BETTER CROPS
WITH PLANT FOOD

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2015 International Year of Soils

In This Issue...

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Our cover: Emerging cereal crop seedlings.
Photo by: sanddebeautheil (iStockphoto)

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

Introduction to International Year of Soils Special Issue

Each of us has a close association with soil each day, but we rarely stop to consider its importance. In fact, if there were no soil, there would be no life on earth! In recognition of the essential role that soils play in sustaining our water, air, and food, the United Nations has declared 2015 to be the International Year of Soils.

The importance of soils is central to the mission of the International Plant Nutrition Institute (IPNI), which is to promote responsible management of plant nutrition for the benefit of the human family. Soils and their ability to support adequate agricultural production will play a key role in accomplishing our goal. We are pleased to devote this issue of Better Crops to highlight a few key areas related to the essential role of soil.

The fundamental link between soil and food security is inescapable. Throughout history, fertile and productive soils have supported healthy and flourishing societies. The food we grow to provide energy, proteins, vitamins, and minerals depends directly on the condition of the soil.

The majority of soils in the world require some degree of improvement before crops can reach their full yield potential. Fortunately, we live in an age where we understand these limiting factors. But implementing strategies to overcome them remain a challenge in many parts of the world. Soil degradation inevitably occurs when soils are neglected, leading to declining crop yields and a drop in farmer prosperity. Poor nutrient management is a major factor leading to soil degradation.

The ability of soils to perform crucial air and water services, and to support plant growth relies on many unseen, but vital processes. Plant roots grow in an incredibly complex soil environment that teems with soil organisms. There remains much to learn about this vital linkage between plant roots and the soil microbial community. The role of soils in providing the chemical, physical, and biological environment where roots can support healthy plant growth also is becoming better appreciated.

Proper care of soil resources allows the maximum amount of food to be produced on an area of land, thereby conserving additional land from being used for cropping. This concept of sustainable intensification requires careful application of stewardship and conservation techniques. Selection of specific management practices for soil protection will consider acceptable social, environmental, and economic outcomes.

When soils are lacking in any of the essential plant nutrients, they cannot support healthy crop growth and reduced yield and quality will result. There is no longer good reason for nutrient shortages to hinder food production with our advanced knowledge of plant nutrition and nutrient management, and with the abundance of excellent fertilizer materials. However, plant nutrients need to be used with appropriate stewardship techniques. IPNI has adopted the educational framework of the 4R's (Right Source, Right Rate, Right Time and Right Place of nutrient application) to provide guidance to nutrient stewardship decisions. Implementing the 4R principles is the application of precision agriculture concepts of using only the specific nutrients required in each part of a field.

Comprehensive soil stewardship practices must be more widely adopted in order to meet the food needs of a growing global population. IPNI remains committed to this goal by continuing to lead research and educational efforts on soil stewardship that result in continued improvements in plant nutrition. BC

Rob Mikkelsen

Dr. Robert Mikkelsen
IPNI Vice President, Communications

Throughout 2015, IPNI will be featuring resources related to the International Year of Soils online at http://info.ipni.net/IYS2015. Please check back regularly for updates.

Soil and Food Security

By Terry L. Roberts and John Ryan

The food we grow provides the energy, proteins, fats, vitamins, and minerals people need and the crop's ability to produce nutritious foods depends directly on the health of the soil. Food security and healthy, or fertile, productive soils are intrinsically linked. Indeed there is a close link between civilization and the quality of the soil; fertile productive soils supported flourishing societies while poor soils were—and still are—associated with poverty and underdevelopment.


iStockphoto/Son-Ha

Terraced soils supporting intensive rice production in Mu Cang Chai, Yen Bai, Vietnam.

In the past century, innovations in agricultural science and technology have alleviated society's concerns about the capacity of global agriculture to feed and clothe the world's burgeoning population. However, predictions that the world population is likely to increase from its current 7 billion to 9 billion, or more, by mid century have questioned whether mankind can respond to the challenges inherent in such demographic changes. Considering increased affluence in developing countries, especially for the demand for meat, world food production has to be doubled by 2050. The challenge of meeting this goal of enhanced output is all the more acute as it has to be achieved on ever-decreasing per capita availability of arable land, exacerbated by urbanization and soil degradation and greatly increased water and energy use (Lal and Stewart, 2010). Agriculture has to compete with other soil uses. Ensuring mankind's capacity to produce an adequate food supply has never been more daunting (Godfray et al., 2010). While reducing food waste, changing diets, and expanding aquaculture can help in meeting food demand, enhancing crop productivity and closing the yield gap between efficient producers and subsistence ones will be the major goal.

Food security is more than food production at farm level; it is influenced by economic, social, political, and administrative factors that affect stability, access and safety of the world's food supply. In its simplest terms, food security implies that all people have sufficient, safe and nutritious food so they can maintain a healthy and active life. Healthy soils sustain plants, animals and humans and function as a living ecosystem maintaining a diverse community of soil organisms that not only improve crop production, but also promote the quality of our air and water environments (FAO, 2008). While healthy soils are primarily associated with good crop yields, more recent attention has been given to the nutritional quality of such yields although the economic benefit of this aspect of crop nutrition is difficult to assess.

The chemical composition of plants reflects that of the soil, where nutrients in the soil are low, concentrations of those nutrients are low or deficient in plant tissue. Conversely, where nutrients or other minerals are in excess in the soil, toxic effects can occur for humans or animals that consume such produce (Brevik and Burgess, 2012). Fertilizer use can improve nutritional quality of crops (Bruulsema et al., 2012). For example, N can increase plant protein depending on the level of application, while P fertilizers increase the P content of crop produce, and trace elements such as Zn and Se can be increased by fertilization. Before the widespread use of P fertilizers, P deficiency was widespread in animals and humans, while Zn deficiency in humans is currently widespread globally.

Because of its close relationship with crop growth, nutrients and their availability have been intensively studied. Soil fertility, or its supply of available plant nutrients, is a critical component of a healthy and productive soil. It integrates physical (i.e., texture and structure, water, and air), biological (microorganisms and organic matter) and chemical (minerals and nutrients) processes in supplying essential nutrients to plants. A productive soil is always a fertile soil, but nutrient status alone does not ensure soil productivity. Soil moisture, temperature, drainage, physical condition, soil acidity, soil salinity, biotic stresses (weeds, insects, disease), and other factors can reduce the productivity of even the most fertile soils.

While physical properties of soils are relatively stable,

Abbreviations and notes: N = nitrogen; P = phosphorus; K = potassium; S = sulfur; Ca = calcium; Mn = manganese; Se = selenium; Zn = zinc.

soil fertility is dynamic or subject to change both in time and space. Nutrients are constantly being removed from the soil in harvested plant products, being lost from the soil through leaching, erosion and other natural processes, or being tied up by soil clays and minerals. Soil organisms immobilize and then release nutrients and nutrients become imbedded in soil organic matter (SOM). Plant nutrients continuously cycle, but the system is not closed; in addition to plant removal some nutrients leak from the system, reducing their efficiency and potentially impacting the environment.

While world soil types vary in their fertility, none have unlimited capacity to sustain crop yields indefinitely. Prior to the modern era of chemical fertilization, which took hold in the middle of the last century, agricultural output and crop productivity was dependent on the native fertility involving plant-available nutrients in the soil. When nutrients are removed from the system through plant and animal products or lost through other processes, they must be replaced to maintain the fertility and productivity of the soil. If nutrient removal continuously exceeds nutrient inputs the soil becomes degraded. Soil organic matter is a vital component of healthy soils (Johnston et al., 2009); where it becomes depleted, soil structure tends to breakdown, making the soil more susceptible to erosion and eventually unable sustain a productive agricultural system. Plant nutrients must be returned to the system through mineral or organic nutrient sources, and other conservation measures must be implemented to allow the organic matter levels to build up until the soil is restored to its health and productive potential.

The advent of the chemical fertilizer age was, along with improvements in medicine, a major factor underpinning the expansion in world population since the beginning of the 20th century. Along with mechanization and improved crop varieties, fertilizers have been a main factor supporting the world's expanded crop yields. Mineral fertilizers have been the major pathway of nutrient additions to soil and have played a decisive role in humankind's access to food.

Notwithstanding the misplaced concerns in modern society—indeed outright antipathy—and reservations of environmentalists about chemical fertilizer use, the overwhelming evidence clearly shows that global food production is largely dependent on chemical fertilizer use. Indeed the late Norman Borlaug, the father of the Green Revolution, a few decades ago, stated that a world without chemical fertilizers would support no more than one sixth of the world population. Based on numerous long-term trials across the world, Stewart et al. (2005) attributed over 50% of crop yields to chemical fertilizer use; these authors suggested that dependence would even further increase with increasing crop yields in the future.

The relationship between fertilizers and food security is most clearly shown in the case of N, the dominant nutrient in terms of global use. Erisman et al. (2008) estimated that N fertilizer, made possible by the Haber-Bosch process, was responsible for feeding 48% of the world's population since 1908. While inherent soil fertility, climatic conditions, cropping systems, plant breeding, genetic modifications, and agronomic management make it difficult to quantify exactly how much of the global population is dependent on fertilizer inputs to produce food, estimates suggest 40 to 60% of the worlds' cereal production is due to fertilizers (Roberts and Tasistro, 2012). Given the disparity in fertilizer use in the developed and developing world, allied to the diversity of crops for human consumption, and the time frame being considered, such a range in response is not unexpected. Some data are pertinent to indicate the agricultural significance of fertilizers.

As N dominates commercial fertilizer use, it is relevant to examine its impact in U.S. cereal production (**Table 1**). Omitting N fertilizer reduced yields of maize, rice, barley and wheat by 16 to 41%. Fertilizer P and K and other secondary and micronutrients are equally important in ensuring crops received a balanced diet of needed elements. Organic nutrients are also important. While the relative importance of organic manures as a production factor in agriculture in developed countries has declined relative to chemical fertilizer use, the disposal of excess supplies of animal manures has posed an environmental pollution threat. However, many subsistence farmers in developing countries rely to a large extent on locally produced manures.

Table 1. Estimated effect of omitting nitrogen fertilizer on cereal yields in the USA (Stewart et al., 2005).

Crop	Estimated crop yield, t/ha Baseline yield	 Without N	% reduction from no N
Maize	7.65	4.52	41
Rice	6.16	4.48	27
Barley	2.53	2.04	19
Wheat	2.15	1.81	16

Organic and mineral fertilizers are complementary; often the best yields are only achieved when inorganic and organic nutrients are applied together. Data from a 9-year field trial in India showed that highest yields were obtained when fertilizer was applied in combination with farmyard manure (**Table 2**).

Table 2. Effect of fertilizer and farmyard manure (FYM) on millet yield and yield stability over nine years in Bangalore, India (Roberts and Tasistro, 2012).

Annual treatment	Mean grain yield, t/ha	Number of years in which grain yield (t/ha) was: <2	 2 to 3	 3 to 4	 4 to 5
Control	1.51	9	0	0	0
FYM	2.55	1	6	2	0
NPK	2.94	0	5	4	0
FYM (10 t/ha) + NPK*	3.57	0	1	5	3

*Fertilizer 50-50-25 (kg/ha N-P_2O_5-K_2O)

Together inorganic and inorganic nutrients produced grain yields of at least 3 t/ha in 8 of the 9 years of the study. This is most evident on soils where nutrient mining, or depletion of nutrients over the years (where nutrient off take greatly exceeds inputs) has degraded the soil to the point where response to mineral fertilizer is only possible if applied together with manure or other organic materials. For example, degraded soils in sub-Saharan Africa are best managed when fertilizer is used together with manure. An additional advantage of manures in such situations is that it increases SOM, and improves the physical properties of the soils (i.e., aggregation) which in turn facilitates crop growth through improved microbial status, aeration, and water relations. Rusinamhodzi et al. (2014) re-

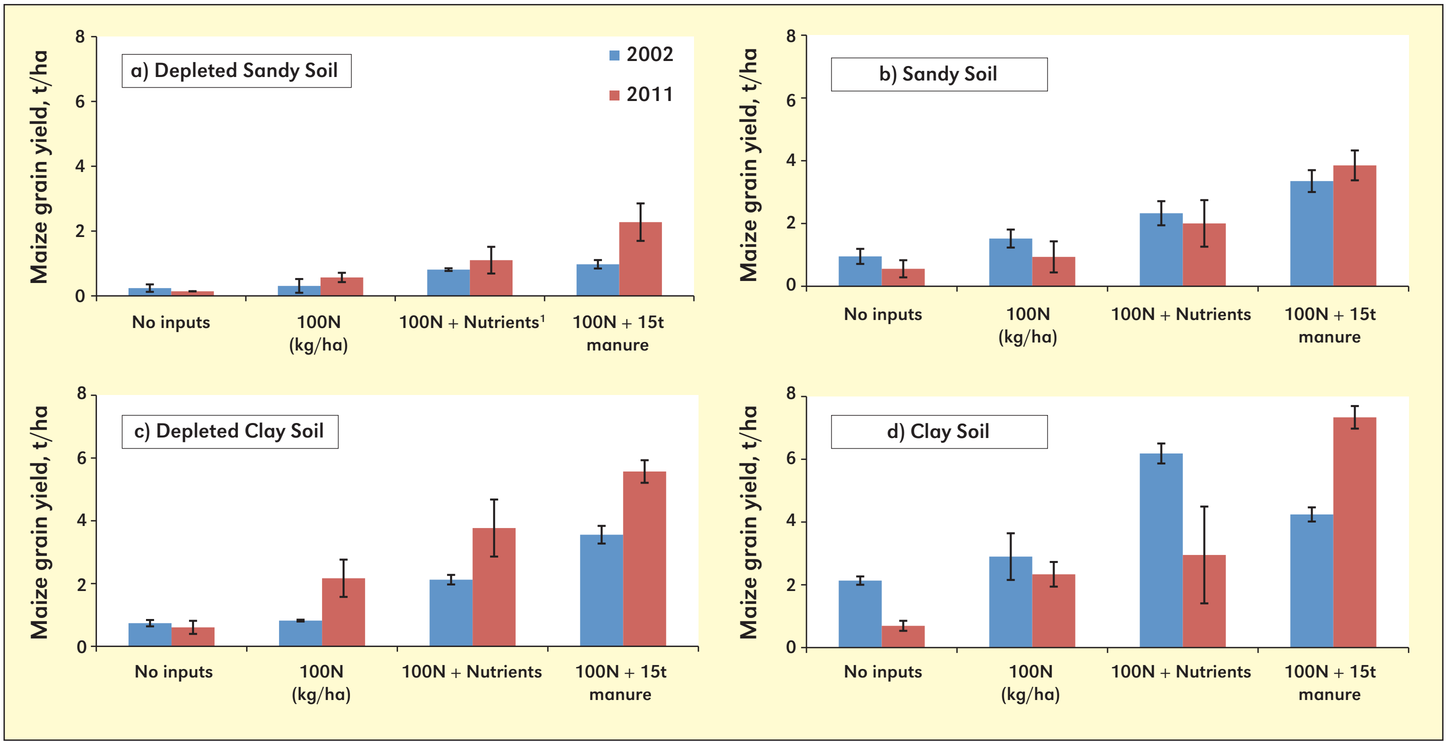

Figure 1. Initial and final maize yields and yield responses to long-term application of manure and mineral fertilizers under variable soil fertility conditions in Zimbabwe. Bars represent standard error of means. [1]Nutrients = application (kg/ha) of 30 P + 25 S + 20 Ca + 5 Mn + 5 Zn (from Rusinamhodzi et al., 2014).

ported on a 9-year study in Zimbabwe that found smallholder maize yields on nutrient-depleted soils were only marginally increased with mineral fertilizers and were decreased when N was used alone, but increased when cattle manure was used with N fertilizer (**Figure 1**). Maize response to fertilizer and manure varied with soil texture and the soil fertility status. This is but one illustration of the need to accommodate fertility management practices to the characteristics of soils that affect growth (e.g., soil depth, sub-soil layers, acidity).

