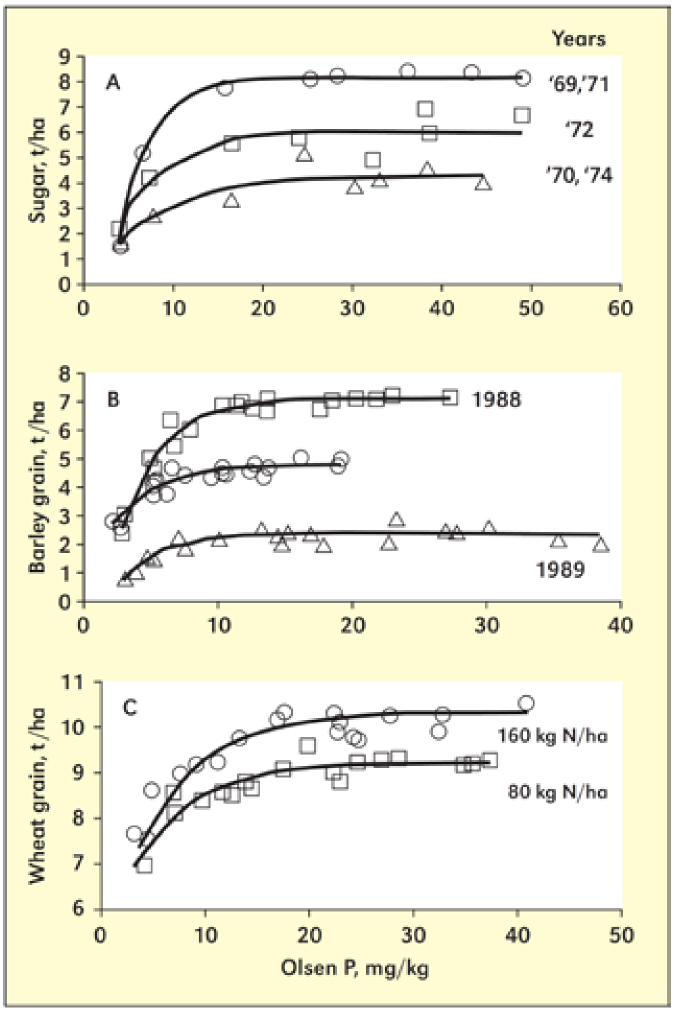

Figure 4. Example of critical values for arable crops.

Rotham-sted experiments are shown in **Figure 4**. For the three crops, sugar beet (sugar yield), spring barley, and winter wheat, although the maximum yield differed between years due to weather factors or to the amount of N applied, the critical level differed little. To achieve the larger asymptotic yield did not require more Olsen P in the 23 cm of topsoil.

The second question is: "How much P must be added to increase plant-available P to the critical level?"

The answer to this question is site-specific. For this reason much further work is required. Soil type, soil bulk density, depth of P incorporation and sampling will influence the result. Two examples show what can be done. An experiment started in 1856 on the silty clay loam at Rothamsted Research has been modified to measure the amount of P required to increase Olsen P (Poulton and Johnston, personal communication). Five P treatments between 1856 and 1901 had given a narrow range of Olsen P levels. The range of Olsen P was increased between 1986 and 1991 by applying 264 to 786 kg P/ha. Av-eraged over appropriate treatments, the total P applied, the P balance, and the initial and final Olsen P levels are given in **Table 1**. On soils initially with 7 mg/kg Olsen P, a positive P balance of 182 kg P/ha increased Olsen P to 18 mg/kg. Spring barley was grown each year (1986 to 1991). From the P response curve, the mean 98% asymptotic grain yield was 52.1 t/ha and the associated Olsen P was 14 mg/kg. Thus, 182 kg P/ha incorporated into the top 23 cm of soil was sufficient to increase Olsen P in 6 years to above the critical level. In the experiment discussed by McCollum (1991), the soil was a fine sandy loam and Mehlich-1 P was measured in the top 15 cm of soil during the initial 9-year period when P was added. At the start of the experiment, the soil was already at about the critical level for maize (18 to 22 g/m3) and above that for soybean. However, over the 9-year period, 0 to 1,120 kg P/ha was applied; the increase in Mehlich-1 P was linear and 10 kg P/ha increased Mehlich-1 P by 1 g/m^3.

The third question is: "How much P is needed to maintain the critical level of Olsen P?"

The Rothamsted experiment was continued, but no

Table 1. Total P added and P balance 1986-1991; Olsen P, mg/kg, in 1986 and 1991.

P added, kg/ha	P balance[1], kg/ha	Olsen P, mg/kg	
		1986 r.	1991 r.
786	700	7	48
522	437	8	38
264	182	7	18

[1]P applied in excess of removal by crops.

Table 2. Relationship between Olsen P, maximum yield of winter wheat grain, total P removed in grain plus straw, P applied annually, and percent recovery of applied P, estimated by the balance method.

Olsen P, mg/kg, in 2004	9	14	23	31
Winter wheat grain, t/ha	7.1	7.8	7.9	7.9
P removed in grain plus straw, kg/ha	14	27	19	19
P applied annually, kg/ha	20	20	20	20
Percent recovery of applied P estimated by the balance method	70	85	95	95

P was added between 1993 and 1999. By 1999, Olsen P ranged from 2 to 31 mg/kg so that the yield response to Olsen P could be measured. From 2002 to 2006 when winter wheat was grown, 20 kg P/ha was applied each year to replace the maximum offtake in grain plus straw on plots that had received P from 1986 to 1991. These additions maintained the 1999 Olsen P levels.

The data from this experiment show that maximum grain yield was with a soil at the critical level of plant available P (Olsen P) and when this level was maintained by replacing the P removed in the harvested crop, then P use efficiency of the annual application exceeded 90% (**Table 2**).

Table 2 shows that the maximum yield was 7.9 t/ha at 23 mg/kg Olsen P and yield was not further increased at 31 mg/kg. On soil with less than 14 mg/kg Olsen P, yield was decreased, which would result in a financial loss to the farmer. Maintaining the Olsen P at the critical level by replacing the P removed in the harvested crop resulted in more than 95% efficiency of the annual application. Similarly, in the experiment described by McCollum (1991), replacing the P removed in the harvested crop maintained the critical level of Mehlich-1 P.

Summary

A recent review of the behavior of soil and fertilizer P envisages soil P as existing in four pools according to the availability of the P for uptake by roots and extractability of the P by reagents used for routine soil analysis, and that these two measures are closely correlated.

This concept has practical implications for the efficient use of P fertilizer. Namely, for most soils the amount of P in the readily plant-available pool of soil P should be raised to a critical level such that yield is not limited by lack of P and the benefits of all other inputs, especially N, required to achieve optimum yield are used as effectively as possible. For most soils that can be maintained at about the critical level of P, replacing the P removed each year in the harvested crop will typically result in P efficiency exceeding 90% when measured by the balance method. A project to develop an experimental protocol is being formulated, and sponsors sought, to extend the critical P concept to a wider range of cropping systems, soil types, and climates.

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Role of Crop Nutrition in Narrowing the Yield Gap for Spring Wheat in Siberia

By G. Gamzikov and V. Nosov

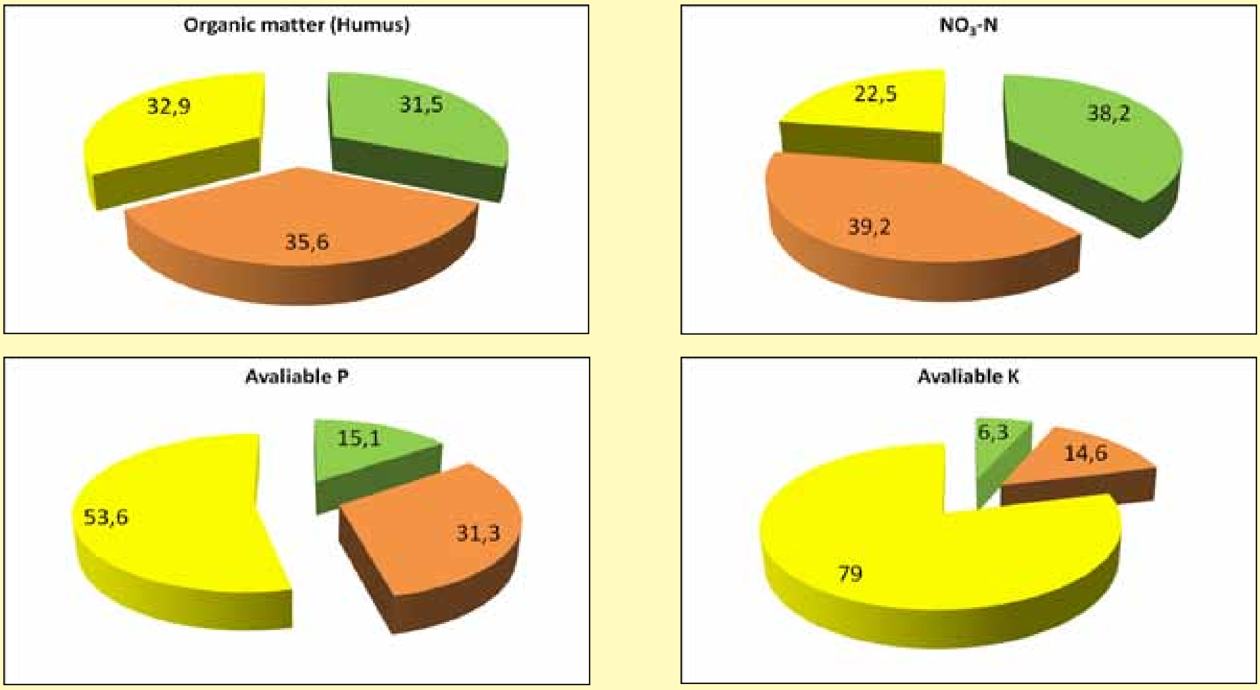
Mineral fertilizers and other agro-inputs are important for achieving high and stable yields of spring wheat, the principle field crop in Siberia. This article reviews the at-tainable yield of spring wheat by the major soil-climatic zones through the region. The authors characterize the present status of fertilizer consumption in Siberia and, based on minimum nutrient requirements of crops, give a short-term estimate of fertilizer consumption in the region.

Siberia is located in the Asian part of Russia, occupying an area of about 10 million square kilometers (M km2). Arable farming and animal husbandry are concentrated in the southern part of Siberia, with more than 56 M ha of agricultural lands. Siberia has about 23.5 M ha of arable land, representing about one-fifth of the total arable land area in Russia. Spring cereals such as wheat, barley, oats, and millet, as well as buckwheat, pulses, sunflower, potato, and vegetables are traditional crops in Siberia. Winter cereals include rye and triticale. Spring rapeseed, soybean, and sugar beet are promising crops giving high yields in this region. Cereals are grown on 70% of cropped area. Spring wheat dominates the cereal acreage (75 to 80%). However, the average grain yield of spring wheat in Siberia over the 5-year period of 2004 to 2008 was only about 1.3 t/ha.

The grain belt of Siberia, comprising several soil-climatic zones, is characterized by diversity in annual rainfall (230 to 550 mm), the sum of active temperatures above 10 °C (1,400 to 2,800 growing degree days), and length of vegetation or frost-free period…100 to 140 days. In the forest zone, arable soils are represented by soddy-podzolic and grey forest soils occupying 17% of land in Siberia. Podzolized, leached, and common chernozems, and also meadow chernozem soils (63%) are spread throughout the forest-steppe zone. Southern cher-nozems and chestnut soils (14%) are dominant in the steppe zone. Soil fertility parameters affect crop production potential in the various soil zones of Siberia. A recent agrochemical soil survey indicated that organic matter (humus) content in Sibe-rian soils can be very low to low (<4.0%), medium to high (4.1 to 8.0%), and high to very high (>8.1%), with about one-third of the monitored arable area under each group (**Figure 1**). Acid arable soils, which need liming for optimal yield, occupy about 2 M ha in the region.

Nitrate-N (NO3-N), is the major source of soil N for plant nutrition (Gamzikov, 1981). Siberian soils have a high po-tential to accumulate NO3-N during the fallow season, after late summer tillage following perennial grasses, pulses, and annual grasses. Spring wheat grown after fallow and the above-mentioned crops has no requirement for additional ap-plication of N fertilizer. Two-thirds of the area sowed to field crops, following other preceding crops, has low soil N status and requires annual application of N fertilizer. According to routine soil analyses, slightly more than half of Siberian arable soils have high and very high content of available P, about one-third of soils test medium to high, and only 15% of soils are low to very low in available P (**Figure 1**). The lowest content of P (low and very low classes) is observed in soddy-podzolic soils (57%), and in southern chernozems and chestnut soils (40%). Most soils (79%) have high to very high contents of available K (**Figure 1**). Taking into consideration the status of soil nutrients in Siberian soils, annual recommendations for cultivated crops include N on 16 M ha, P fertilizer on more than 10 M ha, and K fertilizer on 5 M ha.

Soil-climatic conditions in three natural zones of Siberia are favorable for obtaining high yields of spring wheat when recom-mended crop management practices are followed (**Table 1**). The role mineral fertilizers play in crop production is most impor-tant in the forest zone.



		High and very high	Medium to high	Very low and low
Organic matter (Humus), %		≥ 8.1	4.1 - 8.0	≤4.0
NO_3-N, ppm (0-40 cm soil layer)		≥ 15.1	10.1 - 15.0	≤10.0
Available P, ppm P_2O_5	0.2 M HCl[1]	≥ 151	51 - 150	≤50
	0.5 M CH_3COOH[2]	≥ 151	51 - 150	≤50
	1% $(NH_4)_2CO_3$[3]	≥ 46	16 - 45	≤15
Available K, ppm K_2O	0.2 M HCl[1]	≥ 171	81 - 170	≤80
	0.5 M CH_3COOH[2]	≥ 121	41 - 120	≤40
	1% $(NH_4)_2CO_3$[3]	≥ 401	201 - 400	≤200

[1]*soddy-podzolic soils* [2]*grey forest soils and noncarbonated chernozems* [3]*carbonated chernozems and chestnut soils*

Figure 1. Distribution (%) of arable soils in Siberia in fertility classes according to status of soil organic matter, NO_3-N, and available P and K. (Source: Russian Res. Inst. of Agrochemistry, 2005.)