While mineral fertilizer use, especially N, increases crop growth, some would argue its long-term use harms the biology of the soil and reduces the soil's capacity to make native nutrients available to plants. There is no basis for this popular misconception, as refuted by two extensive field studies. A recent meta-analysis of 64 long-term crop fertilization trials from 107 datasets from around the world found that the use of N fertilizer increased microbial biomass by 15% and soil organic carbon by 13% (Geisseler and Scow, 2014). A location-specific multi-year rotation trial that assessed various agronomic factors at a semi-arid site in northern Syria, characterized by relatively low SOM, showed that overall soil carbon levels consistently increased with increasing fertilizer N and P application rates (Ryan et al., 2008). Such studies also show that the particular crops in the rotation and the type of tillage condition influence the effects of N on soil quality components (i.e., conventional or minimum or no-tillage systems).

In summary, modern agriculture is related to soil quality and is dependent to varying extents on the use of chemical fertilizers; they support today's high crop yields and thus ensure food security for the world's burgeoning population. Fertilizers can also contribute to improving the biological and physical quality of soils and thus influence the environment through carbon sequestration resulting from enhanced root growth. A secondary benefit of fertilizer use is an indirect contribution to improved human and animal nutrition through nutrient enrichment in crop produce. The key to maximizing the productive potential of soils and exploiting the direct and indirect beneficial effects of fertilizers, while minimizing potentially harmful environmental effects, is the adoption of scientifically proven best management practices. BC

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Human Health Depends on Soil Nutrients

By John Duxbury, Graham Lyons and Tom Bruulsema

The composition of soils influences the composition of crops, in turn influencing the quality of food, its contribution to human nutrition, and ultimately, human health. Agricultural management options for improvement include diversifying cropping systems and correcting deficiencies through fertilization.

Courtesy Fernando Calle and Hernan Ceballos, CIAT

Fertilizing cassava with Se, Zn and I at the International Center for Tropical Agriculture (CIAT) in Colombia, South America.

Human nutrition remains in crisis. While the prevalence of hunger has declined by 21% since 1990, at least 805 million still go hungry. Among children under five, 161 million are estimated to be stunted (low height for age). Micronutrient deficiencies due to lack of dietary vitamins and minerals affect around 2 billion people, with multiple adverse health impacts and often impairing both physical and mental development of children. As atmospheric levels of carbon dioxide increase, Zn deficiencies are likely to increase (Myers et al., 2014).

Most plant nutrients are human nutrients too. Dietary Reference Intakes for human nutrition are provided for every nutrient element considered essential to plants (NAS, 2014). Boron is not fully recognized as essential, but some evidence indicates roles for it in bones, rickets and mental functions. Several roles for Ni are recognized, though its human dietary need is considered to be <100 µg/d (Welch and Graham, 2012).

Abbreviations and notes: N = nitrogen; P = phosphorus; K = potassium; S = sulfur; Ca = calcium; Mg = magnesium; B = boron; Cu = copper; Fe = iron; I = iodine; Mo = molybdenum; Mn = manganese; Ni = nickel; Se = selenium; Si = silicon; Zn = zinc; As = arsenic; ppm = parts per million.

Fertilization with Zn, Ni, I, Mo, and Se increases their concentrations in cereal seeds and in vegetative tissues. On the other hand, fertilization with Fe, Cu, Mn, and Si has little effect on their concentrations in grain. In general, plant tissue has higher levels of micronutrients than grain on a dry weight basis, and thus can be relevant to animal nutrition, and to the nutritional value of food products derived from animals.

Iron, Zn and I are the most important mineral micronutrient deficiencies. For the major staple grains, the Zn content of wheat and maize can be increased two-fold by foliar, and less by soil, fertilization, but gains with rice are generally less

Table 1. Examples of effects of fertilization with Zn on grain Zn concentration in rice and wheat.

			Wheat grain Zn, mg/kg		
Source	Soil pH	No Zn	Soil	Foliar	S+F
1	7.0-8.2	25	35	-	-
2	7.8	10	18	27	35
3	5.5	24	40	48	-
			Brown rice grain Zn, mg/kg		
Source	Soil pH	No Zn	Soil	Foliar	S+F
4	8.2	20	29	-	-
5	4.8-8.8	19	21	24*	26*
6	7.0	20	22	-	25

*Potential contamination as second Zn application 1 week after flowering and unhusked rice had high Zn.
Sources: 1) Malakouti, 1998; 2) Yilmaz et al., 1997; 3 & 6) Bodruzzman and Duxbury, unpublished; 4) Shivay et al., 2014; 5) Phattarakul et al., 2012

than 50% (Tariq et al., 2014; **Table 1**).

The FAO, and many others, have been emphasizing that good nutrition requires sustainable, equitable and resilient food systems. Diversity in cropping systems is important. Pulses and legumes generally contain higher levels of micronutrients than cereals, but their availability relative to that of cereal grains has decreased since the Green Revolution. A notable exception is the growth of soybean cultivation in Bangladesh, expanding from near zero in 1980 to over 40,000 ha in 2010. Sustainable diets for the global human family require the design of agricultural systems to provide better human nutrition.

Vast areas of global soils have low pH, restricting the uptake of Ca and Mg, two macronutrients very important to human health. Simple additions of dolomitic limestone can increase the concentration of these two mineral elements, particularly in vegetables, and thus prevent diseases like rickets. Work supported by Cornell University in Bangladesh has demonstrated yield increases (10 to 50%) and quality improvements in more than 40 crops including: groundnuts, radishes, garlic, cabbage, cauliflower, eggplant, and turmeric, resulting in adoption of liming on over 86,000 ha by over 280,000 farmers. Addition of iodate to irrigation canals has been successfully used in China and Mongolia to address human I deficiency where iodized salt was not accepted (Ren et al., 2008). The fortified irrigation water spread the added I widely through the food system, increasing levels in soils, crops and animal products (meat, eggs and milk). This led to dramatic human health gains, including a 50% decrease in infant mortality. Animal productivity was also greater, emphasizing the benefits of improving the nutritional quality of animal feeds as well as plant foods.

Victor Moritz Goldschmidt (1888-1947), the father of modern geochemistry, introduced the term "biophile" for elements found at high absolute or relative concentrations in living organisms. They include N, S, P, K, Se, I, Zn, and B. This concept points to the importance of managing the soil-plant system for these nutrients for plants, animals and humans.

Selenium and S are strongly biophile elements. As selenate and sulfate they are very leachable. As a consequence of fires, especially on savannahs, they can also be lost to the atmosphere in the form of SeO_2 and SO_2 (Christophersen et al., 2012). When the soil is S-deficient, plant protein content declines, especially for the S-rich proteins. In the more humid parts of sub-Saharan Africa, there are large areas where the human diet is deficient in S amino acids. This deficiency arises from both low protein intake and soil S deficiency. Plant-available Se is very low in many soils in Zambia, Malawi, Rwanda, Burundi, and other sub-Saharan African countries, with common levels less than 20 µg/kg (Hurst et al., 2013). A survey of Zambian maize grain conducted in 2012 revealed a median S concentration of only 1,030 mg/kg and N:S ratios of 13-15 (Lyons et al., 2014), values equivalent to only 60% of critical deficiency levels (Reuter and Robinson, 1997). In programs addressing the primary NPK fertility needs of the soils of sub-Saharan Africa, S and Se need strong additional consideration.

In many studies, selenate has been found to be around five times more effective than selenite in increasing grain/seed Se concentration in cereal (barley, bread and durum wheat) and pulse (chickpeas, peas) crops. An inverse relationship between yield (due to climatic variation) and grain Se concentration, has been observed, indicating a dilution/concentration effect of yield (McGrath et al., 2013).

Decades of experience and research in Finland have documented strong benefits to human Se status from programs of enrichment of fertilizers with Se starting in the 1980s. In the 1970s the per capita dietary intake of Se was 30 µg, of which 70% came through meat and milk. Animal Se deficiency was widespread, but inorganic Se added to animal diets did not transfer much Se to meat or milk. The low levels of Se in food and feed crops were due to strong binding of Se anions to oxides in the typically acid soils. Starting in 1984, selenate was added to all NPK fertilizers for forage crops (Se added at 16 mg/kg) and cereal grains (6 mg/kg) as a strategy to achieve nutritionally adequate and safe levels in humans. The rates were changed to 6 mg/kg for all crops in 1990, and then increased to 10 mg/kg in 1996. The changes were associated with changes in Se levels in foods and with dietary intake (**Table 2**). Outcomes included a doubling of human serum Se levels, and, while other factors were also involved, the mortality rates from heart disease decreased by about two-thirds from 1982 to 1997 (Laatikainen et al., 2005). Effects on cancer rates varied from none to moderate.

Table 2 . Fertilization with Se affected Se levels in foods and dietary intake in Finland (data assembled from Eurola, 2005).

Year	1984	1991	1996	2002
Forage fertilizer Se, mg/kg	16	6	10	10
Cereal fertilizer Se, mg/kg	6	6	10	10
Spring cereal* Se, mg/kg	0.01	0.28	0.07	0.18
Milk Se, mg/kg	0.05	0.20	0.14	0.22
Meat Se, mg/kg	0.20	0.90	0.38	0.60
Dietary intake, µg/d	40	110	80	80

*Winter wheat and rye Se were much lower (0.02 to 0.07 mg/kg) as added selenate was reduced to selenite over winter, but increased to approximately 0.1 mg/kg when added during crop growth.

Micronutrient availability can be influenced by macronutrient additions. When phosphate fertilizers are added to different soils, Se availability to plants may be increased or decreased, as a result of soil sorption and precipitation reactions. Even though marine phosphorites (sedimentary phosphate rock) contain much more Se than igneous phosphate ores (e.g., from the Kola Peninsula), their Se/P concentration ratio is often not as high as that of the topsoils of natural terrestrial ecosystems (McConnell, 1979). The application of commercial fertilizers may lead to a reduction of the total Se/P concentration ratio in the soil (depending on the Se/P ratio of the fertilizer), which would also lead to reduction of the Se/P ratio of food and forage plants. What this points to, as a general principle for management of soil fertility, is that when fertilizers are used to supply the most limiting nutrient, there may be long term implications for the uptake of other nutrients into plants. Continued application of P fertilizer, without regard to other nutrients, risks the development of soil deficiencies in nutrients like S, Se and Zn.

Use of As-contaminated groundwater for household and irrigation purposes in the Bengal basin has led to increased levels of As in both drinking water and in the irrigated crops produced. It is estimated that 140 million people worldwide are at risk for As-related diseases, the majority in Bangladesh. Recent research on animal models has shown a potential role for Se enrichment in countering As toxicity. Feeding lentils of varying Se content (Saskatchewan lentils with 0.3 ppm Se compared to northwestern USA lentils with <0.01 ppm Se) to rats, Sah et al. (2013) found that Se played a role in reducing the retention and increasing the excretion of As, resulting in lower levels of liver damage. The relevance of these findings for human nutrition needs to be confirmed by clinical trials. However, biofortification of Se in lentils through plant breeding and fertilization, and/or selection of foodgrains based on the Se level of the soils in which they were grown, could potentially play a role in addressing the huge human health concern posed by excess As. BC

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Modifying Soil to Improve Crop Productivity

By Luis I. Prochnow and Heitor Cantarella

The majority of the world's agricultural lands require some degree of soil improvement in order to support sustained productivity.

Soil Availability in the World

About 12% of the world's land area—around 1.5 billion ha—is currently used for crop production. Although reasonable amounts of land are still potentially suitable for crop production, much of it is covered by forests, protected for environmental reasons, or used for urban settlements (FAO, 2013). As a direct consequence of increasing world population, arable land per person is decreasing rapidly. It is projected that the world will only have 0.20 ha per person in 2050, as opposed to having 0.45 in 1960. This arable land "crunch" is much more of a developing world issue where the expected availability will be 0.15 ha per person versus 0.45 ha in the developed world (Bruinsma, 2009). As such, the increasing demand for agricultural products will put pressures on expanding into existing pasturelands (3.4 billion ha) or marginal, low productivity grasslands, savannas, and shrublands (1.1 billion ha, Cai et al., 2011). However, most of these areas have at least one suboptimal soil condition that would need to be addressed. All of these points suggest the need to increase the productivity of food, feed, fiber, and energy upon our global inventory of arable lands. This will only be possible through the advancement in technologies focused on integrating the proper management of all conditions that influence crop growth.

Soil Conditions that Affect Crop Growth

Several soil conditions influence crop growth and final yield. The list of factors considered to be most important includes: soil pH, nutrient availability, water status, oxygen availability, soil temperature, salinity, and soil permeability (**Figure 1**). Plants vary in requirements for each of these conditions. However, high and economic yields are only obtained when they are all near an optimum. For example, sustained productivity cannot be achieved in a soil with good nutrient balance if poor soil permeability is restricting plant root growth.

As we strive to meet the challenge of improved yields per unit of managed area, it is important to understand both where and why productivity can lag. The concept of the yield gap is defined by van Ittersum and Cassman (2013) as the difference between the yield obtained under optimum (or best) management and the average yield achieved by local farmers (**Figure 2**). Best management practices (BMPs) are our tools for modifying the condition of soil, ensuring good plant growth, and reducing the size of any existing yield gap. These practices are most effective and sustainable if they are supported by universal scientific principles, and are adapted to the social, economic and environmental contexts in which they are used.

It should be recognized that some problems in soil are relatively easy to manage, while others are influenced only indirectly. Soil pH, nutrient availability, and water availability are examples of soil conditions that can be more easily modified.

Abbreviations and notes: N = nitrogen; Ca = calcium; Al = aluminum.

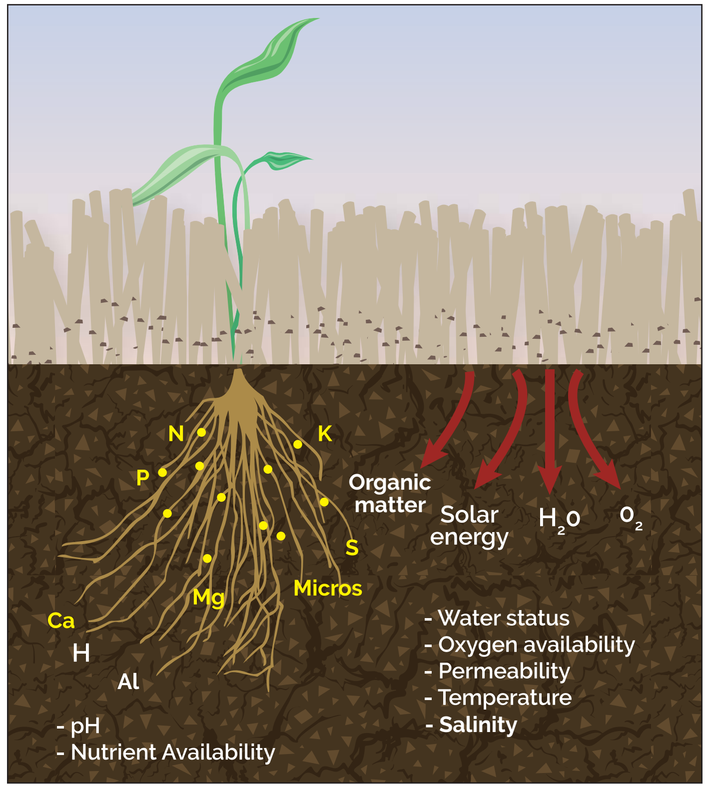

Figure 1. Plant productivity is partially a reflection of soil management, which should create the conditions necessary to optimize all soil factors considered most influential for plant growth.

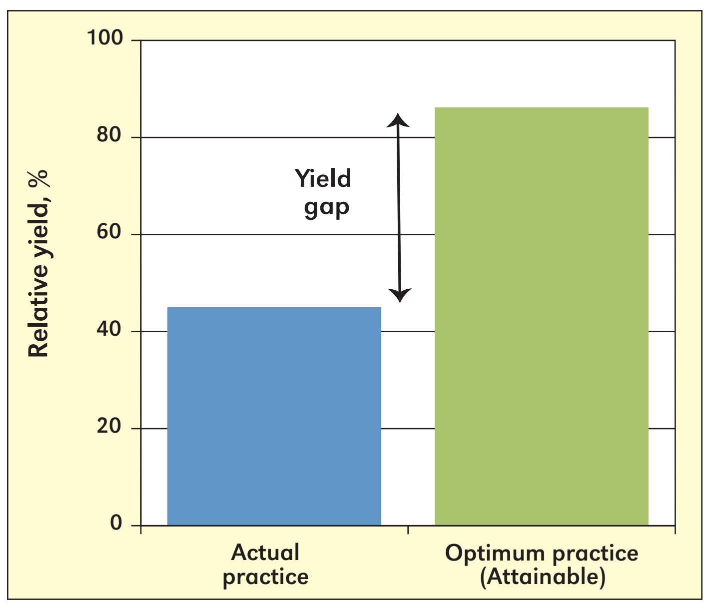

Figure 2. The gap between actual farm yields and what is considered optimum, or attainable, is primarily a reflection of the development and adoption of best management practices.

Soil pH

Excess soil acidity is a major problem in large areas of the globe, especially in highly weathered soils of the tropics, in low-yielding pasture lands, and marginal soils. The capacity of plants to tolerate soil acidity varies, but most plants grow better under slightly acidic soil conditions (pH from 5.5 to 6.5). For example, rice plants grow well in soil pH as low as 4.8; maize typically does best between 6.0 to 6.5; alfalfa grows better if soil pH is near 7.0. Even in highly productive soils, acidification may take place due to leaching of base cations and use of N fertilizers. Monitoring soil acidity with periodic soil analysis and use of lime will prevent the loss of soil quality associated with acidification, especially at depth where soil properties are harder to correct. Liming also can help to bring more soils into high-yielding agricultural production. In some cases, gypsum may be used to alleviate the problems of excess Al^{3+} and lack of Ca^{2+} in the subsoil, thus allowing deep root growth, which is important for the absorption of water and nutrients below the surface soil layers.

ridenfarmsupply.com

Application of lime at a large scale using commercial equipment.

Nutrient availability

Inadequate chemical properties associated with nutrient availability can be modified to improve biomass production. A good and consistent supply of nutrients from the soil is fundamental for adequate plant production and it can be evaluated and managed by the use of different tools. Calibrated soil analysis and nutrient recommendations based on yield response curves under local conditions and with consideration of nutrient experts, is an effective means of securing high yields, preventing soil degradation due to unbalanced nutrient input, and making good use of lands with limiting fertility. Proper diagnostics of nutrient availability creates site-specific fertilizer recommendations, reduces costs, and avoids excess nutrient accumulation and its undesirable environmental impacts. Other technologies that can help the understanding of soil nutrient availability include diagnostics for interpreting visual symptoms of deficiency or toxicity, plant tissue analysis, and local agronomic experimentation. In countries where these techniques are not available, or feasible, other tools should be developed to help understand soil nutrient availability and the 4Rs of Nutrient Stewardship (i.e, right source, right rate, right time, and right place) at a field-scale. A successful example is the development of the Nutrient Expert® decision support tool, which relies on the combined use of nutrient omission field trials and nutrient accumulation modeling to ultimately determine crop-specific nutrient uptake requirements, and provide a farmer with a regionalized fertilizer recommendation (Pampolino et al., 2012).

Water status

Soil water availability is a factor of increasing concern for most crop production systems. The selection of well-adapted, water-efficient crop varieties is critical to achieving the best use of soil water. Efficient field tools and sophisticated instrumentation techniques needed to monitor soil moisture and crop demand for water—both in rainfed and irrigated systems—are often readily accessible in many parts of the world affected by drought. Adaptive management practices (e.g., conservation tillage, cover cropping) are needed to promote optimal soil physical, chemical and biological properties, stimulate deep rooting within the soil profile, and lessen the impact of reduced water availability.

Practices to Improve Soil Conditions

Soil compaction, salinization, erosion, crusting, loss of soil organic matter and soil microbiological diversity can be corrected with several restorative agronomic practices. In some cases, sub-soiling and other mechanical operations and equipment (i.e., use of adequate tires in the field) can directly minimize or correct problems of compaction and deficient soil aeration. Many adaptive practices are adopted with the short-term goal of improving the cropping system first and the longer-term goal of improving the underlying soil condition over time. Two clear examples of such practices are no-till and region-specific crop rotation.

No-till

No-till (also called zero tillage or conservation tillage) is a way of growing crops or pasture from year-to-year with minimal physical soil disturbance. It usually promotes an increase in organic matter retention, modifies macro and micro soil porosity, and also influences the cycling of nutrients. In many

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Use of minimum tillage will reduce the potential for erosion, but more soil acidifying processes (like crop residue decomposition, nitrification of N fertilizers, etc.) occur at the soil surface.

Photo credits: Emerson Borghi (A and B) and Rogério Soratto (C and D)

Figure 3. Examples of brachiaria grass used with corn – seen at different stages: (A) before harvest, (B) at harvest, (C) soon after harvest, and (D) some weeks after harvest.

regions it can reduce or eliminate soil erosion. As a result of such modifications, no-till can positively influence soil conditions such as aeration, heat and soil permeability. It may also influence nutrient and water availability, all of these leading to better conditions for plant growth.

Crop rotation

Region-specific crop rotation (i.e., cropping sequence adapted to the region) can also have a positive influence on soil conditions. Creative alternatives, such as the Brazilian practice of using forage grasses in rotation with cereal crops, can generate clear benefits for soil conditions and nutrient availability (**Figure 3**). The rotation of crops with different root architecture and physiology help to access nutrients in different layers and chemical forms in the soil. Longer root extension and root exudate release increase the capacity to access forms of nutrients not easily available in traditional cereal crop systems (Crusciol et al., 2010).

Conclusion

Good soil husbandry is essential to improve and maintain soil quality and to increase crop productivity. Nutrient management, associated with other agronomic measures, is central among these practices, especially to modify soils with permanent or temporary limiting conditions, in order to incorporate them to the agricultural system. The literature is dense in offering knowledge so the soil can be modified as per best management practices, which should be always adapted to local conditions. BC

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Strategies to Protect and Conserve Soil Resources

By Ana Wingeyer and Fernando O. García

The growing global demand for food, feed, fiber, biofuels, and biomaterials has placed a high level of pressure on agro-ecosystems in which soils are a key non-renewable resource. Soil management practices should address this global demand by providing not only for agricultural productivity, but also for protection and conservation of soils. Best management practices (BMPs) for soil management should be socially acceptable, economically viable and environmentally sustainable.

Land and soil management practices affect soil processes and properties at different scales of intervention (UNEP, 2014). The effectiveness of these practices for meeting various soil management needs should be evaluated simultaneously at the field/farm, watershed and regional/global scales.

Adoption of **conservation tillage practices**, including no-tillage (NT), has been a leading practice in South America. Common benefits of NT include better economic results, improved or more stable yields through improved water use efficiency, erosion control, saving of fuel and labor/time, improved soil biological activity, among others. No-tillage has been adopted in approximately 70 to 90% of the field crop area in Paraguay, Brazil, Argentina, Bolivia, and Uruguay (**Table 1**).

Table 1. Area under no-tillage in countries of South America (Derpsch and Friedrich, 2009).

Country	No-tillage area (2008-09), ha	% of total cropped area
Brazil	25,502,000	70
Argentina	19,719,000	70
Paraguay	2,400,000	90
Bolivia	706,000	72
Uruguay	655,100	82

However, adoption of NT without the implementation of necessary water and wind erosion controls (e.g., windbreaks, terraces), crop rotations, balanced nutrition, and other practices would result in a failure to sustainably fulfill stakeholder expectations for agricultural productivity and soil protection.

Soybean monocultures provide less C inputs and promote increased soil organic C (SOC) decomposition rates than **crop rotations** with corn or sorghum, which can lead to a loss of 3 t SOC/ha/y under soybean monoculture regardless of NT implementation (Huggins et al., 2007). Crop rotations would provide for soil protection through continuous soil cover; diversification in crops and rooting patterns and depth; microbial populations and activity; return of residues; improved water and nutrient use; reduction in diseases and pests; more efficient weed control; and even better social and working conditions. These effects of crop rotations and cover crops have been verified through indicators such as SOC, biological activity, water use efficiency, and soil physical parameters. Intensification of land use (e.g., reduction of fallow period, use of double crops), cover crops and inclusion of pasture in the crop rotation is associated with larger SOC stocks and better aggregate stability under NT (Novelli et al., 2013). The increase of the frequency of a given crop in the rotation (i.e., towards monoculture) has negative impacts on both SOC stocks and aggregate stability (**Figure 1**). Soybean frequency index was the most closely associated index to the reduction of SOC stocks and aggregate stability.

Abbreviations and notes: N = nitrogen; P = phosphorus; K = potassium; C = carbon; mean weight diameter = an index of soil aggregation status.

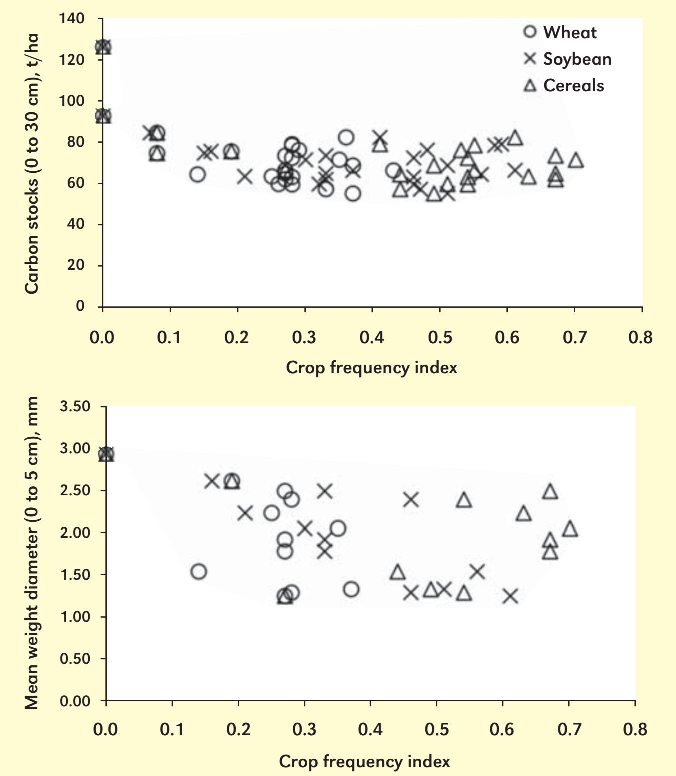

Figure 1. Soil organic carbon stocks in the 0 to 30 cm depth of a Vertisol and a Mollisol (top) and mean weight diameter of soil aggregates in the 0 to 5 cm depth of a Mollisol (bottom) as a function of crop frequency in the rotation under no-till (Adapted from Novelli et al., 2013).

Incorporation of **cover crops** in between cash crops would emphasize many of the benefits indicated for crop rotations. Soil protection from wind and water erosion, reduction of nutrient losses through runoff, sediment transport, leaching or gaseous losses, incorporation of N through biological fixation by legumes, soil biological activity and SOC sequestration are among the most frequently cited processes that benefit with the use of cover crops.

Residue management is a key component of ecosystem services at different scales (**Figure 2**). Agricultural productivity, soil and water conservation, and soil quality are positively impacted by residue retention. On average, crop residues contain 40% C, 0.8% N, 0.1% P, and 1.3% K, providing food and habitat for soil biota. Removal of crop residues for use as biofuel, feed, or other competing purposes increases nutrient

Soybeans planted directly into preceding maize straw residue at María-Teresa, Santa-Fe, Argentina.