Table 1. Possible grain yields (t/ha) of spring wheat depending on soil-climatic conditions and systems of agriculture in Siberia (Gamzikov et al., 2008).

Natural zone	Climatic and soil limitations[1]			System of agriculture[5]		
	Solar radiation[2]	Rainfall[3]	Soil fertility[4]	Extensive	Ordinary	Intensive
Forest	4.0-5.8	3.8-5.0	0.6-1.5	0.5-1.0	0.7-1.6	2.6-4.5
Forest-steppe	5.0-7.2	1.7-4.0	1.2-2.4	0.8-1.5	1.0-1.8	2.2-4.0
Steppe	6.0-8.6	0.8-2.2	1.0-1.6	0.4-1.0	0.8-1.6	1.5-2.2
Distribution of agricultural enterprises, %				35-40	50-60	10-15

[1]Possible yields when climate and soil factors are not limiting.
[2]Possible yield range with application of fertilizer (and lime if required) plus optimal rainfall.
[3]Possible yield range with application of fertilizer (and lime if required).
[4]Possible yield range without fertilizer or lime.
[5]Extensive: without fertilizers and plant protection. Ordinary: 10 to 20 kg/ha N+P_2O_5+K_2O in seed row and plant protection in selected fields.Intensive system: recommended crop management technologies; use of all agro-inputs.

Table 2. Long-term average effect of mineral fertilizer use on grain yield of spring wheat on Siberian soils (Gamzikov et al., 2008)..

Soil	Yield without fertilizers, t/ha	Yield increase with fertilizers1, t/ha			
		N	P	NP	NPK
Soddy-podzolic soil	1.06	0.46	0.32	0.57	0.79
Grey forest soil	1.57	0.41	0.30	0.60	0.67
Chernozem	1.68	0.33	0.22	0.49	0.52
Chestnut soil	1.14	0.16	1.18	0.31	0.31

Without plant protection and application of mineral fertilizer, spring wheat grain yields fail to exceed 1.0 t/ha. But intensive agro-technologies can produce 2.6 to 4.5 t/ha. Unstable rainfall, low soil NO3-N, and low available P in some soil provinces limit yield formation on dark grey forest soils, podzolized, leached and common chernozems, and meadow chernozem soils in the forest-steppe zone. Here, the average grain yield for spring wheat does not exceed 1.5 t/ha under extensive systems of crop production, and only 2.0 t/ha in years with especially favorable hydrothermal condi-tions. Attainable grain yields with recommended, intensive agro-technologies range be-tween 2.2 and 4.0 t/ha. In the steppe zone (in view of the considerable moisture deficit in these southern chernozems and chestnut soils, and their low capacity to mobilize N), the average grain yield for spring wheat under an exten-sive system of crop produc-tion is usually under 1.0 t/ha. Nevertheless, it is possible to improve yield to 1.5 to 2.2 t/ha in this zone if all recommended agro-technologies are applied.

The application of min-eral and organic fertilizers in combination with other agro-inputs and recommended agro-technologies allows grow-ers to realize the existing yield potential in every soil-climatic zone while eliminating, or at least alleviating, the negative impact of common natural and anthropogenic factors. **Table 2** summarizes the average grain yield increase for spring wheat due to application of combina-tions of fertilizer nutrients in Siberia. The highest effect of fertilizers on grain yield can be observed on soddy-podzolic and grey forest soils – the agronomic efficiency of applied fertilizer nutrients is generally in a range of 4 to 9 kg high quality grain per kg of nutrients (N+P2O5+K2O).

The appropriate tillage method in combination with

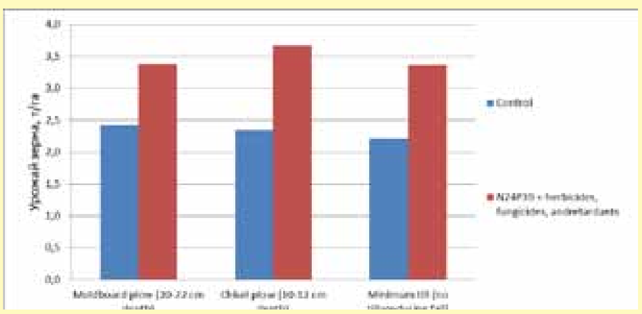


Figure 2. Effect of fall tillage method on grain yield of spring wheat grown after fallow in fallow-wheat-maize-wheat-barley crop rotation on leached chernozem; mean 1988-2000 (Kholmov and Yushkevich, 2006).

Available P and K content (0.5 M CH_3COOH) – 80 to 95 ppm P_2O_5 and 400 to 500 ppm K_2O. Fertilizer rates: 24 kg/ha N and 39 kg/ha P_2O_5

the recommended use of fertilizers and other agro-inputs allows growers to better realize their yield potential (**Figure 2**). Accumulated research data and growers' practice indicate that conservation tillage technologies coupled with recommended applica-tion of all agro-inputs, including mineral fertilizers, generates the highest grain yields (1.5 times higher), decreases the cost of grain production (by 17%), and thus increases profits (by 25%).

Despite this, mineral fertilizer use in Siberian agriculture has declined by more than 10 times over the last 20 years (**Table 3**). Nutrient balance calcula-tions for Siberia clearly indicate a negative balance for all three nutrients (**Table 4**). In fact, total fertilizer inputs account for only 11% of crop nutrient removal in recent years. The short-term forecast (up to 2015) for increased mineral fertilizer consumption gives hope for a gradual alleviation of nutrient deficiencies and a considerable gain in spring wheat yields. Currently, Siberian agriculture has to rely

Table 3. Average annual fertilizer consumption (N+P2O5+K2O) in Siberian agriculture, '000 ton.

Region	1986-1990	2001-2005	2006-2009	2015-2020 (outlook)
Western Siberia	832	53.7	70.9	260
Eastern Siberia	470	45.3	46.9	135
Siberia Total	1302	99.0	117.8	395

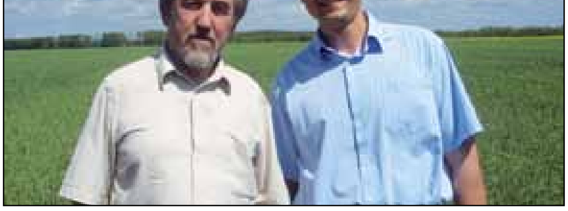
Table 4. Average nutrient balance (kg/ha/year) in Siberian agriculture (2006-2009).

Nutrient	Crop removal	Fertilizer input			Balance	Input/ Removal, %
		Mineral	Organic	Total		
N	30.7	2.5	1.2	3.7	-27.0	12
P_2O_5	10.1	0.9	0.6	1.5	-8.6	15
K_2O	24.4	0.3	1.7	2.0	-22.4	8
Total	65.2	3.7	3.5	7.2	-58.0	11

Spring wheat is grown on millions of hectares of land in Siberia, but yields in recent years have averaged only about 1.3 t/ha.

on crop management systems that exploit indigenous soil fertility because of its limited use of mineral fertilizers and other inputs. Including fallow (the best predecessor for wheat in all natural zones of Siberia) in the rotation is the most commonly used practice. The fallow season in 3 to 4 year rotations allows for high ac-cumulation of moisture reserves (160 to 220 mm within a 100 cm soil depth) and NO3-N (100 to 120 kg/ha within a 40 cm soil depth). Fallow also decreases the number of weed seeds per square meter (to 30 to 35).

Specific soil-climatic conditions in Siberia (i.e., deep and prolonged soil freezing during the winter season, uneven distri-bution of rainfall through the vegetative period, and periodical droughts) increase the role of crop variety and its interaction with the crop management system. Spring wheat breeding in Siberia is done by 11 research institutions and agrarian uni-versities. The State Register of Russia was expanded over the last 30 years (1977 to 2007) to include 63 new soft and 9 new durum varieties of spring wheat (Ruts and Kashevarov, 2008). It is noteworthy that Siberian varieties at present occupy 95% of the total area under spring wheat in the region. Breeding for higher yields of soft and durum spring wheat has progressed by 50% and 35%, respectively. Grain quality parameters have improved by 14 to 25% and 9 to 20%, respectively, during these last 30 years (Gamzikov, 1997; Ruts and Kashevarov, 2008). Modern spring wheat varieties have high yield potential (3.5 to 7.0 t/ha) and high grain quality (1,000 grain weight of 40 to 50 g, test weight of 780 to 820 g/l, protein content of 15 to 18%, gluten content of 32 to 40%). Most varieties registered for production over the last 8 years have complex immunity to pathogens and resistance to leaf rust, powdery mildew, and loose smut. Siberian research on the genetics of mineral nutrition of spring wheat has resulted in fundamentally new information about the genetic control of uptake and utilization of macronutrients and micronutrients in plants (Gamzikova, 2008). Specific genomes, chromosomes, genes, and cytoplasms controlling uptake and utilization of nutrients in wheat plants have been identified. Concepts and methodologies have been designed for breeding nutrient-efficient genotypes that are more adept at using soil and applied nutrients compared to modern varieties.



Dr. Gamzikov, left, and **Dr. Nosov**

In the near-term, spring wheat will continue to be the dominant crop in Siberian agriculture. High and stable yields of spring wheat and also high grain quality in growers' fields will depend on adoption of best management practices rec-ommended by researchers. This may be achieved with the corresponding development of grain export capabilities from Siberia and attractive grain prices at the grower's gate.

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Starter Fertilizer Application Method and Composition in Reduced-Tillage Corn Production

By W.B. Gordon

Field studies were conducted at the North Central Kansas Experiment Field to evaluate four methods of starter fertilizer application (in-furrow, 2x2, 2x0, and placed in an 8-in. wide band centered on the row). Starter fertilizer consisted of 5, 15, 30, 45, or 60 lb N/A with 15 lb P_2O_5 and 5 lb K_2O/A. A no starter check was also included. Starter placed in the seed furrow reduced plant populations and yield. Dribble (2x0) application of starter in a narrow surface band was approximately equal to 2x2 applied starter. Increasing the amount of N in the starter up to 30 lb/A consistently increased P uptake and yield. The use of a dicarboxylic copolymer product in starters was also evaluated and found to be beneficial in increasing P fertilizer performance and corn yield.

Conservation tillage production systems are being used by an increasing number of producers in the central Great Plains because of several inherent advantages. These include reduction of soil erosion losses, increases in soil water-use efficiency, and improved soil quality. However, the large amount of surface residue present in reduced-tillage systems can reduce seed zone temperatures, which may inhibit root growth and reduce nutrient uptake.

Starter fertilizer applications have proven effective in enhancing nutrient uptake, even on soils that are not low in available nutrients. Many producers favor placing fertilizer with seed (in-furrow) or surface starter applications because of the low initial cost of planter-mounted equipment and prob-lems associated with knife and coulter systems in high-residue environments. It has long been recognized that crop injury can occur when excessive amounts of fertilizer containing N and/or K are placed in contact with the seed. However, surface application of starter fertilizer is an option that has not been exten-sively investigated and compared to sub-surface applications. Additionally, a new class of long-chain, high cation exchange capacity polymers that apparently has the ability to enhance fertilizer P performance has recently become available. This product is marketed under the name AVAIL®[1]. The objective of this research was to determine corn response to different liquid starter fertilizer combinations using four application methods, and to evaluate the use of AVAIL® in starters.

Irrigated, reduced-tillage experiments were conducted at the North Central Kansas Experiment Field on a Crete silt loam soil (fine, smectitic, mesic Pachic Argiustoll). Soil test P values were in the upper-part of the medium range and soil test K was in the high range. Soil organic matter was 2.5% and pH was 7.0.

The study consisted of four methods of starter fertilizer application: in-furrow with the seed; 2 in. to the side and 2 in. below the seed at planting (2x2); dribbled in a narrow band on the soil surface 2 in. to the side of the row at planting (2x0); and placed on the soil surface in an 8 in. band centered on the row. Starter fertilizer consisted of combinations that included either 5, 15, 30, 45, or 60 lb N/A with 15 lb P_2O_5/A and 5 lb K_2O/A. Nitrogen as 28% UAN was balanced so that all plots received 220 lb N/A regardless of starter treatment. Starter fertilizer combinations were made using liquid 10-34-0, 28% UAN, and KCl (muriate of potash). Additional studies compared starter fertilizer with and without the AVAIL® additive.

When starter fertilizer containing 5 lb N and 5 lb K_2O/A was applied in-furrow with the seed, plant population was re-duced by over 6,000 plants/A (**Table 1**). As N rate increased, plant population continued to decrease. When averaged over starter fertilizer rate, corn yield was 36 bu/A lower when starter fertilizer was applied in-furrow with the seed than when ap-plied 2x2 (**Table 2**).

Dribble application of starter fertilizer in the 2x0 configuration was statistically equal to starter that was placed in the traditional 2x2 band. A surface band is much easier and less costly for producers to apply than the 2x2 band. The 8-in. band over the row treatment resulted in yields that were greater than the in-furrow treatment, but less than the 2x2 or 2x0 treatments. The wide fertilizer band was just too diffuse to provide the full benefit of a starter fertilizer application. Regardless of whether the starter

Table 1. Starter fertilizer placement and composition effects on plant population, 3-year average.

Starter, lb/A $N-P_2O_5-K_2O$	In-furrow	2x2	2x0	Row band
	plants/A			
5-15-5	25,202	31,266	31,170	31,266
15-15-5	23,142	30,729	31,655	31,552
30-15-5	23,307	31,266	30,492	30,589
45-15-5	21,329	30,976	30,392	30,492
60-15-5	20,371	30,687	30,613	30,298
Average	22,670	30,985	30,864	30,839

Table 2. Starter fertilizer placement and composition effects on corn grain yield, 3-year average.

Starter, lb/A $N-P_2O_5-K_2O$	In-furrow	2x2	2x0	Row band
	plants/A			
5-15-5	172	194	190	179
15-15-5	177	197	198	180
30-15-5	174	216	212	192
45-15-5	171	215	213	195
60-15-5	163	214	213	201
Average	171	207	205	189

[1] The mention of a product does not imply endorsement by Kansas State University or by this publication.

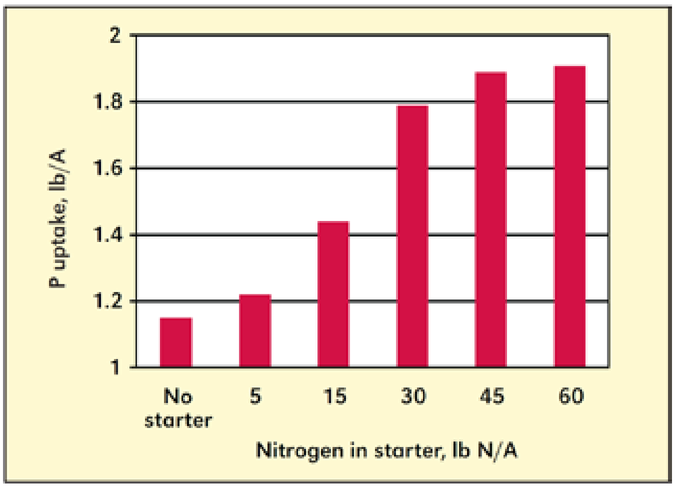

Figure 1. Average starter N-rate effects on 6-leaf stage whole plant P uptake (P and K rate constant at 15 lb P_2O_5 and 5 lb K_2O/A), 3-year average.

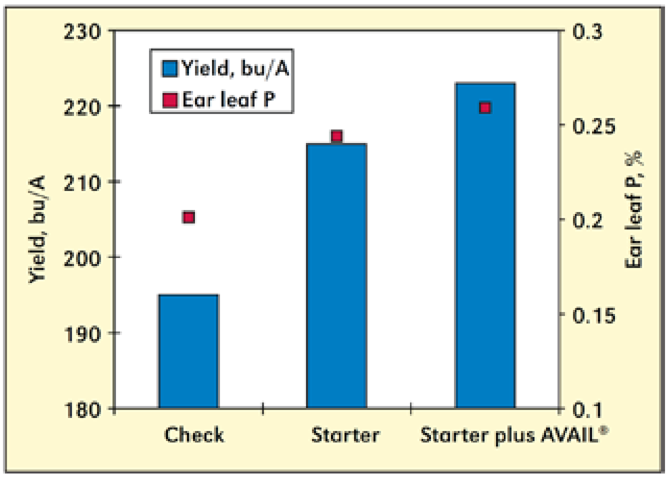

Figure 2. Starter and starter plus AVAIL® effects on corn grain yield and ear leaf P concentration, 3-year average.

fertilizer was placed 2x2 or 2x0 , yields increased with increasing starter N rate up to the 30 lb N/A rate. Plant P content also increased with increasing N up to the 30 lb N/A rate (**Figure 1**).

The results of this research have shown that the addition of AVAIL® can improve P fertilizer performance. This work compared a no-starter check to fluid starter containing both N and P with and without AVAIL®. Use of starter increased corn grain yield by 19 bu/A over the no starter check (**Figure 2**). The addition of the polymer AVAIL® to the starter fertil-izer further increased yield by an additional 9 bu/A. Corn ear leaf concentrations at silking were greater in plots receiving the starter plus polymer than in plots receiving no starter or starter alone. This indicates that the use of AVAIL® can result in an increase in P uptake by plants and ultimately in higher grain yield.

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Improving Soil Fertility and Wheat Crop Management Through the Long-term Study of Cereal Crop Rotations

By Brian Arnall and Fernando García

Long-term fertility trials are established and used across the globe. Unfortunately, for many reasons long-term trials are regularly discontinued. These trials are a wealth of data and information laden with golden nuggets of new and amaz-ing insight. In this article, such nuggets gleaned from long-term wheat trials in Canada, United States, and Argentina are presented.

Nothern Great Plains

The Swift Current "Old Crop" rotation is located in south-east Saskatchewan and was established in 1967. Swift Current is located in the driest portion of the Canadian Prairies and is known for its long-cold winters and short grow-ing seasons (Pelton et al. 1967). This report will focus on four of the original 12 treatments implemented in 1967: fallow-wheat-wheat with N and P fertilizer (FNP); fallow-wheat-wheat with P fertilizer only (FP); continuous wheat with N and P fertilizer (CNP), and continuous wheat with P fertilizer only (CP). On average, all cropped treatments designated to receive P received 9 to 10 kg P/ha/yr. The data, f gures, and results are derived from Selles et al. (2011).

To evaluate trends over time, the data set was evaluated as three periods identif ed by water def cit estimations of 1967 to 1979; 1980 to 1993; and 1994 to 2005. The response in Olsen P (0 to 15 cm) soil test values were signif cantly affected by treatments among the three periods. During the f rst 12 years, there were no differences among the four treatments. During the second period; treatments began to separate, due to the higher frequency of cropping and therefore fertilization, and as a result the Olsen P of the CW rotations became signif cantly higher than the FWW. In the third period, FNP had signif cantly lower Olsen P than the other treatments. Phosphorus balance, calculated as fertilizer added – grain P removal, of the CW rota-tion was signif cantly higher than the FWW. During this time period, FWW received 43 kg P/ha less than the CW treatments. In the second period, P balance of the FWW was signif cantly lower than the f rst period and again signif cantly lower than the CW treatments. By the third period, the P balance of the FP and CNP was similar and the CP signif cantly higher than other treatments. The P balance of the FNP became negative; however, the Olsen P level was still signif cantly higher than at establishment.

The temporal trend in Olsen P levels was also assessed (**Figure 1**). All treatments showed linear positive trends that persisted for the f rst 20 years of the experiment. The P only treatments, CP and FP, maintained the increasing trend over the duration of 0.68 and 0.45 kg P/ha/yr, respectively. The rotations receiving both N and P created linear trends of 0.64 and 0.56 for CNP and FNP, respectively, for the f rst 20 years of the experiment then Olsen P stabilized for the remainder (**Figure 1**).

Many long-term trials have opportunity to incorporate split plots; the Old Crop rotation is one of those. In 1993, the researchers decided to split treatments receiving P fertilizer to provide an area in which P fertilization was discontinued. Withholding fertilizer P had no impact on grain yield in either treatment in the FWW rotation; however, 10% reduction in grain yield was observed in the CW systems (**Table 1**). Selles et al. (2011) noted that the yield reduction in CW was not consistent; however, for both CNP and CP there were 2 years in which yield reduction was more than 35%.

The results demonstrate that residual soil P accumulated during the previous 27 years (1967 to 1993) remained in forms readily available to the crop, conf rming that in soils with high levels of residual P, crops rarely suffer production losses when fertilizer P is not supplied (Selles et al. 2011).

Central Great Plains

Oklahoma is home of several long-term winter wheat trials; including the Magruder Plots, the oldest continuous wheat plot west of the Mississippi River. These data are derived from a continuous winter wheat NPK study established in 1971 in northwestern Oklahoma. This report will focus on data from six treatments over a range of N rates from 0 to 112 kg/ha in 22.4 kg increments. Each treatment receives 20 kg P/ha and 56 kg K/ha annually.

For more than 30 years of production the N check plot recorded yields ranging from 0.75 to 2.84 t/ha, averaging 1.78 t/ha per year. The 112 kg N/ha plot (highest N rate) recorded a low of 1.42 t/ha and high of 5.94 t/ha with a 30-year average of 2.96 t/ha. The standard deviation of the grain yield from the two treatments was 0.55 and 1 t/ha, respectively. To aid in the review of these data, they were grouped into 5-year segments where general tends become visible. One is the increase in yield due to the addition of N fertilizer, calculated by subtract-ing the yield of the zero from the fertilized. With exception of the early 1980s, yield response has increased over time (**Figure 2**). It is evident the difference between good years and bad years, within each 5-year grouping, is also increasing in the fertilized plot. The last three periods: 1995 to 2000, 2001 to 2005, and 2006 to 2010, resulted in yield differences of 2.36, 3.20, and 3.83 t/ha, respectively (**Figure 3**). This trend identif es that the likelihood of either over or under fertilizing is also increasing as the variability in annual N removal increases. For each year, the economic optimum nitrogen rate (EONR) was calculated. When evaluated in 5-year groupings, EONR has been static at 112 kg N/ha since the early 1990s (**Figure 4**). However, within each 5-year grouping the range of EONR has been 90 kg N/ha or more since the

Table 1. Effect of withholding P on total wheat grain production during the period of 1994 to 2005.

Rotation	Grain Production, t/ha	
	P applied	P withheld
CNP	29.1	26.3*
CP	19.8	18.7*
FNP	21.3	21.0
FP	18.0	16.8
Nested LSD	1.8	

Significance between P applied and P withheld at p < 0.05.

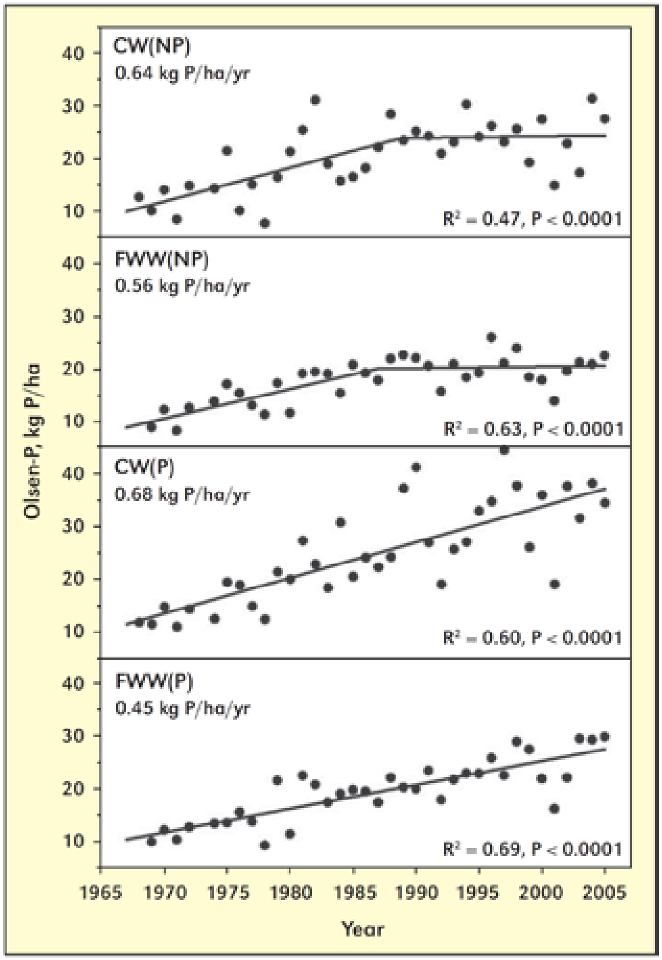

Figure 1. Trends in Olsen P for the original plots, 1967 to 2005. [Trend models given by following expressions: CW(NP) if time ≤22, y = 9.9 + 0.64 x time, otherwise y = 9.9 + 0.64 x time – 0.61 x (time – 22); FWW(NP) if time ≤20 y = 8.9 + 0.56 x time, otherwise y = 8.9 + 0.56 x time – 0.59 x (time – 20); CW(P) y = 11.5 + 0.68 x time; FWW(P) y = 10.4 + 0.45 x time]. From Selles et al. (2011).

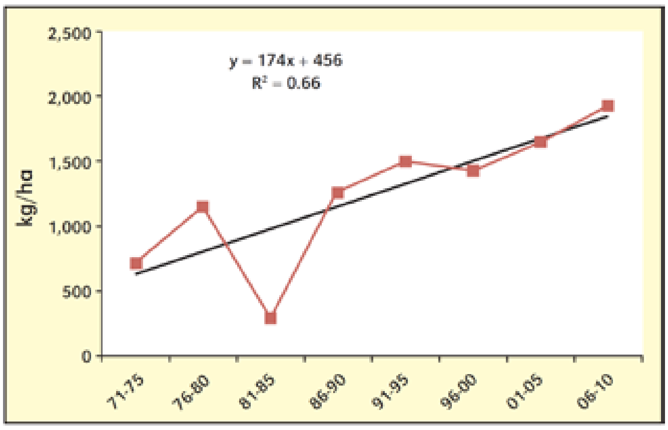

Figure 2. Yield increase due to N over time. Increase calculated as yield of the 112 kg N/ha treatment minus the yield of the 0 N treatment.

late 1990s (**Figure 4**).

Typical N management of the region consists of average yield goals calculated from the previous 5 years, plus 20%. This strategy would result in the over application of 1,672 kg N/ha over the period between 1976 and 2011. Use of 5-year EONR reduced over application to 1,187 kg N/ha, 30% less than the strategy based on yield goals plus 20%.

The data not only shows how the yield potential of winter wheat grown on the Great Plains has increased, but also how the response to added fertilizer N is also increasing with time. Much of this increase could be a consequence of improved varieties and better crop management strategies. More im-portantly, these data indicate the magnitude of the temporal variability in maximum yield and N requirements. This shows the need for in-season measurements that can adjust total N recommendation based upon environment and crop status.

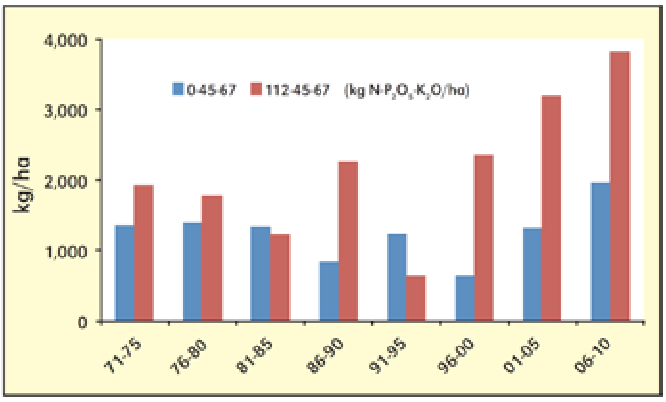

Figure 3. Yield difference between the highest and lowest yielding years within each 5-year grouping.