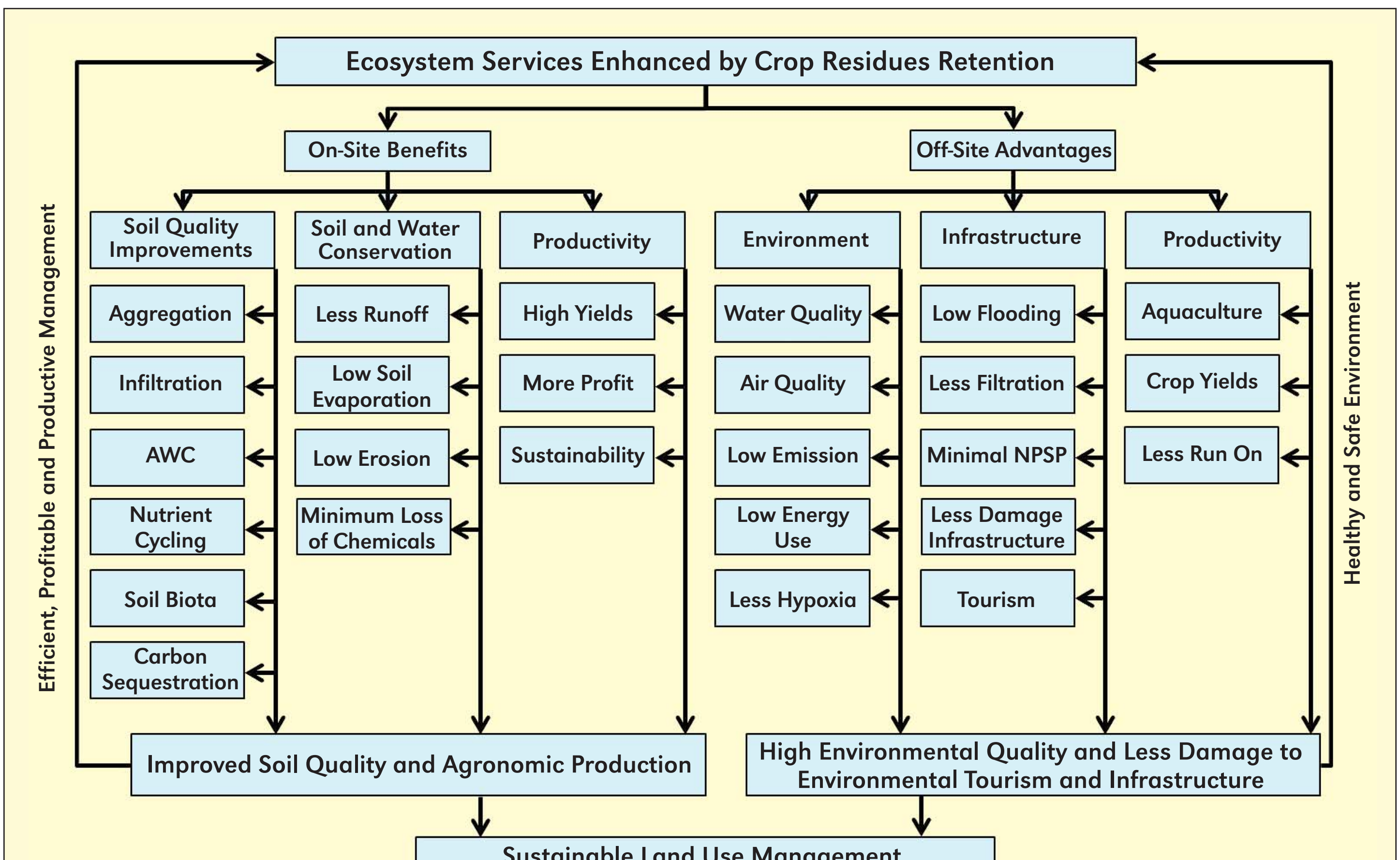

Figure 2. Agronomic productivity and environmental quality impacts of crop residues retention. AWC = available water capacity, NPSP = non-point source pollution (Adapted from Lal, 2008).

removal by agriculture and exposes soil to erosion and degradation, with multiple off-site adverse impacts on soil, air and water quality. Thus, soil amendment with crop residue is necessary to enhance/maintain soil quality and sustain agronomic productivity.

Balanced nutrition contributes to agricultural productivity and soil health. **Figure 3** shows the effect of balanced nutrition on microbial activity and glomalin concentration. Glomalin is a substance that accumulates in the cell walls of soil fungi and contribute to soil aggregate formation. Implementation of 4R Nutrient Stewardship (i.e., application of the right nutrient source at the right rate, time and place) would also help avoid, or decrease, externalities associated to water or air pollution.

Protection and conservation of soil resources through appropriate management techniques is essential to sustainable agro-ecosystems, and to fulfill the global demands for food, feed, biomaterials, and biofuels. Practices, as the ones described above, would contribute to this goal. BC

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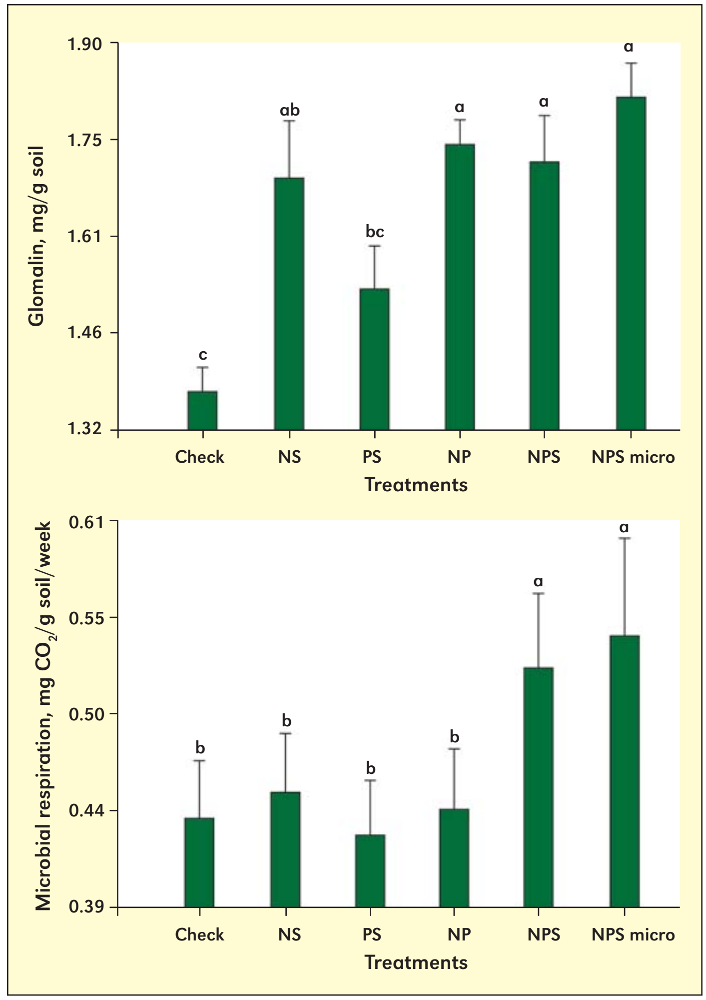

Figure 3. Soil glomalin concentration (top) and microbial activity (bottom) under different fertilization treatments in southern Santa Fe province, Argentina (Grümberg et al. 2012). Letters above columns denote significant differences between treatments at p = 0.05.

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2015 IPNI Scholar Award Program for Graduate Students

The International Plant Nutrition Institute (IPNI) is pleased to announce the availability of its IPNI Scholar Award program for 2015.

"Our Scholar Award provides a well-deserved nod of encouragement," explains IPNI President Dr. Terry Roberts. "These awards are made possible through the generous support of our member companies and is evidence of their strong respect for the development of emerging scientists."

The IPNI Scholar Award is available to M.Sc. or Ph.D. degree candidates in the disciplines of soil and plant sciences including: agronomy, horticulture, ecology, soil fertility, soil chemistry, crop physiology, environmental science, and other areas related to plant nutrition.

Eligible students must be from any country where an IPNI regional program exists. Only a limited number of recipients are selected for the award, worth US$2,000 each. Funding for the scholar award program is provided through support of IPNI member companies, primary producers of nitrogen, phosphate, potash, and other fertilizers.

The application period is open until April 30, 2015. Recipients will be announced in September 2015.

For more information about past winners of the IPNI Scholar Award, plus details on requirements for eligibility and the application procedure, please see our Scholar awards website: www.ipni.net/scholar.

2014 Crop Nutrient Deficiency Photo Contest Winners

IPNI is pleased to announce the winners of the 2014 Crop Nutrient Deficiency Photo Contest. As is tradition, preference was given to well-photographed entries that provided: (1) a good representation of the impact of the deficiency to the whole plant, (2) adequate soil and/or plant tissue nutrient analyses information, and (3) details concerning current or historical fertilization at the site.

IPNI greatly appreciates the efforts of all entrants providing photos to our annual contest. As a group you are helping to contribute to our mission to increase awareness on diagnosing crop nutrient deficiencies.

Congratulations to all of this year's winners who, in addition to their cash award, will also be receiving our most recent USB flash drive collection of crop nutrient deficiency images. For more details on this collection please see: http://ipni.info/nutrientimagecollection.

Please check back regularly with www.ipni.net/photocontest for details on submitting your entries for 2015.

Featured Category (Forage Crops)

First Prize (US$300) – Iron Deficiency in Sorghum – K.M. Sellamuthu, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India. This image captured a vivid example of Fe deficiency in a local variety of sorghum from a farmer's field near Karur, Tamil Nadu. The crop was destined for animal feed. A strong interveinal chlorosis is apparent in the plant's young leaves. Soil testing found a calcareous site with low Fe availability (2.8 mg/kg DTPA-extractable). Leaf Fe content of deficient tissue was 56 mg/kg while healthy leaves had 136 mg/kg.

Second Prize (US$200) – Iron Deficiency in Cereal Grass – Boopathi Raja, Tamil Nadu Agricultural University, Tiruchirapalli, Tamil Nadu, India. Taken at Anbil Dharmalingam Agricultural College and Research Insititute in Tiruchirapalli, Tamil Nadu, this Fe deficiency clearly shows the characteristic interveinal chlorosis on young grass leaves. The plant progressed to complete chlorosis with whole leaves become white. Soil at this experimental site had high pH (8.4) and exchangeable sodium percentage (19). Available soil Fe was 1.5 mg/kg (DTPA-extractable). Deficient leaf tissue had a Fe concentration of 15 mg/kg, which was lower than normal leaves (100 mg/kg).

Nitrogen Category

First Prize (US$150) – Nitrogen Deficiency in Potato – Bhushan Prakash Phadnis, IMT Technologies Ltd., Pune, Maharashtra, India. Taken near Machchiwara, Punjab, this example of N deficiency is a result of a farmer's decision to deliberately skip a soil analysis as means to reduce costs. The uniform pale yellow of matured leaves (chlorosis without necrosis) is very indicative of a N deficiency. The farm site had sandy loam soils with significant potential for nutrient loss through leaching. The farmer also only applied 25 kg urea/ha (12 kg N/ha) at the time of sowing. The crop is 35 days old at the time the photo was taken. Farmers usually apply urea + KCl 3 weeks after crop emergence.

Second Prize (US$100) – Nitrogen Deficiency in Maize – Arnab Pari, Bidhan Chandra Krishi Viswavidyalaya, Mohanpur, West Bengal, India. This photo was taken at a field experiment located near the village of Madandanga in Gayeshpur, West Bengal. This hybrid maize crop is in tasseling stage. The N omission plot had deficient plants with yellowing of leaves followed by stunting of growth. Total N concentration in deficient leaves was 1.35%.

Abbreviations and notes: N = nitrogen; P = phosphorus; K = potassium; Fe = iron; Zn = zinc; DTPA = diethylene triamine pentaacetic acid; DAP = diammonium phosphate; KCl = potassium chloride.

Phosphorus Category

First Prize (US$150) – Phosphorus Deficiency in Lentil – Onkar Singh, Command Area Development, Chambal, Kota, Rajasthan, India. This photo was taken from a pot experiment conducted by the Adaptive Trial Centre, Agriculture Research Station, in Kota, Rajasthan. Phosphorus deficient lentil plants were observed in the control treatment, which shows the purpling of lower leaves due to anthocyanin pigmentation and normal, green upper leaves. The P concentration in the plant tissue was 0.16%. The experimental soil had a pH of 7.8 and a low available P concentration of 12 kg/ha (Olsen extraction).

Second Prize (US$100) – Phosphorus Deficiency in Guava – U.K. Shanwad, University of Agricultural Sciences, Raichur, Karnataka, India. This photo of a one-year-old guava plant with P deficiency was taken at a farmer field in Raichur District, North Karnataka. The site had a soil with a pH of 7.7 and 8.2 kg available P/ha. Tissue testing of the affected leaf tissue determined a P content of 0.016%.

Potassium Category

First Prize (US$150) – Potassium Deficiency in Mango – S. Srinivasan, Tamil Nadu Agricultural University, Killikulam, Vallanad, Tamil Nadu, India. Taken near Tirunelveli, Tamil Nadu, this photo of a three-year-old mango plant shows a close-up view of K deficiency. The symptom was noticed during the dry season in trees grown on red soil with a pH of 5.6. The deficiency shows irregularly distributed yellow spots in the oldest leaves and necrosis at a later stage along the leaf margins. Under acute deficiency, the upper leaves can also show marginal chlorosis and necrosis. Potassium content in the affected tree was found to be low at 0.24%. The extractable K content of the soil was also low at 23 kg/ha.

Second Prize (US$100) – Potassium Deficiency in Soybean – Claudinei Kappes, Mato Grosso Foundation, Rondonópolis, Mato Grosso, Brazil. This K deficiency was spotted on the experimental station of the Mato Grosso Foundation near Itiquira city. Soybean was in R2 stage (full flowering). Soybean and maize had been cultivated at this site without K application for the last four years. Available soil K (Mehlich-1) was low at 24 mg/kg, while plant analysis recorded leaf tissue K at 1.6%.

Secondary and Micronutrient Category

First Prize (US$150) – Magnesium Deficiency in Coffee – Luis Fernando Cristancho Sierra, Federacion Nacional de Cafeteros de Colombia, Cundinamarca, Colombia. The photo is from a three-year-old plantation near Nilo, Cundinamarca. This Mg deficiency is characterized by interveinal chlorosis of the older leaves and productive branches. The crop was planted under highly acidic soil (pH of 4.1). Magnesium concentration and saturation in this soil were low at 0.12 $cmol_c/kg$ and 3.0%, respectively. Leaf tissue analysis reported a low Mg concentration of 0.20%. Besides the low soil pH, traditional fertilization that omits Mg, promotes the depletion of soil Mg.

Second Prize (US$100) – Zinc Deficiency in Maize – Saad Drissi, Hassan II Agronomy and Veterinary Institute. Rabat, Morocco. This photo of a Zn deficient maize plant was taken in northwestern Morocco just prior to crop harvest. The plant shows an example of severe Zn deficiency, marked by white bands between the midrib and the margin of leaves. Shoot Zn content at harvest was insufficient at 7.8 mg/kg. The soil was 89% sand with a very low amount of DTPA extractable Zn (0.13 mg/kg).

Soil Microorganisms Contribute to Plant Nutrition and Root Health

By Mark S. Coyne and Robert Mikkelsen

Soil microorganisms provide an essential function in nourishing and protecting plants. They also play a crucial role in providing soil, air, and water services that are absolutely critical to human survival. Understanding this linkage allows better nutrient management decisions.