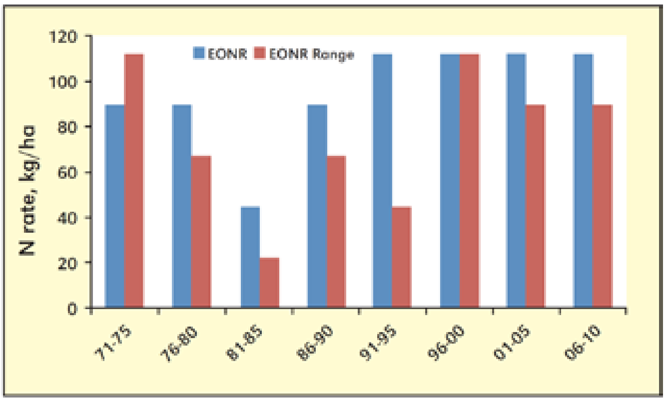

Figure 4. Economical optimum N rate (EONR) for 5-year groupings and the range in EONR value within each grouping.

Argentinean Pampas

The youngest of the three studies discussed is located in the Pampas Region of Argentina. Unlike the previous two experi-ments, this fertility study comprises 11 on-farm experimental locations. Sites belong to the Nutrition Network of CREA Southern Santa Fe, and reside in the three provinces of Santa Fe, Cordoba, and Buenos Aires. CREA (Regional Consortia for Agricultural Experimentation) are farm groups dedicated to develop and share knowledge and information on crop, soil, and farm management.

The 11 locations are separated according to crop rotation into two categories: corn-wheat/soybean (C-W/S) and corn-soybean-wheat/soybean (C-S-W/S). Six treatments are applied at all locations: 1) Check, 2) PS, 3) NS, 4) NP, 5) NPS, and 6) Complete (NPS plus: K, Mg, B, Cu and Zn). Nutrient rates ap-plied to cereal crops were equivalent to grain nutrient removal + 10%, except for N for which rates were decided according to local calibrations of soil nitrate-N test at planting.

A summary of the f rst 6 years was presented in García et al. (2007), and since establishment in 2000; wheat has been included in 33 site/years: f ve cropping seasons from the C-W/S locations and three from the C-S-W/S sites. From these trials the correlation between crop response and soil test can be evaluated. Over the 33 site/years, there were signif cant grain yield increases at 16 site/years for N, 25 site/years for P, 6 site/years for S, 20 site/years for NPS, and 4 site/years for other nutrients (García et al., 2010).

Significant relationships were established between N response and soil nitrate-N availability at planting (0 to 60 cm), and sap nitrate concentration at tillering. Critical soil nitrate-N of 130 to 140 kg N/ha at planting (soil N + fertilizer N) have been established for wheat yields of 4 t/ha. Phosphorus responses were observed in 95% of the sites with soil Bray P levels lower than 15 mg/kg, as reported by Berardo (1994) and Zamuner et al. (2004) for the southern Pampas. A critical range of 15 to 20 mg Bray 1 P/kg has been def ned. There was no relationship between S response and sulfate-S availability at planting, as it was observed for other wheat experiments in the Pampas (García, 2004). Conversely, corn yield responses to S were related with sulfate-S at planting (0 to 20 cm).

Yield differences among fertilized treatments and the check increased along years of evaluation, suggesting that

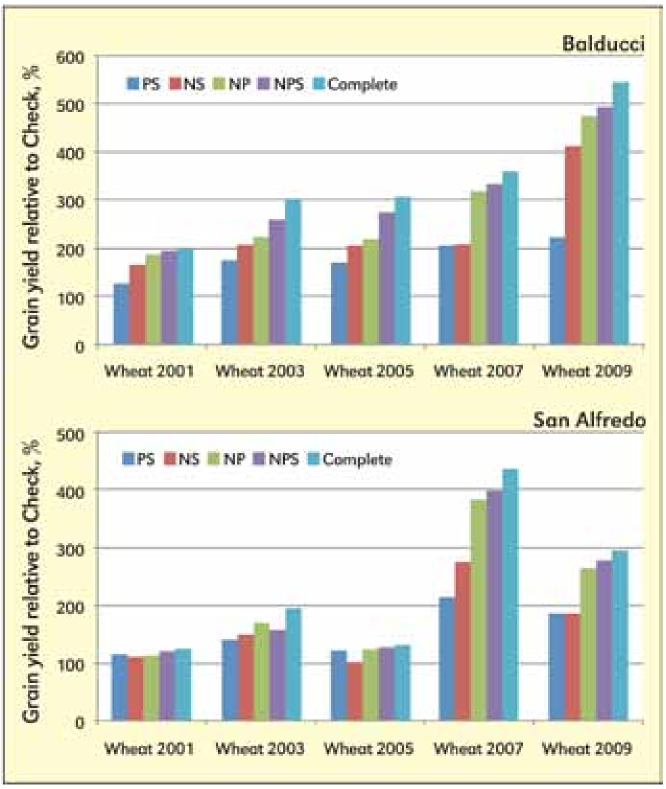

Figure 5. Relative wheat grain yields for different fertilization treat-ments in the sites of Balducci (C-W/S rotation) and San Alfredo (C-W/S rotation), considering the check yield as 100%.

changes in soil fertility status, other than Bray P, have oc-curred. These increased differences are attributed not only to decreasing check yield, but also increased fertilized yields. **Figure 5** demonstrates the increase in response and yield at two C-W/S locations.

Increases of soil Bray P differences between P fertilized and non-fertilized treatments were determined. The 10-year review (2000 to 2011) identif ed an increase in Bray 1 P of 1.9 to 3.1 ppm per year in those treatments receiving P. In the NS treatments, Bray 1 P decreased by an average rate of 0.50 to 1.0 ppm per year.

Summary

The Old Crop Swift Current trial reveals that in the low rainfall environments of the southwestern Canadian prairies, fertilizer P may remain in a labile form in areas of positive P balance and that producers may be able to take advantage of the past fertilization in years of high P prices. The long-term plots in Oklahoma shed light on the volatility of yield potential and N demands of winter wheat grown in the US Central Great Plains. The On-Farm CREA trials within the Central Pampas of Argentina demonstrate that soil test N and P adequately identify areas in which responses to fertilizer can be expected, while soil test S is providing little estimation of yield response in wheat production. This brief glimpse into the data from these long-term studies carried out across North and South America highlights the importance of such studies to contributing to our understanding of strategies to improve soil fertility and nutrient management for wheat production worldwide.

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Nutrient Management for Wheat in a Variable Climate

By Rob Norton

Profitable use of N and P to meet crop requirements in a variable climate such as the grain belt of southeastern Australia means adopting strategies that minimize risk. Using yield potentials, N and P demands can be estimated, but research shows there is no particular penalty if N is provided as the yield develops during the season. As yet there are no strate-gies for in-crop P application although research is pointing the way.

Nineteenth century poet Dorothea Mackellar described Australia as a land "of drought and flooding rains" and this phrase still resonates today. The southeastern wheat belt of Australia has been through an extended drought from the late 1990's until the floods of 2010 and 2011. **Figure 1** shows the annual rainfall for Horsham in the Victorian grain belt, indicating the large annual variation in rainfall, driven by conditions in the Pacific, Southern, and Indian Oceans.

This rainfall variation is an important driver of yield variation, where soil water at sowing plus in-crop rainfall can account for 61% of yield variation (Hochman et al. 2009). **Figure 1** also gives the wheat yields from a farm in the Horsham district, showing how yields generally follow rainfall. Wheat yields reflect the large differences in rainfall and simple and more complex models based

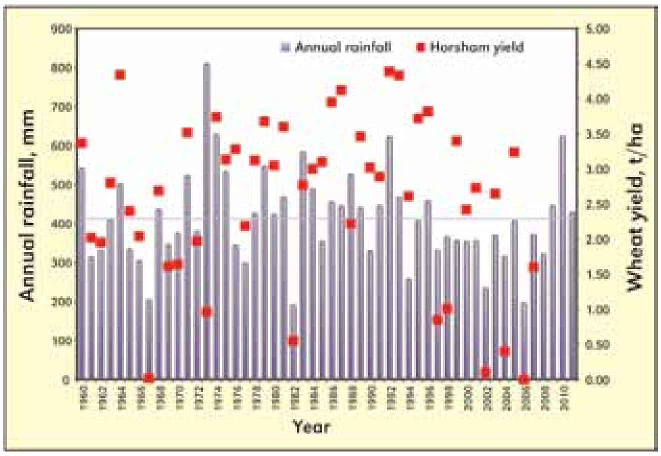

Figure 1. Annual rainfall and wheat grain yield from a farm near Horsham in the Victorian grain belt.

Table 1. Comparison of a range of various timings for N strategies on grain yield (t/ha) for eight site-years tested in the Victorian grain belt.

Post Sowing	2005 Sealake	2006 Hopetoun	2007 Walpeup	2005 Marnoo	2007 Kalkee	2005 Inverleigh	2006 Inverleigh	2007 Inverleigh
Urea deep banded	4.35	0.95	1.44	3.95	2.35	3.48	2.20	5.20
Urea deep banded + 50%@ Zadoks 31	4.11	0.98	1.40	3.98	2.83	3.40	2.54	5.69
Urea deep banded + 33%@ Zadoks 31 + 33% @ Zadoks 41	4.29	-	1.39	4.17	2.77	3.91	-	5.59
Urea topdressed @ Zadoks 31	4.44	0.93	1.61	4.27	2.72	3.43	2.25	5.24
LSD (p=0.05)	0.27	0.22	0.23	0.30	0.28	0.54	0.23	0.40

on rainfall allow growers to estimate yield potential at or near sowing, and therefore nutrient demand. Over application of N and P is a waste of money and resources, and too much N in particular in dry seasons can result in small grain size and a large price penalty. Under application means that yield potentials are not met.

Selecting the Right Rate for N and P

To estimate fertilizer rate, an achievable or target yield needs to be predicted. This water limited yield potential can be based on a water use efficiency of 20 kg/ha/mm of seasonal water supply (French and Schultz, 1983). The water supply includes measured or estimated plant available stored soil water plus an estimate of future rainfall. From this is it possible to then develop a nutrient budget based on the predicted yield of the crop (**Box 1**).

Based on the example in **Box 1**, it would be estimated that the crop would need 116 kg N/ha to achieve this target yield. There are several assumptions within this estimate including that the rooting depth of the crop is not restricted, the efficiency of soil and fertilizer N to grain N is 50%, and the mineralization rate of these soils will follow the model in **Box 2**. More significantly, it makes an assumption that there will be 250 mm of seasonal rainfall and the distribution of this rainfall is appropriate to achieve that yield.

A similar approach can be taken for P demand, using a water-limited yield potential and therefore an expected P removal. Typical grain P contents are around 3 kg/t of grain mean a target yield of 4.8 t/ha would need to be balanced with around 15 kg P/ha. This base rate would need to be adjusted for the P buffering capacity of the soil, any demands for P to raise soil P test, and account taken of any P lost through transport off the paddock. Because grain P can vary from 2.0 to 4.0 kg P/t (Jensen and Norton, 2012), growers may improve the precision of this budget by measuring actual grain P and derive actual removal.

Box 1: Yield Estimate
Available Soil Water – 100 mm
Expected seasonal water – 250 mm
Total Water Supply = 350 mm
Water Use Efficiency (WUE) – 20 kg/ha/mm
Non-Productive soil water – 110 mm
Yield Potential = WUE x (Available Water – Non-productive water)
= 20 x (350 – 110)
= 4,800 kg/ha (4.8 t/ha)

Box 2: Nitrogen Balance Estimate
Yield Potential = 4.8 t/ha
N demand = 45 kg N/t of grain = 216 kg N/ha
Mineral N at sowing = 50 kg N/ha (measured)
% Organic C (%OC) = 1.2%
In-crop mineralization estimate = %OC x (seasonal rainfall)/6
= 1.2 x (250)/6 = 50 kg N/ha
Soil N supply = N at sowing + Mineralization
= 50 kg N/ha + 50 kg N/ha = 100 kg N/ha
Fertilizer N to meet yield potential = (216 – 100) = 116 kg N/ha

Managing Risk Around the Right Rate for N

Given the uncertainty of future rainfall once the crop has been sown, applying the full dose of N at sowing is when least is known about the seasonal conditions. From fieldwork in the Victorian grain belt, Norton et al. (2009) compared timing strategies where N was deferred either in part or full to tillering or even later (**Table 1**). The delayed application of all N until tillering produced significantly higher yields at three sites and did not reduce yields at any site when compared to an atsowing application. Splitting 50:50 the applications did give benefits in three sites and no yield reduction at any site.

Based on these results, there would seem to be little yield penalty by delaying part or the entire N until later in the season, even on relatively high yielding sites. The caution here is that all those sites had at least 40 kg N at sowing in the profile, and this soil N supply was likely to be adequate to carry the crop through to tillering with little N stress.

If the season does not provide good rains in the late winter or spring, yield potentials can be adjusted down. Because part of the N has been withheld, there would be no penalty due to haying off, or a financial loss with low fertilizer efficiency. Growers now tend to apply maybe 20 to 30% of the N at sowing, and then apply added N (or not) as the seasonal conditions roll out.

Most wheat growers would now use some sort of tool to estimate yield potential and then match N supply to meet that potential. The rules of thumb used in the examples in **Box 1** and **Box 2** have been integrated with sophisticated crop simulation models and tools – such as Yield Prophet® (http://www.yieldprophet.com.au/yp/wfLogin.aspx), which enables an ongoing view of the yield and the potential response to N (Hunt et al. 2010).

Figure 2 shows part of a screenshot from the Yield

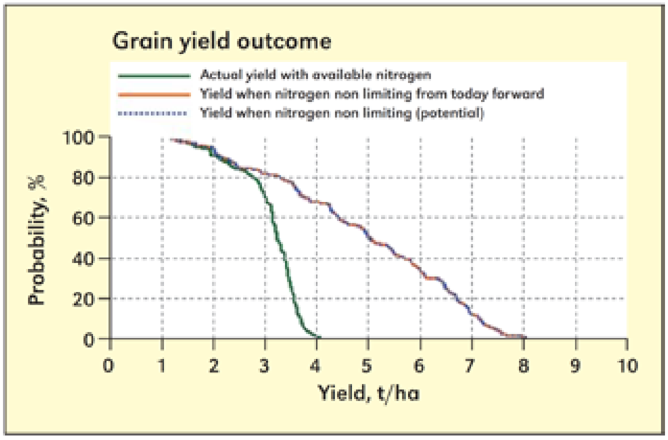

Figure 2. Probability of exceedance for a range of seasonal conditions using weather conditions to June 22, measured soil N and other agronomic inputs for a wheat paddock in the Wimmera region of Victoria.

Prophet® website showing the probability of exceedance of grain yield at a site in the Wimmera of Victoria. The outcome in the graph is based on yields from 100 years of rainfall records from the date of the report until crop maturity. This shows that if no added N is used, the median (50% probability) yield would be around 3.3 t/ha, while the conditions suggest yields would not exceed 4 t/ha. This outcome is based on the current N status of the paddock (101 kg N/ha).

The second line on the graph shows the yield in response to added N modeled over 100 years. This shows there is adequate water to take the median yield to 5 t/ha if N was not limiting, and the yield response ranges from 0 to 4 t/ha. This provides growers with the magnitude of the typical response, plus the range of responses likely given the variable climate.

Managing Risk Around the Right Rate for P

Phosphorus is usually applied at seeding in the drill row as this has long been seen as the most efficient delivery strategy. Rates are usually based on average removal, but this tends to over apply P in poor years and under apply it in better years. Topdressing of P in-crop does not supply the P near the roots because it is relatively immobile and will not leach into the root zone. Provided the important early crop demands are met with an at-sowing P source, and if products are developed that do not damage the crop canopy at appropriate use rates, P application could become tactical (Noack et al. 2010), similar to common N management strategies. Research into the right source, rate, time, and place for tactical P for wheat is currently under investigation (Noack et al. 2010).

Conclusion

In a variable climate, matching nutrient demand to supply relies on a good estimate of the yield potential. Nutrient budgets for N can be tailored around these variable yields to provide adequate N to prevent N stress early in the crop's life with little or no yield penalty. As the seasonal conditions unfold, additional N can be added (or not) to meet the rising (or falling) yield potential and nutrient demand. A similar approach to tactical application of P is an attractive option and current research is investigating appropriate products and their deployment to make this a viable strategy.

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Modern Corn Hybrids' Nutrient Uptake Patterns

By Ross R. Bender, Jason W. Haegele, Matias L. Ruffo, and Fred E. Below

Biotechnology, breeding, and agronomic advancements have propelled corn yields to new highs with little guidance as to how to fertilize these modern corn hybrids to achieve their maximum yield potential. Current fertilization practices, developed decades ago, may not match uptake capabilities of modern hybrids that contain transgenic insect protection now grown at population densities higher than ever before. A re-evaluation of nutrient uptake and partitioning can provide the foundation for fine-tuning our practices as we strive to achieve corn's maximum yield potential.

As summarized by Bruulsema et al. (2012), optimizing nutrient management includes using the right source at the right rate, right time, and right place—the 4R ap-proach. Research pertaining to primary macronutrient uptake, partitioning, and timing (Sayre, 1948; Hanway, 1962; Karlen et al., 1988), though fundamentally accurate for previous hybrids and management practices, may be unrepresentative of modern hybrids in higher yielding environments. The objective of this study was to determine how modern, transgenic insect-protected corn hybrids in high-yielding systems take up and utilize nutrients.

Nutrient contents of N, P, K, S, Zn, and B were determined at six incrementally spaced growth stages: V6 (vegetative leaf stage 6), V10, V14, R2 (blister), R4 (dough), and R6 (physiological maturity) (Hanway, 1963). Field experiments were conducted at the Northern Illinois Agronomy Research Center in DeKalb, Illinois and the Department of Crop Sciences Research and Education Center in Urbana, Illinois. A total of six hybrids ranging in relative maturity from 111 to 114 days were used with genetic resistance to feeding from Western Corn Rootworm (Diabrotica virgifera virgifera), European Corn Borer (Ostrinia nubilalis), and other species in the Lepidoptera order. In all cases, hybrids were seeded to obtain a final stand of 34,000 plants/A. Representative plants were separated, analyzed, and evaluated in four tissue fractions: 1) stalk and leaf sheaths; 2) leaf blades; 3) tassel, cob, and husk leaves; and 4) corn grain, respectively referred to as stalk, leaf, reproductive, and grain tissues. Agronomic management at planting included a soil insecticide and a broadcast application of 150 lb P_2O_5/A as MicroEssentials® SZ™ along with 180 lb N/A as urea. This was followed by 60 lb N/A as Super-U (with urease and nitrification inhibitors) side-dressed at V6 and a fungicide at VT/R1 (tasseling/silking).

Nutrient Uptake and Removal

Across the two sites in 2010, these transgenic corn root-worm resistant hybrids yielded an average of 230 bu/A (range of 190 to 255 bu/A) and we will base our discussion of nutrient needs assuming this yield level.

When developing fertilizer recommendations, two major aspects of plant nutrition are important to understand and manage in high yield corn production including: 1) the amount of a given mineral nutrient that needs to be acquired during the growing season, referred to as "total nutrient uptake," or nutrients required for production, and 2) the amount of that nutrient contained in the grain, referred to as "removed with grain" (**Table 1**). Our grain nutrient concentration values, in units of lb/bu (**Table 1**) are in agreement with those recently used by the fertilizer industry to determine replacement fertilizer rates (Bruulsema et al., 2012). In the past 50 years, however, the quantity of N, P, and K required for production and the amount of nutrients removed with the grain have nearly doubled across a variety of management systems used in the 1960s (Hanway, 1962).

Individual nutrient HI values were calculated, which quantify the percentage of total plant uptake that is removed with the grain. Nutrients with high requirements for production (N, P, K) or that have a high HI (P, Zn, S, N) allude to key nutrients for high yield (**Table 1**). In relation to total uptake for example, nearly 80% of P is removed in corn grain compared to K and B, which are retained to a greater percentage in stover. For each nutrient, the fraction that is not removed with the grain remains in leaf, stalk, and reproductive tissues and constitutes the stover contribution that is returned to the field. Production practices that utilize all or portions of aboveground stover (i.e. cellulosic ethanol, corn grown for silage) may remove an additional 20.8 lb N, 4.0 lb P_2O_5, 23.3 lb K_2O, 1.9 lb S, 0.5 oz Zn, and 0.2 oz B per ton of dry matter.

Common abbreviations and notes: N = nitrogen; P = phosphorus; K = potassium; S = sulfur; Zn = zinc; and B = boron; HI = harvest index; R1 = silking (silks visible outside the husks); R2 = blister (kernels are white and resemble a blister in shape); R4 = dough (milky inner f uid thickens to a pasty consistency); R5 = dent (nearly all kernels are denting); R6 = physiological maturity (the black abscission layer has formed); V6 = six leaves with collars visible; V10 = 10 leaves with collars visible; V14 = 14 leaves with collars visible; VT = last branch of tassel is completely visible.

Fully-filled ears of corn—an indicator of successfully matching soil nutrient supply with crop demand.

Maximum Uptake Rates

Further improving fertility practices require matching in-season nutrient uptake with availability, a component of the right source applied at the right rate and right time. The maximum rate of nutrient uptake coincided with the greatest period of dry matter accumulation during vegetative growth (**Figure 1**) for all observed nutrients (**Figures 2** to **7**). Be-tween V10 and V14, greater than one-third of total B uptake occurred, compared to the other nutrients which ranged from 20 to 30%. During the V10 to V14 growth stages, corn required the availability of 7.8 lb N/day, 2.1 lb P_2O_5/day, 5.4 lb K_2O/day, 0.56 lb S/day, 0.21 oz Zn/day, and 0.05 oz B/day. Fertilizer sources that supply nutrients at the rate and time that match corn

Table 1. Total macronutrient and micronutrient uptake and removal in Urbana, IL and DeKalb, IL (2010).

Nutrient	Total nutrient uptake	Removed with grain	Harvest index, %	Nutrient removal coefficient, lb/bu
	- - - - - lb/A - - - - - -			
N	256	148	58	0.64
P_2O_5	101	80	79	0.35
K_2O	180	59	33	0.26
S	23	13	57	0.06
Zn	7.1	4.4	62	0.019
B	1.2	0.3	23	0.001

† Zn and B are expressed in oz (i.e. oz/A and oz/bu).Each value is a mean of six hybrids at both locations (mean = 230 bu/A). Harvest index was calculated as the ratio between nutrient removed with grain and total nutrient uptake and is reported as a percent. Multiply grain yield by Nutrient Removal Coefficient to obtain the quantity of nutrient removal.

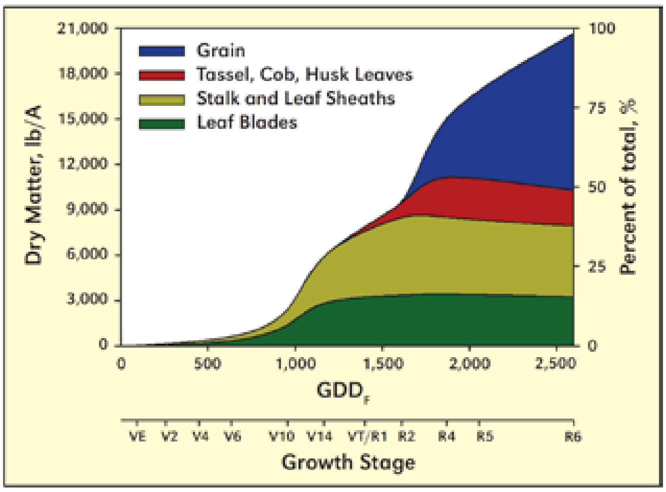

Figure 1. Total maize dry matter production and partitioning across four plant stover fractions: leaf, stalk, reproductive, and grain tissues. Each value is a mean of six hybrids across two site-years at Urbana, IL (2010) and DeKalb, IL (2010). GGDF = growing degree days (Fahrenheit)

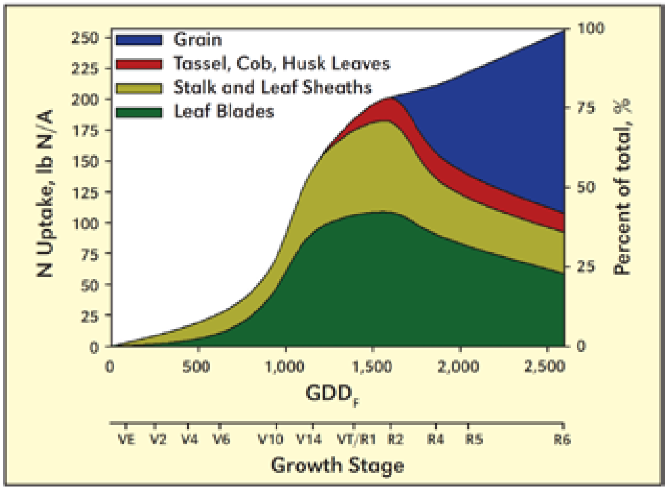

Figure 2. Total maize N uptake and partitioning across four plant stover fractions: leaf, stalk, reproductive, and grain tissues. Each value is a mean of six hybrids across two site-years at Urbana, IL (2010) and DeKalb, IL (2010). GGDF = growing degree days (Fahrenheit)

nutritional needs are critical for optimizing nutrient use and yield.

Timing of Nutrient Uptake

Effectively minimizing nutrient stress requires matching nutrient supply with plant needs, especially in high-yielding conditions. Sulfur and N, for example, are susceptible to simi-lar environmental challenges in the overall goal of improving nutrient availability and uptake. However, the timing of N uptake (**Figure 2**) in comparison to S (**Figure 5**) is surpris-ingly different, suggesting practices that are effective for one may not improve uptake of the other. Nitrogen uptake, unlike S, followed a more traditional sigmoidal (S-shaped) uptake pattern with two-thirds of the total plant uptake acquired by VT/R1. In contrast, S accumulation was greater during grain-filling stages with more than one-half of S uptake occurring after VT/R1 (**Figure 5**). Potassium, like N, accumulated two-thirds of total uptake by VT/R1 (**Figure 4**). Interestingly, greater than one-half of total P uptake occurred after VT/R1 as well (**Figure 3**). These figures suggest that season-long supply of P and S is critical for corn nutrition while the majority of K and N uptake occurs during vegetative growth.

Unlike N, P, K, and S, which have a sigmoidal or relatively constant rate of uptake, micronutrients exhibited more intricate uptake patterns. Uptake of Zn and B, for example, began with a sigmoidal (S-shaped) uptake pattern in the early vegetative stages and plateaued at VT/R1 (**Figures 6** and **7**). Thereafter, Zn exhibited a constant uptake rate similar to that of P and S, while B uptake included a second major sigmoidal uptake phase concluding around R5 (dent). Zinc and B favored shorter periods of more intense uptake in comparison to macronutrients. During only one-third of the growing season, late vegetative and reproductive growth accounted for as much as 71% of Zn uptake (**Figure 6**). A similar trend was noted for B; as much as 65% of B uptake occurred over only one-fifth of the growing season (**Figure 7**). Matching corn micronutrient needs in high-yielding conditions clearly requires supplying nutrient sources and rates that can meet crop needs during key growth stages.