Sustainable crop production is essential to a healthy and adequate food supply. At first glance, a healthy crop reveals only the above ground plant; the roots that support the visible plant are seldom seen.

But these plant roots grow in an incredibly complex environment, teeming with billions of soil organisms, particularly bacteria and fungi, which play a crucial role in promoting root health and maintaining an adequate supply of plant nutrients for crop growth.

There is still much to learn about the complex interaction between soil microorganisms and plant nutrition, but the importance of these relationships are now clearly recognized. Only a few of the key interactions between soil microbes and plant nutrition can be discussed in this brief summary.

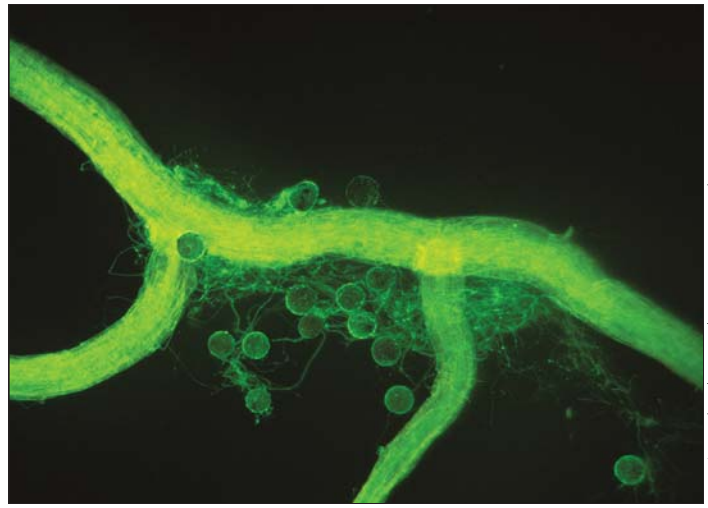
It has long been observed that plants conspicuously modify their soil environment by exuding large amounts of carbon from their roots. This rhizosphere zone becomes a biological hotspot in the soil. Adding carbon to the soil surrounding the roots leads to a huge increase in the number of microorganisms living within and outside the roots. These root exudates are composed of a complex mixture of low-molecular weight compounds such as amino acids, organic acids, sugars, and phenolics. Root mucilage, a carbon-rich gel layer surrounding the root tip, also provides a complex mixture of sugars, proteins, and enzymes to rhizosphere organisms. In some plants, as much as one-third to one-half of all the total carbon assimilated by photosynthesis can be transferred to the soil through the roots (Kuzyakov and Domanski, 2000).

As soluble carbon is released by roots, microorganisms are stimulated and colonize the soil surrounding the roots. This can result in competition for nutrients because plants and microbes rely on the same essential nutrients for growth.

Nutrients are Converted to Plant-Available Forms

Living organisms have a crucial role in controlling the transformations of plant nutrients in soil. In most soils, N, P and S are mainly present as various organic compounds that are unavailable for plant uptake. Understanding the role of microorganisms in regulating the conversion of these organic pools into plant-available forms has received considerable attention from soil scientists and agronomists.

Abbreviations and notes: N = nitrogen; P = phosphorus; K = potassium; S = sulfur; Cu = copper; Fe = iron; Mn = manganese; Mo = molybdenum; Zn = zinc.



USDA/Agricultural Research Service - Sara Wright

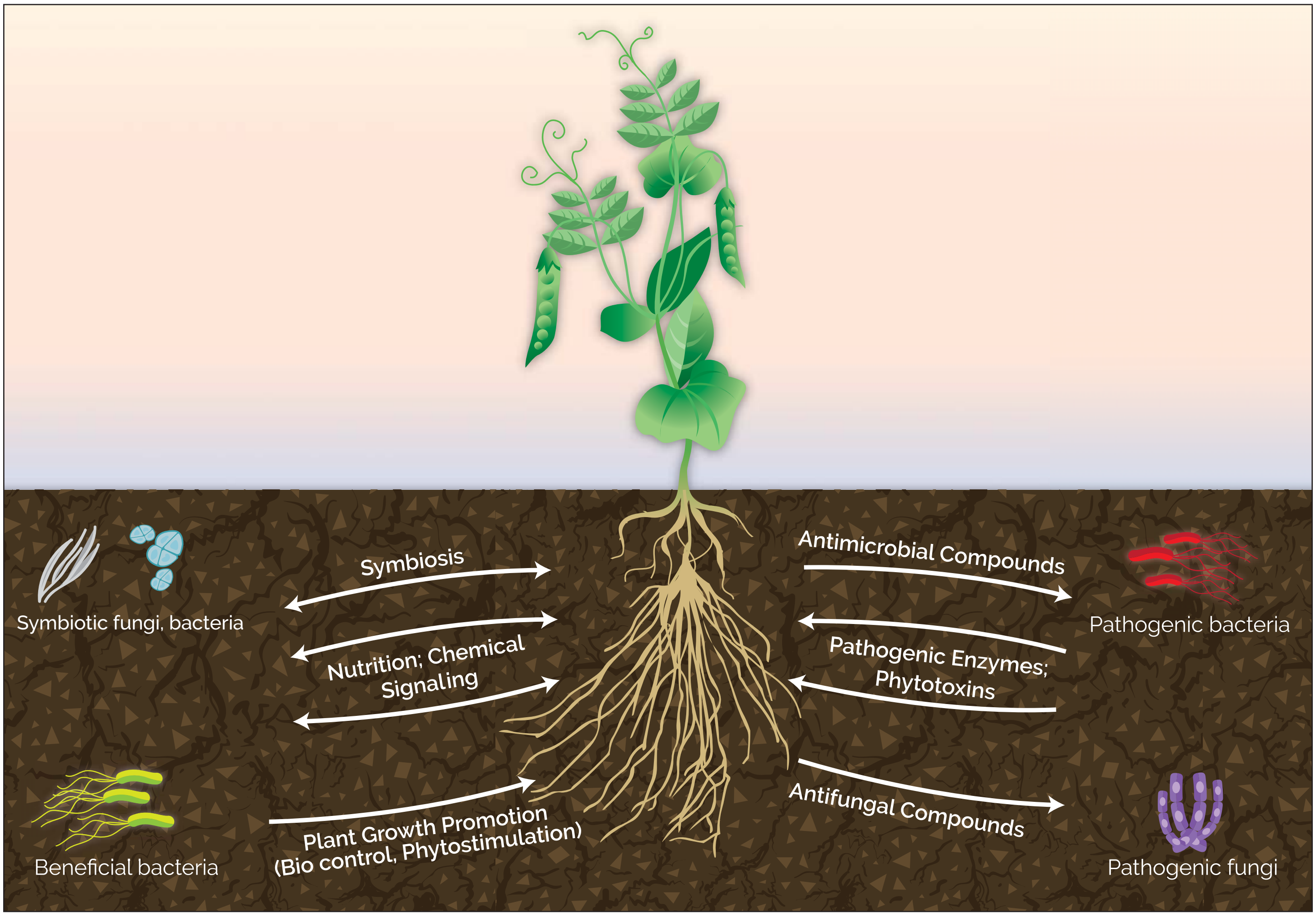
Glomalin, the substance coating this microscopic fungus growing on a corn root, can keep carbon in the soil from decomposing for up to 100 years.

The microbial conversion of nutrients into a soluble form takes place through numerous mechanisms (**Table 1**). Extracellular enzymes and organic compounds can be specifically excreted to solubilize plant-available nutrients from soil organic matter, crop residues, or manures. Organic acids released by microbes can dissolve precipitated nutrients on soil minerals and speed mineral weathering. Nutrients can be made more soluble (e.g., Fe) as microbes derive energy from oxidation and reduction reactions.

Management practices, including tillage, irrigation, residue placement, manure utilization, addition of specific biological inhibitors and stimulators, and inoculation are all commonly

Table 1. Selected examples of microbially mediated soil transformations that influence plant nutrient availability.

Nutrient	Microbial transformation
Nitrogen	Mineralization, immobilization, nitrification, denitrification, urea hydrolysis, N_2 fixation, extracellular protease and chitinase activity
Phosphorus	Mineralization, immobilization, extracellular phosphatase activity, acidic dissolution of mineral P, facilitated uptake by mycorrhizal fungi
Potassium	K solubilization
Sulfur	Mineralization, immobilization, oxidation, reduction, extracellular sulfatase activity
Iron	Change in oxidation state, production of siderophores, chelation
Zinc	Facilitated uptake by mycorrhizal fungi
Copper	Facilitated uptake by exudates and mycorrhizal fungi
Manganese	Change in oxidation state



Representation of the complex interactions that take place in the rhizosphere between plant roots and microorganisms (from Haichar et al., 2014).

used to influence these important microbial processes. Failure to account for soil processes such as mineralization and immobilization can result in excessive nutrient loss or in plant nutrient deficiency, with a significant reduction in crop yield or quality.

Nutrient Recovery is Enhanced

Mycorrhizal fungi are found in symbiotic association with the roots of 80% of land plants. Among the mycorrhizal fungi adapted for specific association with plant species are ecto-mycorrhizal fungi (especially woody plants), arbuscular mycorrhizal fungi (AMF, numerous crop plants), and ericoid mycorrhizal fungi. The AMF fungi penetrate the root cells and form an extension of the plant root system through hair-thin strands (hyphae) that extend into the soil. The small diameter of the fungal hyphae allows greater access to soil pores than roots alone, providing better utilization of water and nutrients, and maintaining root sorption activity in older parts of the root.

Mycorrhizal fungi can increase the supply of various nutrients to plants (including Cu, Fe, N, P, and Zn) in exchange for plant carbon. The boost in P uptake provided by mycorrhizal fungi is especially important for crops with high P requirements or for plants growing in soil with low concentrations of soluble P. Mycorrhizal fungi also release various enzymes to solubilize organic P and they can extract soluble P from the soil at lower concentrations than plant roots are able to do alone.

Nitrogen Fixation is Facilitated

Certain specialized symbiotic bacteria can fix atmospheric N_2 into ammonium-based compounds for plant nutrition. The most important of these organisms for agricultural plants are from the species *Rhizobium* and *Bradyrhizobium*. There are also symbiotic N_2 fixing bacteria (*Frankia*) that infect woody shrubs. An additional group of root-associated asymbiotic bacteria, such as *Azospirillum*, can provide some additional N to the roots of grasses such as sugarcane. It is estimated that N_2 fixation provides between 10 and 20% of the N requirement for cultivated crops and between 25 and 40% of the entire annual reactive N in the world.

Much work has been done to understand N_2 fixation and how to optimize its contribution to plant nutrition. This includes matching the proper bacteria inoculum with the correct host crop, and also optimizing soil conditions (such as providing adequate soluble P and Mo and adjusting soil pH) to increase the effectiveness of the symbiosis. A better understanding of the contribution of rhizosphere microbes to associative N_2 fixation is also needed.

Improved Soil Structure Promotes Root Growth

An often-overlooked contribution of soil microorganisms to plant nutrition is their enhancement of soil physical properties. Good soil structure enhances plant root growth and results in greater extraction of water and nutrients. For example, long-term trials at Rothamsted, UK show that less soluble P is required for plant growth when good soil structure is maintained.

Individual soil particles are bound into aggregates by various organic compounds (especially polysaccharides) released from soil microbes. Glomalin, a protein released by mycorrhizal fungi, binds soil particles and improves overall soil structure. The small hyphal strands of mycorrhizal fungi also contribute to improved soil aggregation by binding small particles together. More aggregation results in greater porosity, which often results in greater soil aeration and water storage capacity.

Pathogens are Controlled

There is growing appreciation of the link between soil microbes and plant pathogen control. Many reports show the benefits of soil microorganisms to improved plant growth and enhanced resistance to disease and stress. Soil bacteria that produce siderophores can deprive pathogenic fungi of Fe because fungal siderophores have less affinity for Fe. Various antibiotics have been identified in soil that can suppress pathogenic organisms. Certain bacteria can detoxify pathogenic viruses, while others can trigger "induced systemic resistance" in plants. Rhizosphere organisms can compete with pathogens for attachment to the plant root and essential nutrients for growth.

There is still much more to learn about how soil microorganisms improve the health of plant root systems and overall nutrient efficiency. Unfortunately, much research apart from the well-known microbial symbioses has failed to translate into measurable crop yield and quality benefits in the field. This is commonly because of insufficient soil colonization by the added microbes, the harsh soil environment to which these microbial additives are introduced, or the lack of an ecological niche that allows them to survive and fully function. Advances in rhizosphere engineering or improved manipulation of the soil environment may allow some of these potential benefits to be realized in the future.

Effects of Fertilizer on Soil Microbial Communities

Any management practice has the potential to influence soil microbial communities in positive or negative ways. For example, most mineral fertilizers added to soil consist of concentrated soluble nutrients that will impact short-term microbial activity. The concentrated salt around a dissolving fertilizer granule or band can cause temporary osmotic stress to nearby microorganisms until the nutrients diffuse into the soil. Similarly, the elevated pH surrounding the injection point of anhydrous ammonia will temporarily inhibit microbial activity.

The long-term effect of mineral fertilizer inputs on microbial processes was studied in a 160-year field experiment with contrasting fertilizer inputs at Rothamsted, UK. (Ogilvie et al., 2008). Balanced fertilization did not significantly influence the diversity of the bacterial population or two genes specific to important N transformations (N fixation and ammonium uptake).

A meta-analysis of world literature by Geissler and Scow (2014) reported that mineral N fertilizer application was associated with an average 15% increase in microbial biomass and 13% increase in soil organic carbon, compared with unfertilized control soils. They found that increases in microbial biomass were largest in studies with at least 20 years of fertilization. However, when the acidifying effects of nitrification were not addressed by liming (soil pH <5), microbial biomass was negatively affected.

Complex reactions with symbiotic and free-living microorganisms are necessary and normal for healthy crop growth. Soil microorganisms interact intimately with plants to stimulate productivity by supplying essential nutrients in a soluble form. Healthy plants in turn stimulate the microbial community of the soil through the root exudates they secrete and the organic residue they leave behind.

Better understanding the essential link between soil microbes and plant growth will allow more informed management decisions to be made for proper stewardship of soil resources and for sustaining acceptable levels of crop productivity.

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Soils and Plant Roots

By Robert Mikkelsen

Sustaining agricultural productivity relies on maintaining a soil environment to support the growth of healthy roots. Because roots are not immediately visible, their importance is often overlooked. A number of biological, chemical and physical stresses in the soil can impair root function and have an immediate effect on plant growth. Boosting water and nutrient use efficiency by roots is an important key for enhancing sustainable agricultural production. A few important root and soil interactions are highlighted here.

Plant roots have many important functions, such as supporting plants, providing sufficient surface area to allow water and nutrient uptake, and serving as the synthesis site for a number of hormones and growth regulators. Despite their importance, plant breeding programs largely focus on increasing yield and pest resistance, without much attention on incorporating potentially valuable root traits. Some of these key traits might include early root vigor, a high root surface area, and deep rooting ability during times of moisture stress.

Plant roots grow in a complex soil environment densely populated with organisms, including bacteria, fungi, yeasts, protozoa, and insects feeding on multiple substrates. In the rhizosphere soil are a variety of interactions occurring between plant and soil organisms—interactions that can be positive or negative for the root.

A significant amount of the C fixed through photosynthesis is allocated to support growing root cells. For example, between 5 and 30% of the plant C is released into the soil as organic exudates, symbiotic associations with mycorrhizal fungi can use an additional 20% of the C fixed in the leaves. Nitrogen fixation also requires substantial C resources (5 to 10 grams of C for each gram of fixed N). Maintenance of healthy roots requires a large investment of the total plant C.

In times of stress (such as drought or nutrient deficiency), plants generally respond by increasing the C flow to the growth of roots at the expense of the aboveground portion of the plant. This root stimulation increases the likelihood of exploring and exploiting the scarce soil resources, but may reduce the aboveground yield.

Root Growth and Development

Soils must provide sufficient support to anchor the plant for months or years and supply adequate nutrients, water and air from the network of pores. When the physical properties of soil are damaged, the ability of roots to support plant growth is impaired.

Soil compaction can be a major impediment for normal root growth. Compaction from tractor and machinery traffic is significant; especially as the size of farm equipment increases. Soil compaction causes a compression of the large soil pores, resulting in slower water infiltration, air movement, and root growth.

Roots must force their way through soil and only grow in existing pores or soils that are compressible. In compacted soil, roots become stunted if they encounter much resistance. Roots in compacted soils often have shorter overall length, a higher concentration of roots in the top layer of soil (above a hardpan), and fewer roots than normal at greater depth. These smaller root systems can decrease the capacity for water and nutrient uptake, resulting in more susceptibility to stress during the growing season.


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Since many plant nutrients have limited mobility in soil, roots must grow to the soil volume where the nutrients are located. Compacted soils result in reduced root growth and poor recovery of nutrients. For example, low root density in compacted soil results in a greater distance between neighboring roots, resulting in less opportunity to acquire nutrients.

Subsoil tillage can help alleviate root growth limitations, but avoiding compaction is preferred to eliminating it after it occurs. Tillage equipment is available to disrupt existing compacted soil layers, and using controlled traffic patterns in the field keeps wheel compaction in specific areas. Deep-rooted crops can also help to begin to alleviate compacted soils. No-till practices may provide gradual, long-term improvement of compacted soils.

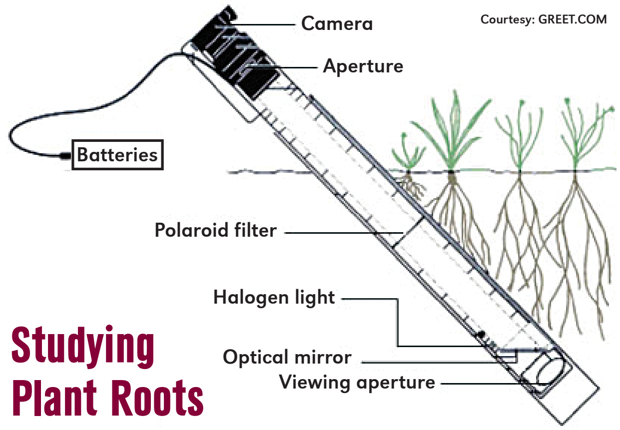
Nutrient Uptake by Roots

Roots develop in coordination with the overall vigor of the entire plant, as influenced by the soil environment. They invariably encounter environmental, chemical or biological stresses during the growing season causing them to rapidly adapt. For example, plants with root systems that are well suited to efficiently use resources in the surface layers of soil need to transform, through plasticity, to access soil moisture or nutrients from deep horizons to be successful during periods of drought.

Nitrogen: Nitrate is the dominant form of inorganic N taken up by most crop plants. One study found that 79% of N supply to maize roots came from mass flow, 20% by diffusion, and 1% by direct interception by roots (Watt et al., 2013). Early root vigor and a high root length density is a useful trait for intercepting nitrate as it moves with soil water before it might be leached below the root zone early in the growing season. When ammonium is a major N source, more soil exploration by roots may be advantageous since this N form is not highly mobile in soil water.

The important symbiotic relationship between roots of leguminous plants and N_2-fixing bacteria contributes to the N requirement of many important crops. A long-term goal for

Abbreviations and notes: N = nitrogen; P = phosphorus; K = potassium; Ca = calcium; C = carbon; Al = aluminum.



Studying Plant Roots

Plant roots have been traditionally studied by extensive digging projects to extract roots from the soil. In the last 50 years, the use of non-destructive techniques has made root studies more convenient and rapid. For example, a variety of rhizotrons and mini-rhizotrons (root windows) have been developed to observe root activity in soil without destructive sampling. Early rhizotrons consisted of glass walls placed on the face of a soil. Minirhizotrons typically involve installation of a transparent tube into the root zone lowering an imaging device into the ground.

In addition to direct observation and root measurement, there are many noninvasive root measurements that can be made directly on growing roots using microsensors and optical sensors.

scientists has been to understand the genetic controls that prevent non-legumes from serving as host for N_2 fixation.

Phosphorus: There is continued interest in improving the recovery and short-term efficiency of applied P fertilizer. Various agronomic practices help achieve this goal, but it is also feasible to accomplish increased P recovery by modifying the plant root architecture.

The concentration of soluble P is quite low in the soil, but plant requirements are fairly high. Because of its strong reactions with soil components, P is principally supplied to plant roots by diffusion. Young root tips, continually expanding into fresh soil, are exposed to higher P concentrations found in the bulk soil solution. The abundance of root hairs and association with mycorrhizal fungi also enhances P uptake from the soil. As P uptake occurs at the root surface, a depletion zone of 0.2 to 1.0 mm develops surrounding the root. This depletion zone around the root is a major driver of rhizosphere chemistry and nutrient availability.

Potassium: Roots take up K directly from the soil solution, which is in equilibrium with the exchangeable K and in a slow quasi-equilibrium with non-exchangeable K. Plant roots have specific mechanisms to acquire K. For example, K transporters and channels facilitate uptake under low a K supply.

The Role of Root Hairs

Root hairs are a major organ for acquiring water and mineral nutrients from the soil. They consist of single, tubular-shaped root cells that can extend up to 80 to 1,500 µm into the soil (approximately the thickness of a credit card). Individual root hairs typically survive for a few days or as long as two weeks. While new root hairs are being produced behind the root tip, older root hairs are dying off.

Root hairs facilitate nutrient uptake primarily by increasing the root surface area in contact with the soil and decreasing the distance that P must diffuse to the root. It is through the additional surface area provided by root hairs that the greatest proportion of P uptake occurs. It has been demonstrated that root systems with root hairs absorbed 78% more P than those without (Barley and Rovira, 1970). Plants growing in P-deficient soil frequently respond by increasing root hair length and density. Increased colonization by mycorrhizal fungi, which can extend up to several centimeters in P-deficient soils also accomplishes a similar result by transferring P to the root. Root hairs are also important for K uptake as they increase the root surface area and the K depletion zone in the soil.

Soil Acidity and Salinity

Soil acidity is one of the most important constraints for global crop production. Impaired plant growth in acid soils is not caused by a single factor, but includes toxicities of Al, H^+ and various nutrient deficiencies (such as Ca and P). The effects of elevated Al concentrations on roots first appear as shortening and thickening. Roots often become brown and branching is reduced as Al is accumulated. Some plant roots can detoxify excessive Al by excreting various organic acids to chelate Al. The application of limestone is the most widespread practice to overcome plant growth constraints in acidic soils. Adding limestone reduces the concentration of soluble Al in the soil by raising the soil pH, and supplies more Ca, which limits root activity when low. Gypsum is also useful as a Ca amendment in acidic soils.

Excessive salt concentrations are also a major constraint to plant growth in many important agricultural soils. Plant nutrients must be dissolved in the soil water before roots can take them up. However when salt concentrations become excessive, the water potential becomes equal to or below the water potential in root cells. Some plants can adjust to these high salt conditions, but many crop plants are not tolerant to osmotic stress so root cells and membranes become permanently damaged. Salt stress is often more visible in the leaves than the roots. Differences in salt tolerance among crops are primarily due to the varying ability of roots to exclude salts from uptake into the plant. Soil salinity is managed by leaching soluble salts from the root zone with additional water and providing adequate drainage to remove dissolved salts from the field.

Summary

Maintaining soil conditions conducive to healthy roots is fundamental for sustaining a secure food supply and promoting environmental stewardship. Enhanced efficiency of water, nutrients and resources is achieved when healthy roots lead to better crop growth. Without healthy roots, the yield potential of plants cannot possibly be met. Recent attention to the importance of various root functions will lead to an improved ability to manage productive cropping systems. BC

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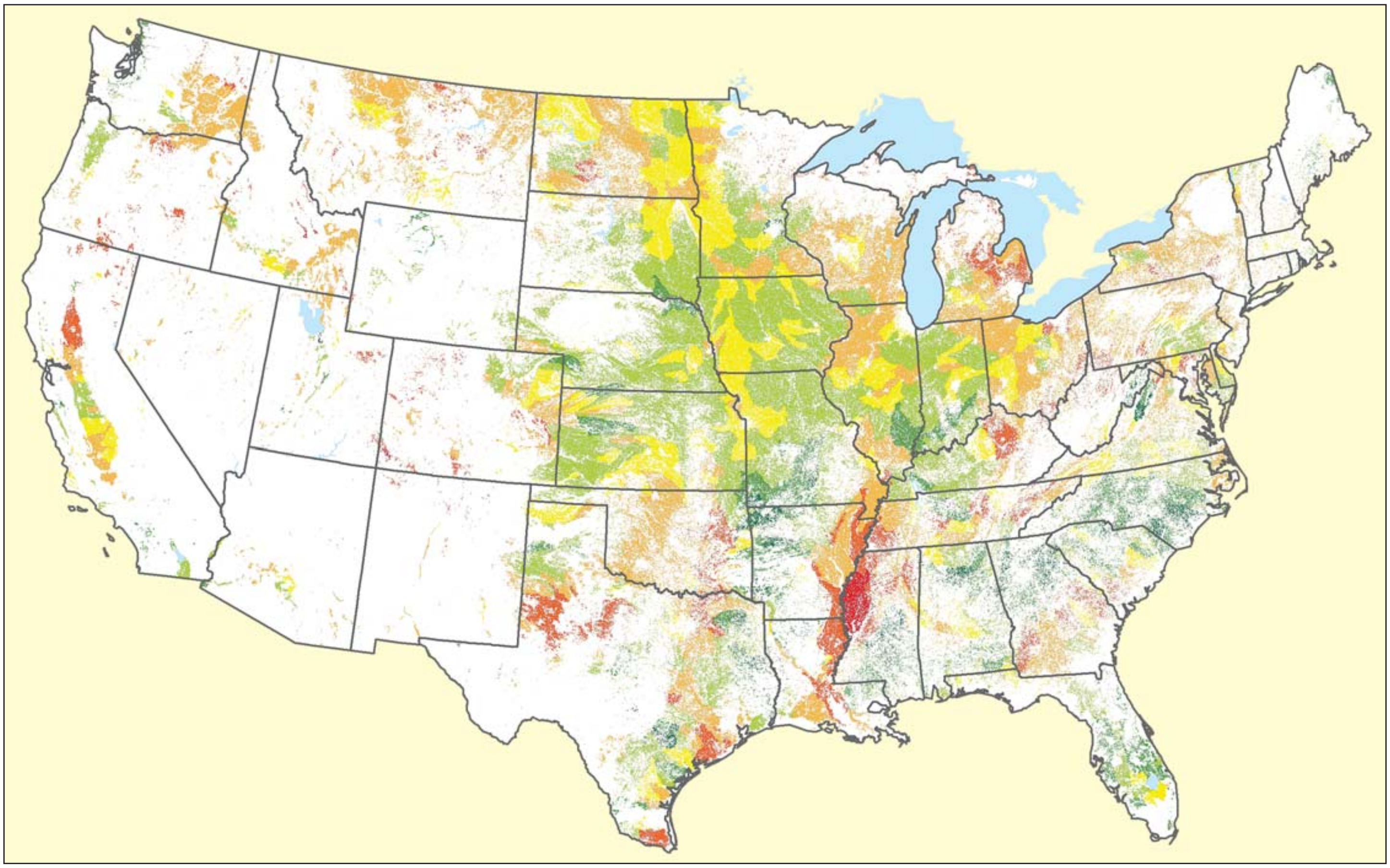
DATA UPDATE

U.S. Nutrient Use Geographic Information System (NuGIS)



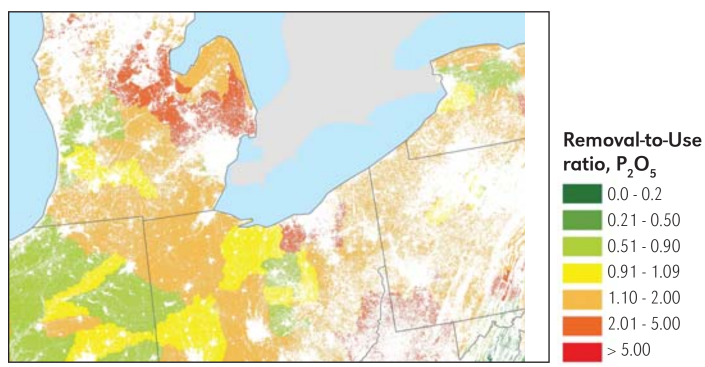
The two primary objectives of the NuGIS project are to assess nutrient use efficiency and balances for defined regions of crop production, and identify weaknesses in the balance estimation processes and the datasets used for these estimations. In the case of the U.S., the model predicts partial nutrient balance and nutrient removal-to-use ratios at county, state and watershed scales.

Sponsored and directed by the International Plant Nutrition Institute (IPNI), NuGIS integrates multiple tabular and spatial datasets to create county-level estimates of nutrients applied to the soil in fertilizer and livestock manure, and nutrients removed by harvested agricultural crops. Estimates coincide with the USDA Census of Agriculture years from 1987 to 2012. Geospatial techniques are used to estimate balances and efficiencies for 8-digit hydrologic units using the county-level data. The results are provided through interactive thematic maps and in tabular form.

In 2015, we added NuGIS analyses for more recent years, including non-Census years, and updated some previous years using improved input data.

Key improvements include:

- 2012 has been added as the most recent year of analysis
- Manure nutrient contributions have been updated based on recently released 2012 Census of Ag data. This currently affects 2010, 2011 and 2012 data. Data for 2008 and 2009 will be updated soon.