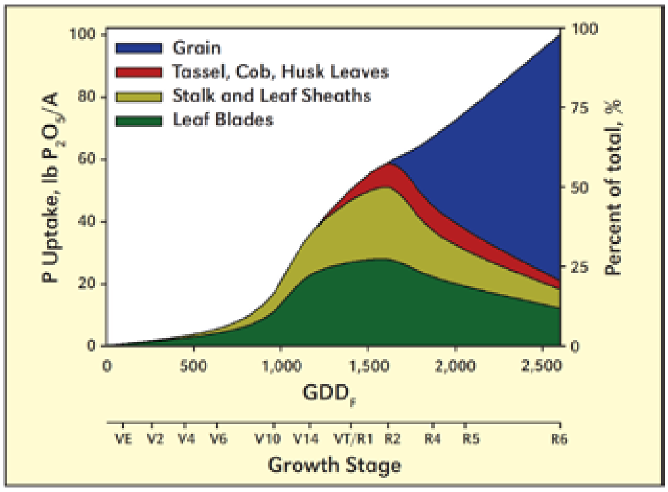

Figure 3. Total maize P uptake and partitioning across four plant stover fractions: leaf, stalk, reproductive, and grain tissues. Each value is a mean of six hybrids across two site-years at Urbana, IL (2010) and DeKalb, IL (2010). GGDF = growing degree days (Fahrenheit)

Plant Nutrient Mobility

Unlike plant dry matter, specific nutrients possess mobility characteristics allowing them to be utilized in one tissue, then later transported (remobilized) and used in another (Sayre, 1948; Hanway, 1962; Karlen et al., 1988). For many nutrients, including N, P, S, and Zn, a large percentage of total uptake is stored in corn grain at maturity (**Table 1**). Nutrients with high HI values accumulated them from a combination of as-similation during grain fill (after VT/R1) and remobilization from other plant parts. Phosphorus, for example, accumulated more than one-half of total uptake after VT/R1 and remobilized a significant portion that was originally stored in leaf and stalk tissues (**Figure 3**). Nitrogen and S achieved similar HI values although through two different mechanisms. Post-flowering S uptake was

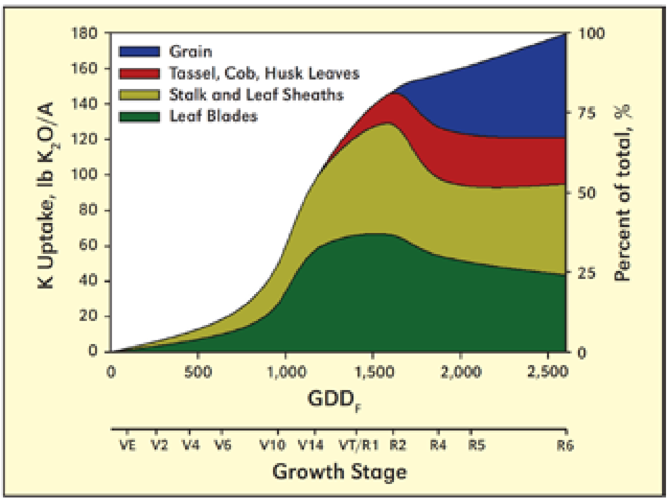

Figure 4. Total maize K uptake and partitioning across four plant stover fractions: leaf, stalk, reproductive, and grain tissues. Each value is a mean of six hybrids across two site-years at Urbana, IL (2010) and DeKalb, IL (2010). GGDF = growing degree days (Fahrenheit)

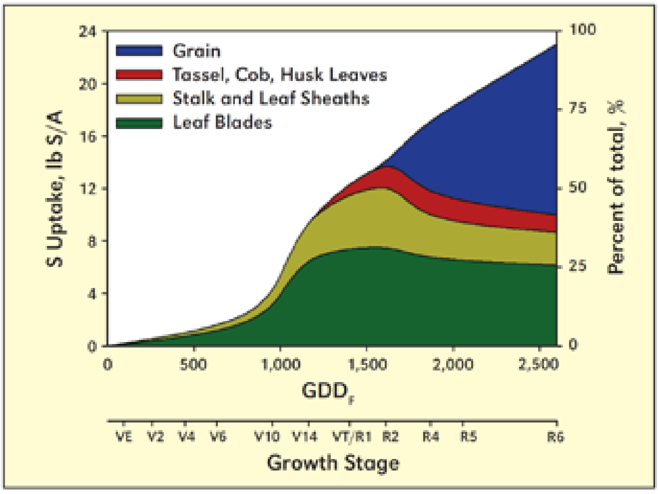

Figure 5. Total maize S uptake and partitioning across four plant stover fractions: leaf, stalk, reproductive, and grain tissues. Each value is a mean of six hybrids across two site-years at Urbana, IL (2010) and DeKalb, IL (2010). GGDF = growing degree days (Fahrenheit)

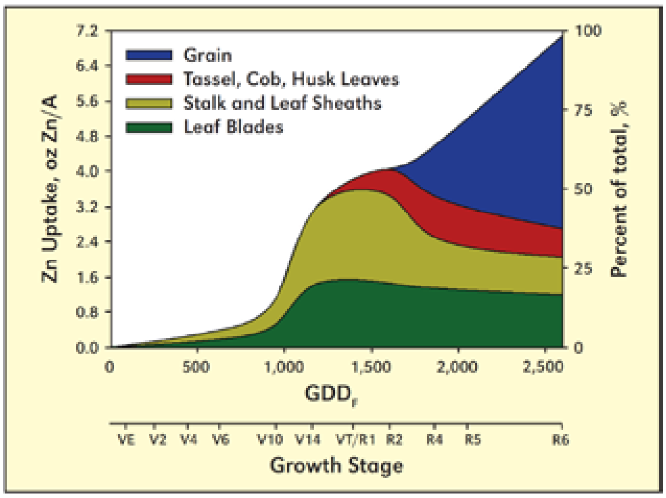

Figure 6. Total maize Zn uptake and partitioning across four plant stover fractions: leaf, stalk, reproductive, and grain tissues. Each value is a mean of six hybrids across two site-years at Urbana, IL (2010) and DeKalb, IL (2010). GGDF = growing degree days (Fahrenheit)

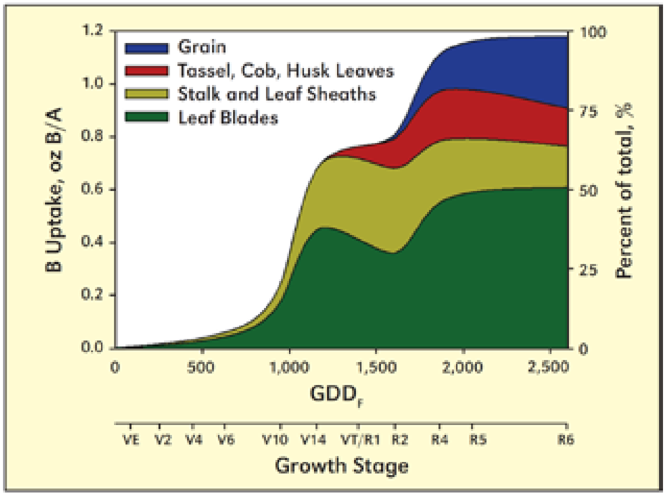

Figure 7. Total maize B uptake and partitioning across four plant stover fractions: leaf, stalk, reproductive, and grain tissues. Each value is a mean of six hybrids across two site-years at Urbana, IL (2010) and DeKalb, IL (2010). GGDF = growing degree days (Fahrenheit)

the major source of grain S (Figure 5) compared to N, which was largely obtained from remobilization (**Figure 2**). Plant Zn exhibited a unique mobility characteristic in which stalk tissue served as a major, but temporal Zn source. By R6, nearly 60% of stalk Zn was remobilized, presumably to corn grain. Similar to that of Karlen et al. (1988), leaf B content appeared to drop around VT/R1, indicative of its role in reproductive growth (**Figure 7**).

Optimization of Nutrient Management

Although nutrient management is a complex process, improving our understanding of uptake timing and rates, partitioning, and remobilization of nutrients by corn plants provides opportunities to optimize fertilizer rates, sources, and application timings. Unlike the other nutrients, P, S, and Zn accumulation were greater during grain-fill than vegetative growth; therefore, season-long supply is critical for balanced crop nutrition. Micronutrients demonstrated more narrow periods of nutrient uptake than macronutrients, especially Zn and B. As a percentage of total uptake, P was removed more than any other nutrient. In a corn-soybean rotation, it is commonplace in Illinois to fertilize for both crops in the corn production year. While farmers fertilize, on average, 93 lbs P2O5 for corn production (Fertilizer and Chemical Usage, 2011), the 80% of soybean fields receiving no applied P would have only 13 lbs P2O5 remaining (Fertilizer, Chemical Usage, and Biotechnology Varieties, 2010). These data suggest a loom-ing soil fertility crisis if adequate adjustments are not made in usage rates as productivity increases. This plant nutrition knowledge is critical in understanding our current nutrient management challenges.

Summary

As a result of improved agronomic, breeding, and bio-technological advancements during the last 50 years, yields have reached levels never before achieved. However, greater yields have been accompanied by a significant drop in soil macronutrient and micronutrient levels. The latest summary on soil test levels in North America by IPNI reported that an increasing percentage of U.S. and Canadian soils have dropped to levels near or below critical P, K, S, and Zn thresholds dur-ing the last 5 years (Fixen et al., 2010). Soils with decreasing fertility levels coupled with higher yielding hybrids suggest that producers have not sufficiently matched nutrient uptake and removal with accurate maintenance fertilizer applications. Integration of new and updated findings in key crops, including corn, will better allow us to achieve the fundamental goal of nutrient management: match plant nutritional needs with the right source and right rate at the right time and right place.

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The Efficient Use of Phosphorus in Agriculture

By Johnny Johnston, Paul Fixen and Paul Poulton

Data from vastly different soils located on two continents, and from both controlled experiments in England and derived state-wide aggregated data in the U.S., were merged to evaluate P use efficiency. The data suggest that there is an underlying "simple rule" for the behaviour of plant-available soil P in these soils, which can be related to a four-pools concept of inorganic soil P.

Phosphorus is an essential, irreplaceable element in all living organisms, and the global resource of readily-minable phosphate rock (PR) is limited. After process-ing, more than 80% of the PR mined annually is used in food production. Thus, extending the life span of this global resource will depend on using P more efficiently in agriculture; especially since P use will increase as the world's expanding population has to be fed. The inefficient use of P in agriculture has a direct cost to farmers.

Behavior of Soil and Fertilizer P

As a contribution to improving P use efficiency in agricul-ture, Syers et al. (2008) reviewed the current understanding of the behaviour of soil and fertilizer P and showed that the long-held view that P was irreversibly fixed in most soils was not supportable. These authors proposed that plant-available, inorganic P in soil could be considered to be in four pools related to the availability for uptake by roots and its extract-ability by reagents used in soil analysis (**Figure 1**). The first two pools are the soil solution P (pool 1, a very small amount) and the readily plant-available P (pool 2). These two pools are only a small proportion of the total P in soil, but the amount can be determined by acceptable, widely used methods for routine soil analysis.

The availability and extractability of P in the four pools is largely determined by the nature and strength of the bonding between the inorganic P and the soil constituents on which it is held. The important feature shown in **Figure 1** is the revers-ible transfer of P among the first three pools as discussed in detail with examples by Syers et al. (2008). Developed from this concept, there is a critical level of plant-available P in pools 1 and 2 below which optimum crop yield is not achieved and above which there is no need to apply P (i.e., such P is used inefficiently).

Efficiency of Fertilizer P Use

The direct determination of the amount of P taken up from an added fertilizer can only be done using 32P-labelled fertil-izer, which is expensive and has a short half-life. Consequently, the recovery of added P has been more commonly determined by the difference method:

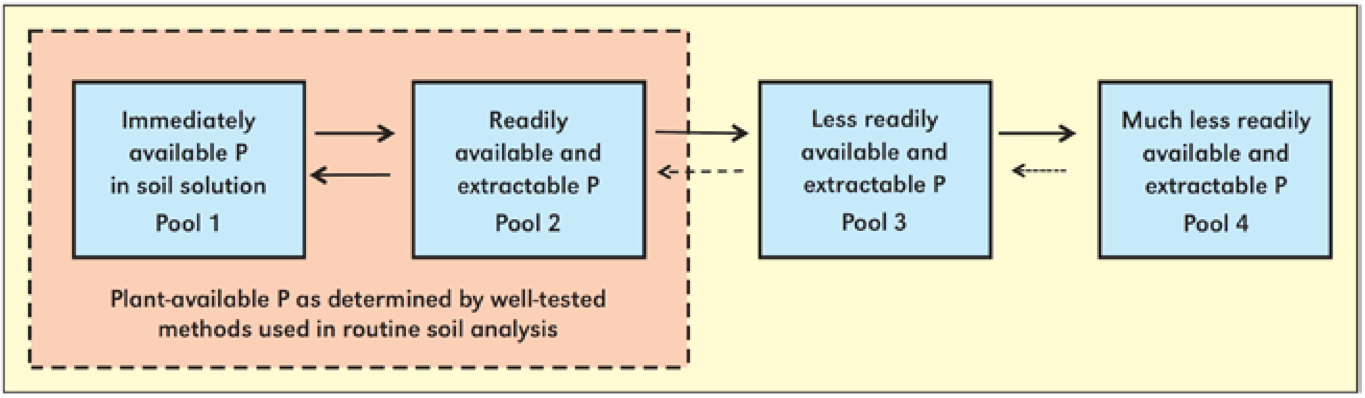

Figure 1. Conceptual diagram for the forms of inorganic P in soils categorized in terms of plant availability and extractability.

$$(Up - Uo)/Fp$$

where Up and Uo are the P taken up by a crop from soils with (Up) and without (Uo) added P and Fp is the amount of P ap-plied, expressed as a percentage.

Often referred to as percent use efficiency, reported values are often 10 to 15% and rarely exceed 25%. Such small values are used to imply that applied P is used inefficiently.

If only a small amount of P in a crop has come directly from P applied as fertilizer or manure then the remainder must have come from soil P reserves, which might be naturally occurring or as accumulated P residues from past applications of fertilizer or manure. Syers et al. (2008) suggested that replacing the P taken up from the soil P reserve was equally as efficient a way of using freshly applied P as was that taken up directly from fertilizer by the crop. The concept is based on the observation that for many soils when P inputs are at a level similar to the amount of P removed in crop harvest, the sum of pools 1 and 2 in **Figure 1** remains constant. Thus, the P removal-to-input ratio, sometimes referred to as partial nutrient balance, is a useful metric of P efficiency, especially when combined with data on plant-available soil P.