Estimated phosphorus removal-to-use ratio by watershed for 2012. Maps reflect Nutrient Removal by Crops / (Fertilizer + Recoverable Manure Nutrients + Legume N Fixation). Maps provided by PAQ Interactive.

- Higher resolution, recently updated land use maps for 2011 and 2012 are now being used to help fine-tune fertilizer input data for 2011 and 2012.
- For years 2010, 2011 and 2012, estimates of nutrient removal by crops are based on annual data rather than 3-year averages

NuGIS is freely available by registering at http://nugis.ipni.net/login

Comments and suggestions for improving this model or the web tool are welcomed and can be submitted by e-mail to nugis@ipni.net. BC

Soil Degradation in sub-Saharan Africa and Crop Production Options for Soil Rehabilitation

By Shamie Zingore, James Mutegi, Beverly Agesa, Lulseged Tamene, and Job Kihara

Soil degradation associated with poor soil fertility management practices is a major factor underlying poor agricultural productivity in sub-Saharan Africa. About 65% of the agricultural land is degraded, mainly due to low nutrient application, soil erosion and soil acidification. Increased fertilizer use and balanced nutrient management in combination with various organic matter inputs offer the best prospects to reverse soil degradation.

The Status and Implications of Soil Degradation

Soil degradation is a major challenge that threatens the sustainability of crop and livestock productivity systems worldwide. Soil degradation in cropping systems is driven by suboptimal management practices that induce declines in soil biological, chemical and physical quality, reducing the capacity of the soil to support production and environmental functions. The impact of soil degradation is most severe in sub-Saharan Africa (SSA), where about 65% of the land area is classified as degraded (Vlek et al., 2008). The occurrence of severely degraded soils is very high. It accounts for about 350 million (M) ha or 20 to 25% of the total land area, of which about 100 M ha is estimated to be severely degraded mainly due to agricultural activities. Soil degradation costs SSA approximately US$68bn per year and reduces the regional annual agricultural GDP by 3%. Soil degradation is recognized as a major factor underlying the low crop productivity and high prevalence of malnutrition in SSA (Sanchez, 2002), and affects the livelihoods of the majority of the population that depends directly on agriculture for food and income. Over the past five decades, yields of cereal crops in SSA have stagnated at less than 1.5 t/ha although the yield potential of most crop varieties exceeds 5 t/ha (FAO, 2010). For legumes, yields have stagnated at less than 1 t/ha, although the potential averages more than 2 t/ha. Therefore, as opposed to other regions of the world, the per-capita food production in SSA is decreasing, increasing the levels of food and nutrition insecurity and poverty. Some of the areas experiencing the most rapid degradation are very densely populated areas with favorable climate and relatively fertile soils in much of the highlands of eastern and central Africa (Smaling et al., 1997).

Types and Causes of Soil Degradation

The major soil constraints in SSA include soil acidity and Al toxicity, nutrient depletion, soil erosion, and shallow soils (**Figure 1**). The main factors driving soil degradation in SSA include water erosion, wind erosion, and deterioration of physical, chemical and biological properties (Muchena et al., 2005). Many of the processes of degradation occur concurrently with detrimental effects on biological productivity and the environment under smallholder farmer management practices. Physical degradation covers deforestation and exposure of the

Abbreviations and notes: N = nitrogen; P = phosphorus; K = potassium; Ca = calcium; Mg = magnesium; Al = aluminum; C = carbon; SOC = soil organic carbon; GDP = gross domestic product.

Land degradation associated with nutrient depletion and poor agronomic practices is widespread in sub-Saharan Africa.

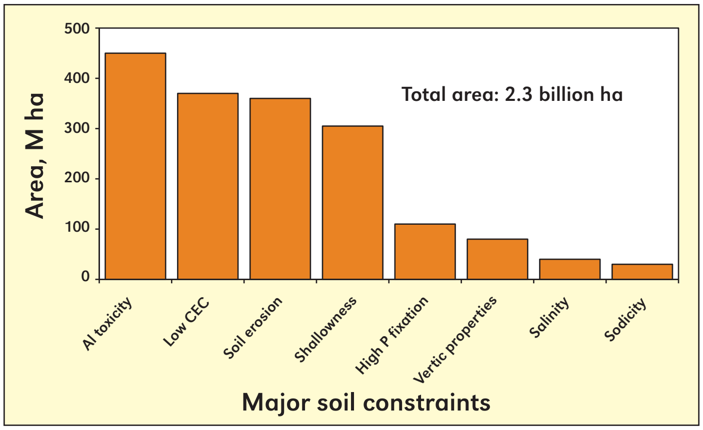


Figure 1. Major soil quality problems in sub-Saharan Africa and their distribution.

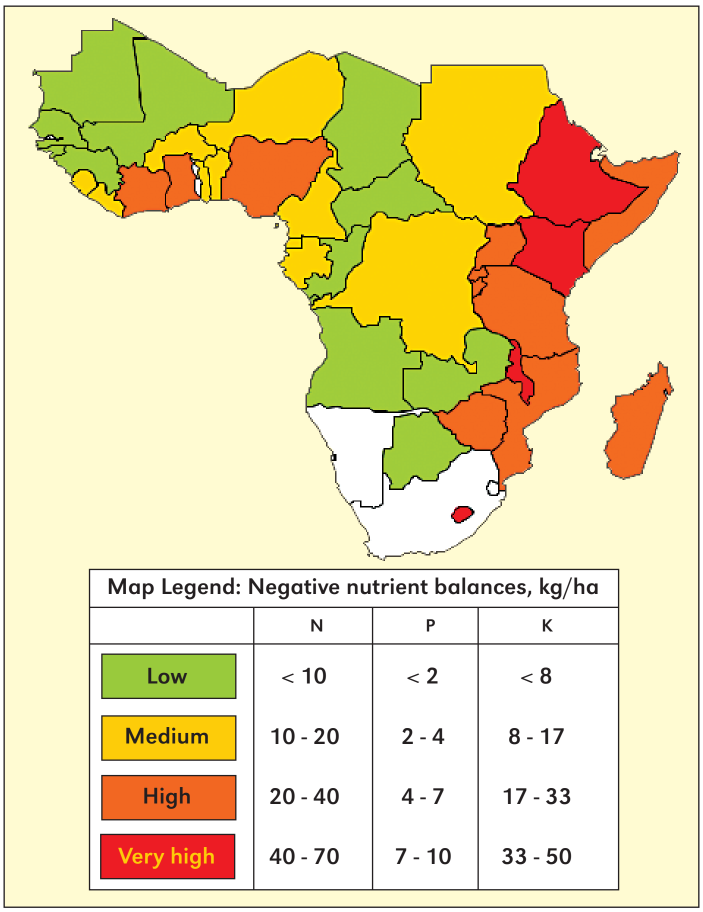


Figure 2. Country-level soil nutrient balances in sub-Saharan Africa.

soil surface to erosion, which leads to the loss of the fertile topsoil. Soil compaction, as a result of excessive soil tillage operations and animal grazing, results in poor crop rooting and water infiltration. Biological degradation is mainly connected to the decline of soil organic matter, which in turn impacts other soil biological, chemical, and physical processes and properties. Chemical degradation includes nutrient depletion and loss of organic matter, salinization, acidification, and chemical pollution.

Sub-Saharan Africa contains some of the oldest and most inherently infertile soils, with many areas characterized by low nutrient contents and soil organic matter, and are highly

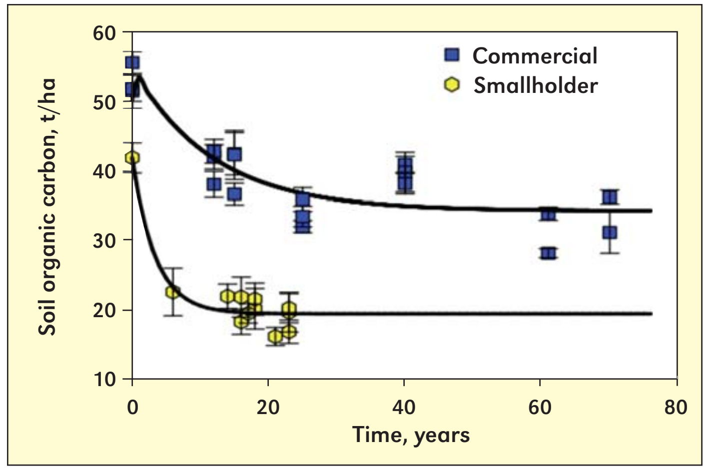


Figure 3. Long-term soil organic matter dynamics in smallholder and commercial farming systems in Zimbabwe (Adapted from Zingore et al., 2005).

susceptible to erosion. The fragile soils are exposed to soil degradation by limited use of both fertilizer (totaling less than 15 kg nutrients per ha) and organic nutrient inputs. Nutrient balances for SSA show overall large negative values, and losses of macronutrients at the country level estimated at 10 to 70 kg N/ha, 2 to 10 kg P/ha, and 8 to 50 kg K/ha annually (Stoorvogel and Smaling, 1998) (**Figure 2**). These large negative balances stem from over-exploitation of soil nutrient stocks as farmers use low levels of nutrients in both organic and inorganic form, coupled with removal of nutrients in harvested produce and losses mainly through erosion.

Long-term changes in soil organic matter and N stocks have been measured where native forestlands were cleared to pave way for food crop production. These soils have shown a rapid decline of >50% of soil organic matter in the initial 10 years of cultivation under low-input smallholder management due to small amount of fertilizer inputs, low crop productivity and removal of stover to feed livestock (**Figure 3**). However, commercial farming with intensive use of mineral fertilizers and incorporation of maize stover led to more gradual decline of soil organic matter. At equilibrium, contents of SOC in a clay soil were 15 t C/ha greater than the contents in similar soils on smallholder farms. Maize yields of 7 to 10 t/ha were sustained, highlighting the importance of good fertilizer management in maintaining yields and environmental sustainability. Low nutrient application and nutrient mining has direct consequences on poor crop growth and concomitant poor aboveground biomass to protect the soils from water and wind erosion, and declining soil organic matter because of limited crop residues available for recycling back to the soil. In studies carried out in central Kenya, soil losses by erosion were very high, up to 200 t/ha (Mutegi et al, 2008). A strong correlation between the rate of soil loss and maize productivity was observed, with maize productivity declining by up to 1.5 t/ha with increasing erosion (**Figure 4**), which represents a seasonal economic loss of more than US$300 per year.

Restoration of Degraded Soils

Lessons from the Green Revolution in other regions globally point to increased fertilizer use, improved crop varieties and irrigation infrastructure as key investments to increased

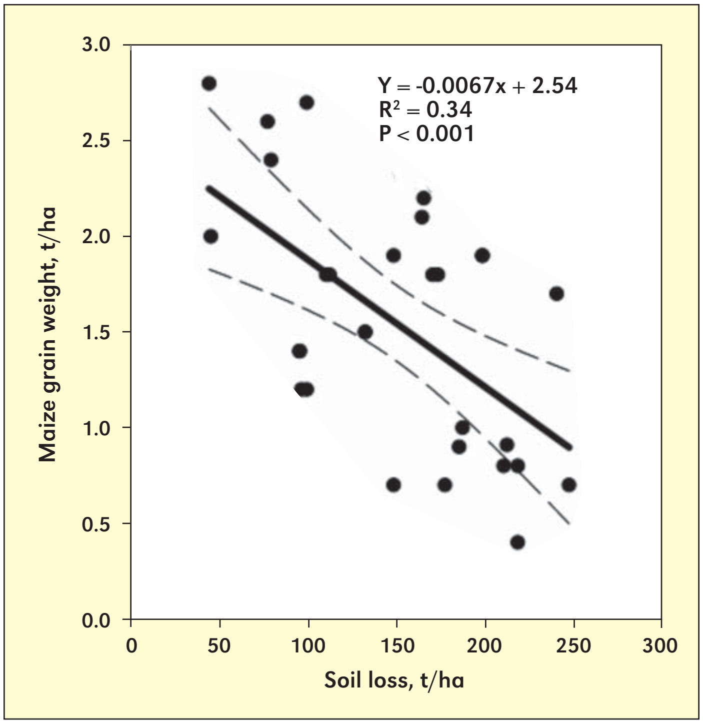


Figure 4. Relationship between soil losses and maize productivity in central highlands of Kenya (adapted from Mutegi et al., 2008).

crop productivity. In the SSA context, efforts to intensify crop production will first require rehabilitation of large areas of degraded soils. Although N and P are considered as the main yield-limiting nutrients in SSA, optimal productivity with N and P fertilizer is only possible in small areas with non-degraded soils. Increasing severity of soil degradation results in the progression of constraints to crop production, in turn increasing the complexity of soil fertility management options required to increase land productivity.

In moderately degraded soils, where multiple nutrient deficiencies are the overriding constraint, yields can be readily increased by balanced application of base cations (K, Mg and Ca) and micronutrients. Integrated soil fertility management (ISFM) provides a framework where both organic and inorganic fertilizers can be provided to the soils to improve soil fertility and boost soil organic C (Vanlauwe et al., 2010). Among the common ISFM practices in SSA are intercropping and rotation of cereals with legumes, manure application, and application of both organic and inorganic materials either simultaneously or sequentially to the same crops. The inclusion of legumes in cereal systems allows cereals to benefit from the N that is fixed by legumes. This enables better crop production, enhancement of soil fertility, and availability of more above and belowground biomass for transfer to the croplands. Furthermore, deep-rooting cover crops capture nutrients that leach and accumulate below the top soil, enabling recycling of nutrients when such cover crops are incorporated into the soil. With increased biomass production, crop residues become available to increase soil organic matter. The main limitations with use of compost and animal manures are low availability and poor quality. Application of the right quality and quantity of lime is also required in soils affected by soil acidity and Al toxicity.

A major challenge exists in restoring productivity of severely degraded soils that respond poorly to nutrient application due to multiple chemical, physical, and/or biological constraints interacting with each other. Under such conditions, multi-purpose options addressing several constraints have been shown to be able to rehabilitate non-responsiveness, but most of the time only after a number of years of increasing soil organic matter to increase retention of soil nutrients and water, improve soil structure, and improvement of soil health through increased soil biodiversity. Zingore et al. (2007) showed that on degraded sandy soils in Zimbabwe, annual application of fertilizer in combination with at least 10 t/ha of animal manure for three years was required to significantly increase crop productivity. Research on the use of biochar is still young, but there is potential to reverse degradation with its use, although this requires large amounts of organic resources that is still a challenge in SSA except in some localized zones (e.g., rice-growing areas).