Efficiency of Fertilizer P Use on Soilsat the Critical Level of Plant-available P

The efficiency of P inputs can often exceed 80%, calculated as a P removal-to-input ratio, when P is applied to maintain the critical level of soil P. In an experiment on a silty clay loam at Rothamsted, Great Britain, a “maintenance” P application (20 kg P/ha each autumn for four years) was tested on soils growing winter wheat and with plant-available P (extractable with Olsen’s reagent; Olsen P) ranging from 9 to 31 mg/kg. The average annual grain yield and the total P removed in grain plus straw increased as Olsen P increased; thus the P balance declined. Where yields were near maximum, and P offtake more nearly matched the amount of P applied, then P-use ef-ficiency exceeded 90% when calculated as a removal-to-input ratio (**Table 1**). Similar experiments showing maintenance of the critical level of plant-available P by replacing that removed in the harvested crop were reported by McCollum (1991) and Halvorson and Black (1985).

Table 1. Maintaining Olsen P by replacing the amount of P removed in four winter wheat crops*, Exhaustion Land, Rothamsted, 2005-2008.

	Olsen P, mg/kg, in 2004***				
	9	14	20	23	31
Average annual grain yield, t/ha	7.6	8.3	8.1	8.5	8.5
Total P applied, kg/ha**	80	80	80	80	80
Total P removed, kg/ha	56	68	66	77	75
Phosphorus balance, kg P/ha	24	12	14	3	5
Olsen P, mg/kg, in 2008***	8	13	18	24	31
P removal-to-input ratio, %	70	85	82	96	94

** Winter wheat grown continuously.*
*** Phosphorus, 20 kg P/ha applied in autumn.*
**** Olsen P in soil sampled in autumn.*

Relating P Removal-to-Input Ratiosto Changes in Plant-available P in Soil

The ratio of P removed by crop harvest compared to P ap-plied as fertilizer, or recovered from manure, should be related to changes in plant-available P in soil. A ratio of 1 implies that output and input are in balance with probably little change in plant-available soil P. A ratio greater than 1 implies that output exceeds input and soil reserves are being depleted; when soils are at, or below, the critical value this increases the risk of not achieving optimum yield. A ratio of less than 1 (i.e., output is less than input) in most soils should allow soil P to build up. Once the critical level is reached, or slightly exceeded, input should generally be reduced to a maintenance amount.

The International Plant Nutrition Institute (IPNI) uses its Nutrient Use Geographic Information System (NuGIS) (http://www.ipni.net/nugis) to get data on nutrient balances and relate them to changes in the plant-available soil P (Fixen et al., 2010, updated by Fixen, personal communication). For example, the IPNI data for the U.S. Northern Great Plains (**Table 2**) show

Table 2. Phosphorus removal-to-input ratio and Bray-1 equiva-lent levels in three States in the U.S.

State	P removal-to-input* ratio			Median Bray-1, mg/kg		
	2002	2007	Average	2001	2005	2010
Montana	0.97	1.04	1.01	12	14	14
North Dakota	1.07	0.94	1.01	10	11	11
South Dakota	1.02	0.91	0.97	11	14	13

** Input = Fertilizer P applied plus recoverable manure P.*
Data derived using IPNI NuGIS data, 1/12/2012, see text.

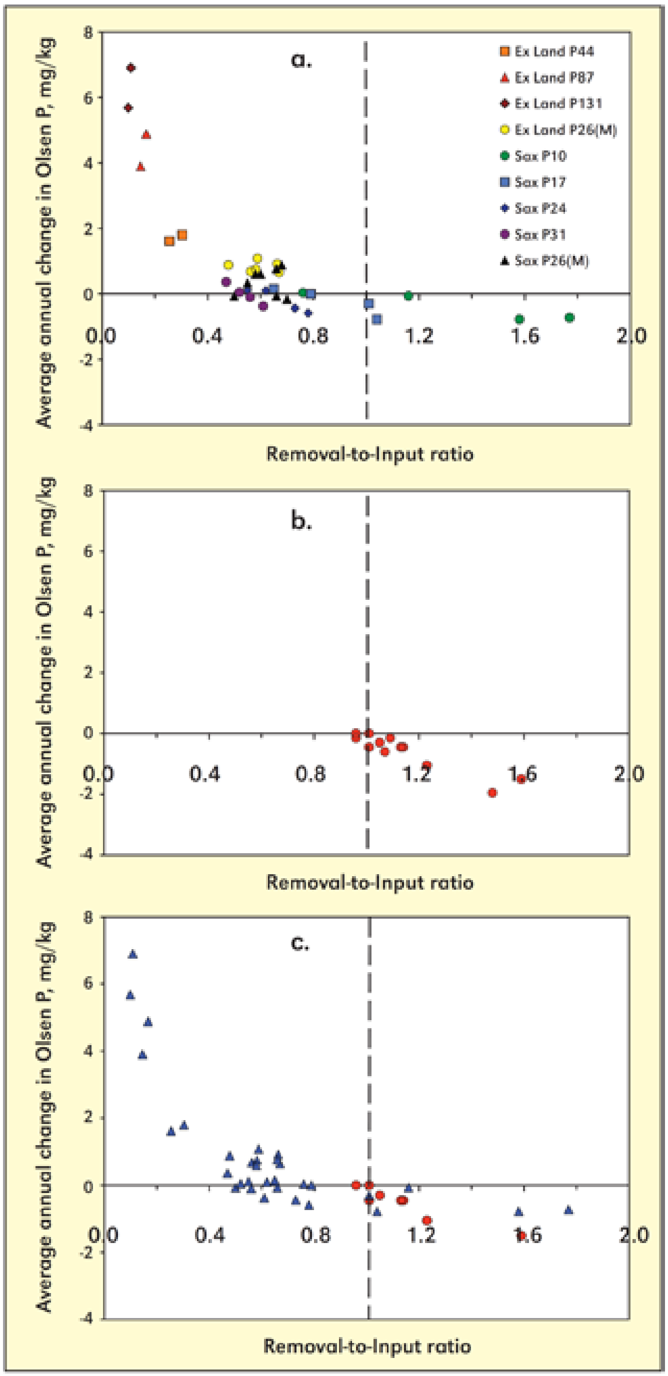

Figure 2. Relationship between the removal-to-input ratio (P removed by the crop divided by fertilizer P inputs) and the change in plant-available P for (a) two long-term experiments in the U.K. [P44 etc. denotes average annual application of fertilizer P; (M) denotes a maintenance dressing]; (b) 12 states in the U.S. (P Fixen, Pers. Comm.); (c) all U.S.●, and U.K.▲, data.

that where the P removal-to-input ratio for each state approxi-mates to 1 there is little change in the median Bray-1 levels for the 340,000 soil samples submitted to soil testing laboratories from these states for the three sampling years available. The conclusion from the data in **Table 1** (Rothamsted) and **Table 2** (U.S.) is that where the P removal-to-input ratio is about 1, and there is little or no change in the level of plant-available soil P then the efficiency of P use is very high as discussed initially by Syers et al. (2008).

Removal-to-input ratios, which are mainly less than 1, and changes in Olsen P in two long-term field experiments at Rothamsted are shown in Figure 2a. There is a strong curvilinear relationship that can be fitted with a polynomial function with an r2 of 0.84.

Figure 2b shows the relationship between P removal-to-input ratios and change in plant-available P for 12 U.S. Corn-Belt States derived using NuGIS. In this case an estimate of "recoverable manure P" is included in the total P input; for this figure, Bray-1 data were converted to Olsen P values by multiplying by 0.75. Although there are uncertainties about the accuracy of individual observations because of the assump-tions that have to be made, each point in Figure 2b is the average of many individual values, which suggests that it is an acceptable approximation of what is occurring for each state. The data can be fitted with a straight-line function with an r2 of 0.85. Most of the ratios are greater than 1 (i.e., there was a negative P balance and soil P reserves are being depleted).

Visual inspection of Figures 2a and 2b suggests that there is a degree of commonality, and it is of considerable interest that when both sets of data were put on the same basis they could be combined to produce Figure 2c. We have chosen not to show a line through the data points because they can be considered in two ways. First, a log function can be fitted to all the data with an r2 of 0.84, or second, a lower straight line can be fitted to the soils with small annual inputs of P with an r^2 of 0.63 and another straight line to the six soils to which large amounts of P were added with an r2 of 0.84. Irrespective of the approach used, this combined graph is for data from vastly different soils and two continents, and from both controlled experiments in England and derived "State-wide" aggregated data in the U.S. That the combined data can be described us-ing a single simple function makes a powerful and convincing statement. It suggests that for the agricultural soils from which these data were obtained, there is an underlying "simple rule" for the behaviour of plant-available soil P, which can be related to the four-pools concept of inorganic soil P proposed by Syers et al. (2008) and discussed in detail by Johnston et al. (2014).

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Spring Snowmelt Impact on Phosphorus Addition to Surface Runoff in the Northern Great Plains

By Tom Jensen, Kevin Tiessen, Esther Salvano, Andrea Kalischuk, and Don N. Flaten

Recent research in Alberta and Manitoba, Canada, confirms that snowmelt runoff is the dominant portion of annual total runoff from agricultural watersheds in the Northern Great Plains (NGP) of North America. The region is character-ized by relatively level landscapes and a dry climate with cold winters and warm summers. Many of the methods used to estimate the risk of P movement into surface streams and lakes were designed for warmer, more humid environments and steeper topography where rainfall runoff is dominant and particulate P associated with soil erosion is the main non-point P source from agricultural land. In the NGP, however, soluble P originating from surface soil, plant residues, and surface-applied manure is a larger proportion of total P runoff than particulate P, especially during the spring snowmelt. Soil erosion control methods that help reduce P loading into surface waters in warmer, more humid climates may be less effective in reducing P losses in the NGP. Recent research in the region also suggests that soil-test P is highly correlated with total P losses in snowmelt runoff. In the NGP, these studies show that P losses in runoff can be most effectively reduced and controlled by avoiding the development of excessively high soil-test P levels.

Movement of nutrients in surface runoff is a natural process in the environment. Under so-called pre-settlement conditions in the NGP, surface runoff naturally moved nutrients from grasslands, parklands, and forests. Nutrients in runoff exist primarily in either dissolved form or particulate form (attached to soil particles). Movement of nutrients in runoff is essential to aquatic ecosystem health as a source of nutrients for microbes, aquatic plants, and aquatic animals.

The movement of nutrients from the landscape to water bodies, however, can be enhanced by human activities including agriculture, forestry, urbanization, industry, and recreation. These activities can promote nutrient loss through land clearing, and the application to land of fertilizers, manures, treated sewage, industrial waste effluents, and sludges. As an example, an 8-year water quality monitoring study of 23 agricultural watersheds in Alberta showed that as agricultural intensity increased, water quality decreased, including increased N and P concentrations in surface water (Lorenz et al., 2008). These additions along with continuing nutrient movement from undisturbed grasslands, parklands, and forests all contribute to the total nutrient loads in surface waters.

Excess P, and N to a lesser extent, can enhance growth of algae (i.e., algal blooms) and other aquatic plants causing eutrophication in freshwater streams, sloughs, and lakes. The growth and subsequent death and decomposition of algal blooms can reduce oxygen content (anoxia) in these surface water bodies. Reduced oxygen content can harm aquatic plants and animals. One example for this concern is the deteriorating water quality in Lake Winnipeg in Manitoba, Canada (the10th largest freshwater lake in the world). The Lake Winnipeg watershed includes most of the southern parts of Alberta, Saskatchewan, and Manitoba. Similar to other water bodies in the NGP, this lake has experienced more frequent and intense algal blooms in recent years, primarily attributed to excess P loading from the watershed (Lake Winnipeg Stewardship Board, 2006).

The actual loading of P in surface waters is dominated by snowmelt runoff in much of the NGP where regular snowfall is received. This is different compared to warmer and more humid areas of the world where loading of P is typically dominated by runoff caused by intense rainfall. Runoff caused by rainfall is often associated with soil erosion, and the majority of total P (TP) entering surface water is particulate P (PP). In contrast, snowmelt runoff is usually less erosive because snowmelt has lower kinetic energy than raindrops and flows over soil that is often still frozen. The majority of P in snowmelt water is dissolved P (DP) rather than PP. Two recent field studies, in Alberta and Manitoba, have shown that the amount of P lost during the snowmelt process is strongly related to the concentration of soil-test P in surface soils (Little et al., 2007; Salvano et al., 2009).

In the study from Alberta, runoff was monitored from eight fieldscale watersheds for 3 years (Little et al., 2007). One of the objectives of this research was to determine the relationships between soil-test P (STP) and the degree of soil P saturation (DPS) with runoff P including TP and dissolved reactive P (DRP). The volume of water and nutrient content of water samples were collected from fieldsized catchments under spring snowmelt and summer rainfall conditions. All eight sites had high runoff potential, uniform management, and no farmyard or non-agricultural influences. The watersheds in the study ranged in size from 5 to 613 acres. The

Image courtesy of Alberta Agriculture and Rural Development

Snowmelt runoff in the Northern Great Plains.

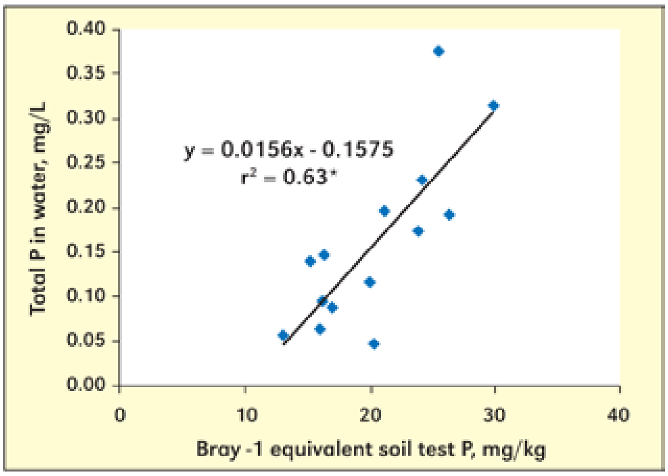

Figure 1. Relationship between overall mean total P in surface water of 14 regional watersheds and Bray-1 equivalent STP concentrations in watersheds.
* Significant at $p < 0.01$. (adapted from Salvano et al. 2009)

majority of runoff (>90% among all sites) was generated from spring snowmelt. Strong linear relationships between STP and P in runoff were determined in this study. Soil-test P accounted for 88% of variation in TP concentrations in the runoff from the watersheds. Reduced levels of STP following the cessation of manure application corresponded directly with reductions in runoff P. Although a number of different STP sampling strategies were examined, a simple average of all soil sampling points was as good a predictor of runoff P concentrations compared to more detailed soil sampling procedures. There were no signiflcant differences among the relationships using different soil sampling depths of 0 to 1 in., 0 to 2 in., and 0 to 6 in. Therefore, it is likely that a common agronomic soil sampling depth of 0 to 6 in. can be used to predict P in runoff from agricultural land in Alberta. Although the DPS holds promise for predicting runoff and leaching losses of P, STP is the standard for agronomic sampling in Alberta and the results suggested that there is no strong reason to use DPS instead of STP.

In the study from Manitoba, Salvano et al. (2009), evaluated the relationship between water quality data for P and three existing P loss risk indicator methods developed to estimate P loss at a regional scale: 1) Birr and Mulla's P Index for Minnesota, 2) the Preliminary P Risk Indicator for Manitoba, and 3) a preliminary version of Canada's National Indicator of Risk of Water Contamination by Phosphorus. Validation of the P loss risk indicators was conducted using long-term water quality monitoring data consisting of TP concentrations collected from 14 watersheds in Manitoba, representing nearly level and rolling landscapes in eastern and western regions of the province, respectively. Water quality data in the watersheds were collected for 11 years from 1989 to 1999. Available STP data for each watershed from 2000 to 2003 were provided by Bodycote Testing Group for fields in each watershed. This was compared to estimated fertilizer P application rates at the regional level using data extracted from the 2001 Census of Agriculture database and Canadian fertilizer consumption recordsSalvano et al. (2009) reported that correlations between the three P risk indicators and P losses to surface waters were poor and generally insignificant. It was thought that the poor correlation was because of the emphasis on soil erosion risk in the risk indicator methods; soil particulate runoff is a low proportion of P in runoff during spring snowmelt, which is the dominate form of runoff. In contrast, STP accounted for 63% ($p<0.01$) of the variation in TP concentrations in water samples (**Figure 1**). Although soil erosion had the most influence on the values generated by the three P risk indicators, STP had the most influence on TP concentrations in runoff water. Therefore, these P risk indicators appear to be too heavily weighted towards soil erosion processes for use under Manitoba conditions.

The extremely poor relationship between erosion and TP concentrations may have implications regarding the value of erosion control measures for reducing P loading in the Manitoba prairie region watersheds. For example, recent studies have determined that P loading to Manitoba waterways is either reduced by only a small degree or even increased by traditional erosion control best management practices (BMPs) such as vegetative buffer strips (Sheppard et al., 2006), and conservation tillage (Glozier et al., 2006), respectively. Therefore, to quantify the risk of P loss and the relative contribution of P loss, Salvano et al. (2009) suggest that research should be conducted that will develop and evaluate BMPs designed to reduce the snowmelt-driven losses of P, mostly in dissolved forms, throughout the nearly level landscapes of the prairie region of southern Manitoba.

Expanding on the report of Glozier et al. (2006), Tiessen et al. (2010) compared the seasonal runoff and nutrient losses from two long-term, adjacent paired watersheds in southern Manitoba. One watershed was 10 acres in size and under conventional tillage (i.e., <30% surface reside after planting, receiving primary and secondary tillage operations followed by a harrowing operation before planting). The other was 13 acres in size and under conservation tillage (i.e., direct seeded or no-till with moderate disturbance and >30% residue from the previous crop remaining on the soil surface after planting) (**Figure 2**). The paired watersheds were monitored between 1993 and 2007, before and after conservation tillage was introduced in 1997 on the 13 acre watershed. Data were separated into three principle time-periods: 1) a 4-year calibration period (1993-1996); 2) a 7-year transitional period (1997-2003); and 3) a 4-year treatment period. The watersheds are 93 miles southwest of Winnipeg, Manitoba.

Yearly runoff patterns at the paired watersheds

Figure 2. Division between the paired watersheds: conventional (on left) and conservation tillage (on right), October 2005.

Table. 1. Four-year average (2004 to 2007) of residue cover and soil-test data at the Manitoba paired watershed study (Tiessen et al., 2010).					
Watershed	**Residue cover, %**	**Snow-water equivalent, in.**	**Nitrate-N 0 to 6 in., lb N/A**	**Olsen-P 0 to 6 in., mg/kg**	**Organic matter, 0 to 6 in.,%**
Conservation tillage	56 a*	0.32	5.8 b	19.1 a	3.8
Conventional tillage	19 b	0.31	7/4 a	13.1 b	3.5
*Within columns values followed by different letters are significantly different ($p<0.05$).					

displayed a spring melt peak, typically in March or April, and multiple rainfall event peaks at various times between May and November. This region of the Canadian prairies typically has one snowmelt period lasting several days, if not weeks, and fewer than five rainfall-induced runoff events per year (Tiessen et al., 2010). Data were split into snowmelt and rainfall seasonal periods. Soil samples were collected after harvest in the fall, before the conventional tillage field was cultivated, from both of the watersheds in each year of the 2004 to 2007 study period. Crop residue cover percentage was also determined in the spring after all field operations were conducted. To determine the quantity of water available for runoff within each watershed, snow depth and density were measured in late winter, just before the spring snowmelt (**Table 1**).

Tiessen et al. (2010) report that snowfall accounted for only 25% of total annual precipitation during the study period. However, snowmelt runoff accounted for 80 to 90% of total annual runoff export from these two watersheds. In this study, on average, concentrations of dissolved nutrients in runoff were higher during snowmelt than rainfall events, whereas, concentrations of total suspended sediment (TSS) and particulate nutrients were greatest during rainfall events during the treatment period. However, because snowmelt was the dominant hydrological process, the majority of particulate and dissolved nutrient export occurred during the snowmelt period (**Figure 3**).

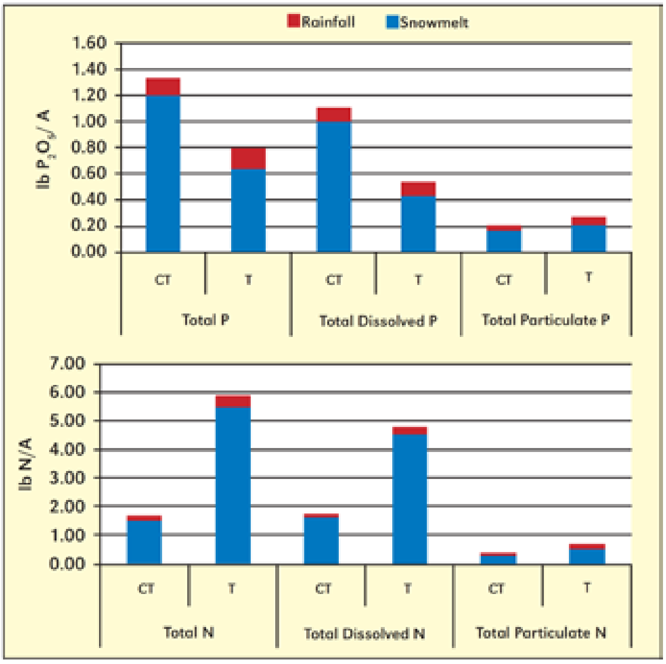

Figure 3. Total, dissolved, and particulate P_2O_5 and N export as annual, snowmelt and rainfall runoff by tillage systems, 4-year average (2004 to 2007). (Note, not controlled for differences in watersheds and seasonal climate variability.)
CT = Conservation Tillage; T = Tilled

Additionally, of total N and P nutrient export, dissolved nutrients were the dominant form of nutrients compared to particulate nutrients from the two watersheds, in both the spring and summer. The importance of dissolved nutrients was especially evident during the spring snowmelt period when >80% of N and P were exported in the dissolved form (**Figure 3**).

The effectiveness of no-till in reducing TSS losses has been well documented (Baker and Laflen, 1983). However, previous studies have reported that no-till reduces total losses of nutrients because of significant decreases in runoff volume and sediment mass. In the study by Tiessen et al. (2010), snowmelt runoff was similar for the two tillage systems at 10,389 and 10,432 ft3/A for conservation tillage and conventional tillage, respectively, while rainfall runoff was about half for conservation tillage compared to conventional tillage (1,143 and 2,472 ft3/A, respectively). These results suggest that under the climatic conditions of subhumid southern Manitoba, conservation tillage can be effective in reducing rainfall runoff, but not snowmelt runoff. One suggested reason is because in this part of the eastern, more humid, portion of the NGP, the snow pack was typically large and premelt snow water equivalent on the conventional tillage and conservation tillage watersheds were almost identical (**Table 1**). In the more arid western part of the NGP, where snowfall can be less and warm Chinook winds occur sporadically during the winter and early spring, there may be differences in snowpack (the magnitude of the snow trapping effect by conservation tillage is expected to be greatest in regions with very little snow), melting, and runoff sessions between conventional and conservation tillage cropping (Pomeroy and Gray, 1995).

Interestingly, Tiessen et al. (2010) report that the two tillage systems affected N and P differently (**Figure 3**). Converting to conservation tillage resulted in lower export of total N (TN), but greater export of TP. After controlling for 1) differences between the two watersheds that existed prior to introducing conservation tillage to one of them, and 2) seasonal and yearly climate and hydrological variability between the two watersheds, particulate P export was determined to have been reduced by 37% after conversion to conservation tillage.

The total dissolved P export, however, increased by 36% after conversion to conservation tillage. Since dissolved P was the dominant form of P export from both watersheds, this increase in dissolved P more than offset any decreases in particulate P export. This increase in P export occurred because the conservation tillage system was more susceptible to losses of soluble P in snowmelt runoff – likely due to the stratification of P at the soil surface (**Table 1**) and the leaching of P from crop and weed residues. Even though the total P losses in this study (i.e., average export of 1.33 lb P_2O_5/A/yr from the conservation tillage watershed from 2004 to 2007) may be minor from an agricultural perspective, they are of ecological significance because as little as 2 to 5 lb P_2O_5/A/yr has been associated with accelerated eutrophication of lakes in the United States (Sharpley and Rekolainen, 1997).

Management practices such as conservation tillage used to improve water quality by reducing sediment and sediment-bound nutrient export from agricultural fields and watersheds in warm, humid regions may be effective for reducing sediment and N losses, but less effective for reducing P losses in cold, dry regions where the nutrient export is snowmelt driven and primarily in the dissolved form. In these situations, it may be more practical to implement management practices that reduce the accumulation of nutrients in crop residues and surface soils. One possible management option raised in the study by Tiessen et al. (2010) is that there may be potential benefits from some tillage operations in the fall prior to freeze-up and snow events. These tillage operations would incorporate a portion of crop and weed residues, as well as any manure applications, so that less soluble P will be at the soil surface and available to be exported from fields during snowmelt runoff. However, further research is required to test this theory.

From a practical viewpoint, all of the studies mentioned above show that STP is a very important factor in the amount of P lost from fields in the NGP, suggesting that P in runoff can be minimized if STP levels are not excessive. The same principles can be applied to N management, in that N additions from manure and inorganic fertilizer sources should be sufficient to supply crop needs, but not excessive to result in unnecessarily high levels of residual inorganic N (NO_3^- and NH_4^+) in topsoil. There needs to be further research determining what STP level guidelines should be, and what management practices can be used to control P losses from fields in cold climate regions of North America.

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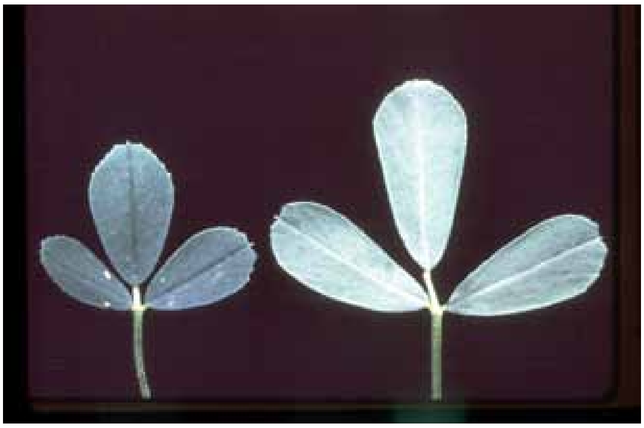
Visual Indicators of Phosphorus Deficiency: Selected Crops

Phosphorus deficiency in canola

Phosphorus deficiency in barley

Affected purple leaves turn dark yellow to orange red.



Phosphorus deficiency in alfalfa

Small deficient leaflet compared with healthy leaflet (right).

Phosphorus deficiency in winter wheat

Wheat crop followed long-term alfalfa with little fertilizer application. Problems with starter fertilizer application are apparent from the poor growth. The P soil test in the effected rows was 3 ppm, while in rows growing normally it was 13 ppm

Phosphorus deficiency in cabernet sauvignon grape.

Phosphorus deficiency in potato (var. Russet Burbank).

Phosphorus deficiency in corn

Corn planted April 12; photo date June 16. Growth stage V-9. Tissue analysis May 22 indicated P at 0.12%.

Phosphorus deficiency in canola

Phosphorus deficiency in corn

Younger leaves turn purple resulting in no, or rudimentary, cob formation. The crop grown on NPK omission plot. The soil test P was 8 mg/kg. The plot received continuous rains for past 45 days. The surface soil partially removed during levelling resulting in poor organic matter status.

Phosphorus deficiency in canola

Direct seeded into alfalfa stubble. The previous alfalfa crop depleted soil P and, in this case, the farmer ran out of seed-row P fertilizer on the last pass during seeding, causing slow and stunted growth.

Phosphorus deficiency in sorghum

Phosphorus deficient sorghum plant that has developed a dark purple colour on its older leaves.

Phosphorus deficiency in cabbage

Grown on an acid soil site with low soil test P.

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