Other legume-based technologies to restore severely degraded soils include deep-rooting hedgerow trees, green manures and legume crops adapted to marginal soil conditions; although these have also been shown to require multiple seasons to increase yields substantially. The dilemma for restoration of degraded soils in SSA is that the problem mostly affects poor farms with very limited access to fertilizer and manure. These farms have very limited land to spare for rehabilitation using technologies that do not contribute directly to food production. The potential to produce crops under degraded conditions is therefore a challenge. Although breeding of efficient genotypes may also be feasible, its potential to address food security under severe soil degradation where multiple limitations are at play, is not yet clear. BC

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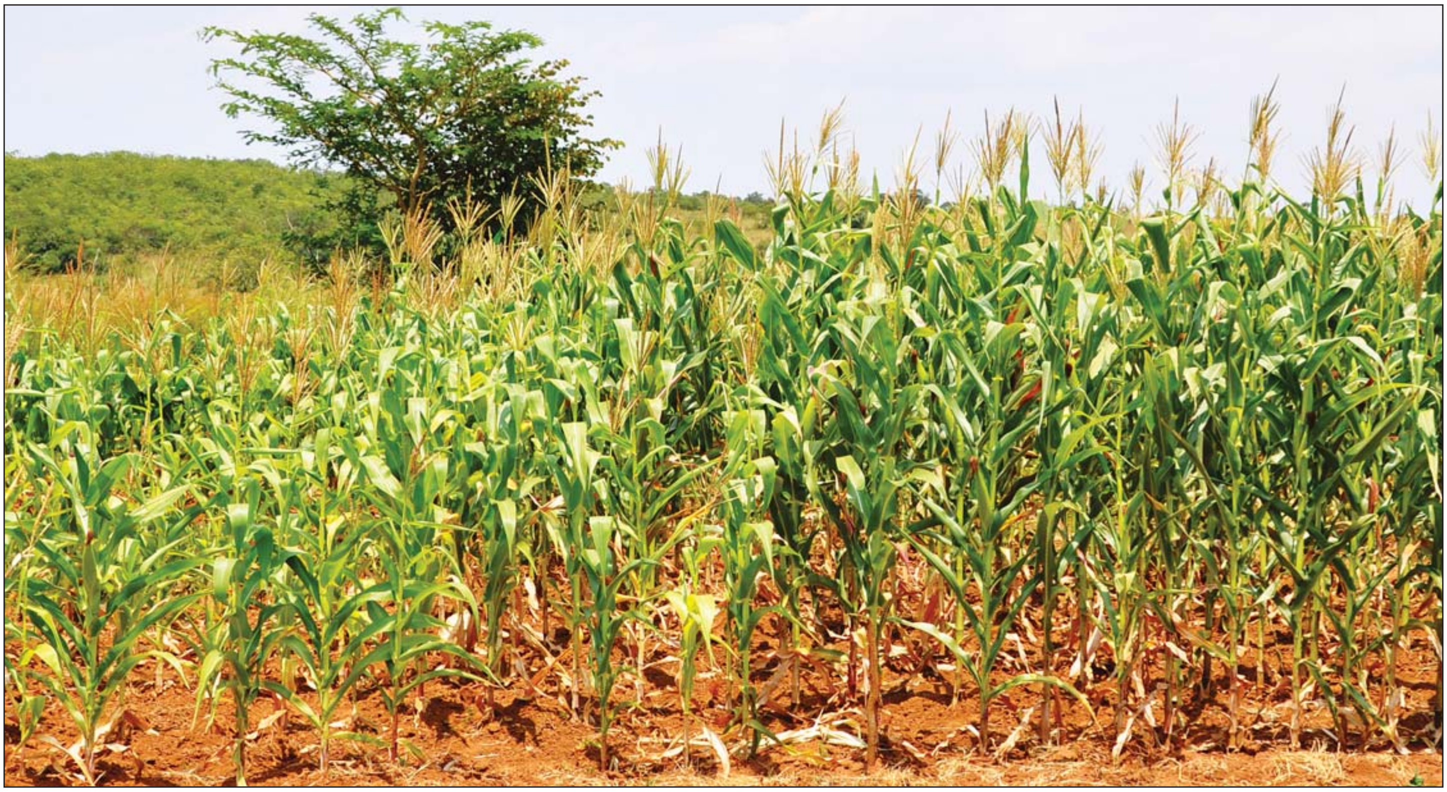
Sustainable Intensification to Protect Soil Resources

By Robert Mikkelsen



IPNI Photo/S. Zingore

Maize yield gap demonstrated in field experiment in Zimbabwe. Control plot on the left versus fertilized NPK plots on right.

Soils have a vital role in role in sustaining global food production, but soils also provide essential support for many other ecosystem services, such as storing and filtering water, sequestering greenhouse gases, processing waste materials, and hosting complex microbial and terrestrial life.

Threats of soil degradation place an increased urgency to protect and replenish soils. Experts calculate a need for 70% more food production by 2050 in order to feed the growing global population. Without improved stewardship of soil resources, it will be impossible to meet this expanding demand.

Leading farmer, scientific, and government groups are rallying around the principle of "sustainable intensification". This concept calls for increasing food production from existing farmland using methods that present less pressure on the environment.

The principles of sustainable intensification arise from the acknowledgement that there is an urgent need to increase food production. However, this goal is best accomplished by achieving higher yields from existing land instead of increasing the area of land under cultivation. It is clear that true food security can only be accomplished by simultaneously achieving environmental sustainability. It is important to recognize that there is no single way to achieve sustainable intensification, since it must be adapted to local resources and conditions.

Abbreviations and notes: N = nitrogen; P = phosphorus; K = potassium.

Table 1. Examples of factors commonly contributing to yield losses that hinder sustainable intensification (from Lobell et al., 2009).

Nutrient deficiency and imbalance	Water stress (drought and floods)
Weed competition	Insect damage
Plant disease	Inferior crop genetics
Improper planting	Soil limitations (such as salinity, acidity, compaction, etc.)

The concept of "Yield Gap" is used to measure the gulf between the most successful farmers (with minimal growth limitations) and the least productive farmers. There are numerous factors that account for yield gaps, but many opportunities exist to improve production by assisting lagging farmers to use their soil, water, and other resources more efficiently (**Table 1**). One recent global assessment of yield gaps found that nearly three quarters of underachieving areas could significantly close their current yield gaps by focusing on appropriate nutrient inputs (**Figure 1**).

Soil scientists and agronomists understand that a shortage of any one of the essential plant nutrients will be detrimental to crop growth and yield. With our advanced knowledge of plant nutrition, nutrient management, and the abundance of excellent fertilizer materials, it is imperative that this single largest cause of yield gaps be promptly addressed.

Comprehensive soil stewardship practices need to be widely implemented if the goals of sustainable intensification are to be met. Some of these practices include keeping the soil covered for as much of the year as possible, using a

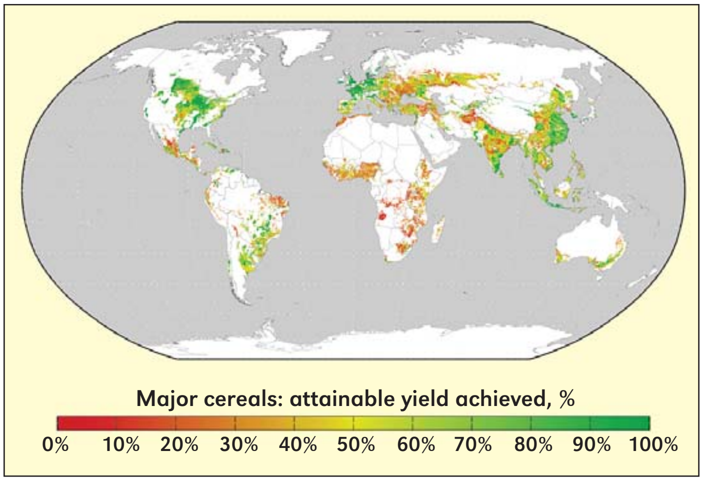


Figure 1. Average yield gaps for maize, wheat and rice. Measured as a percentage of the attainable yield achieved circa the year 2000. Yield gap in each grid cell is calculated as an area-weighted average across the crops and is displayed on the top 98% of growing area (from Mueller et al., 2012).

minimum amount of tillage, using appropriate crop rotations, implementing integrated nutrient management techniques, eliminating growth-limiting soil restrictions (such as acidity or salinity), and adopting erosion prevention and water conservation practices.

The challenge of producing sufficient food while decreasing the environmental impact of agriculture requires a careful reexamination of current practices. Using soil resources to their full potential and preserving vital soil functions demands multi-disciplinary engagement. Many of the tools needed to close existing yield gaps are already developed. The call to action is to now implement sustainable intensification so it benefits humanity in a global context. BC

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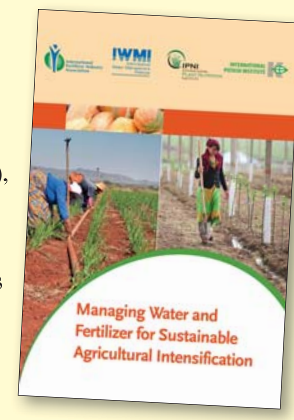
NEW PUBLICATION

Managing Water and Fertilizer for Sustainable Agricultural Intensification



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This is a reference guide to improve general understanding of the best management practices for the use of water and fertilizers throughout the world to enhance crop production, improve farm profitability and resource efficiency, and reduce environmental impacts related to crop production.

For a hardcopy, please contact IPNI Circulation at circulation@ipni.net. A free pdf download of the book is available from IPNI at http://info.ipni.net/IPNI-3392.

CONTENTS

Applying 4R Nutrient Stewardship Principles in Precision Soil Management

By Brian Arnall and Steve Phillips

The goal of every land manager is to be as efficient and productive as possible. In other words, obtain maximum output with minimum input. As we explore the application of the 4R's in soil management, it becomes apparent that application of the 4R's can be closely linked with many existing precision agriculture (PA) technologies.

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By definition, precision means "being precise" or a "measure of exactness" regarding some practice. This definition perfectly describes what we are trying to accomplish at the core of 4R Stewardship in selecting the right source, rate, time, and place. In fact, multiple published sources define PA as "applying the right input at the right time and in the right place". Many people tend to think only of high-tech gadgets, satellites, and computers when defining PA; but in reality, PA is about using site-specific information to better equip advisors and growers to make knowledgeable management decisions and achieve more efficient and effective use of inputs. In some cases, technologies such as auto-guidance and variable-rate applicators makes this process easier, while in other cases low tech decision support tools, like leaf color charts and Nutrient Expert®, just as effectively increase knowledge and reduce the risk of mismanagement. Also important within 4R Stewardship is the dynamic feedback mechanism among stakeholders. The information management strategies common to PA greatly enhance this component of 4R. From immediate feedback to the operator to credibility in reporting to policy makers, PA makes it possible to go beyond "telling" someone that we are making the right decisions on the farm, but to "show" them.

Abbreviations and notes: N = nitrogen; P = phosphorus.

It's the connection between the science of the 4Rs and the tools and technology in PA that enhances the opportunity for producers and land managers to meet their sustainability goals and to achieve their management objectives.

For example, selecting the right nutrient source can have tremendous impact on the uptake efficiency by the plant, negating potential loss pathways, and timely delivery of essential nutrients. One group of nutrient source technologies that are widely used to meet these needs are those found in enhanced efficiency fertilizers. While marketed largely as a source solution, these products embody the interdependency of the 4Rs. By keeping the nutrients in plant-available forms and protecting them from various loss mechanisms in the field, the source can affect the ideal application rate (in some cases lowering it slightly due to higher uptake efficiency), application timing (lower risk of nutrient loss following preplant or early season applications), and nutrient placement (incorporation of the source is not as critical when volatilization and runoff are not a concern).

Choosing the right fertilizer rate of any nutrient is challenging due to temporal variability and spatial variability of nutrient availability and crop demand. The Stanford equation, which has been historically used to determine N fertilizer rate, states that N rate = [(N uptake by the plant – N contributions from the soil) / fertilizer use efficiency]. From the outside looking in this is a very simple calculation; however, each variable included in the equation is affected by variability in the field, creating challenges to be faced by the producer. First, N uptake is driven by yield. While the yield targeted by the producer tends to remain constant, the actual yield achieved can be vastly different from one year to the next, especially for rain-fed farming. In a long-term wheat fertility study conducted in Oklahoma, grain yields from the past ten years averaged 53 bu/A with a yield range of 31 to 88 bu/A (**Figure 1**). The economical optimum N rate for these five years ranged from 20 to 100 lb N/A, representing a nearly 2x swing in agronomic efficiency during the ten year period, due solely to temporal variability that could not have been predicted prior to the growing season. Today producers have access to a suite of in-season tools to help them select the right fertilizer rate. The use of large regional response databases tied to specific soils and environment, multiyear analysis of yield monitor data, crop and weather models, tissue testing, and sensors that measure plant status are all methods currently used to optimize fertilizer rate recommendations.

Establishing multiple management zones within a field based on some combination of factors is a well tested, commonly used way to address spatial variability. However, even when using the best science to identify where fields need to be treated differently, equipment limitations have prevented producers from treating spatial variability in soil nutrients at the resolution at which they existed. Oklahoma State University Extension Machinery Specialist, Dr. Randy Taylor points out that we (farmers) have been variable rate applying N for years, just not always at the grower's discretion. For example, anhydrous ammonia applicators commonly used over the past few years would often result in N delivery rates varying across the applicator and throughout the day as temperatures rise during the day and sink again in the evenings causing pressure changes within the tank. Today's advanced equipment not only allows for uniform rate across the applicator, but also allows for dynamic rate changes as the applicator travels through the field following either a prescription map or on-the-go technologies, such as crop sensors. Current variable rate technologies grant producers the ability to achieve the right fertilizer rate in all areas of the field.

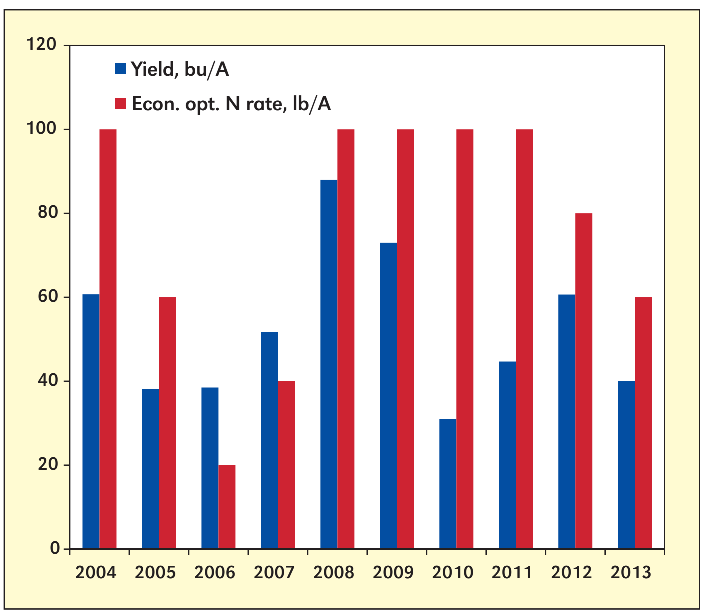
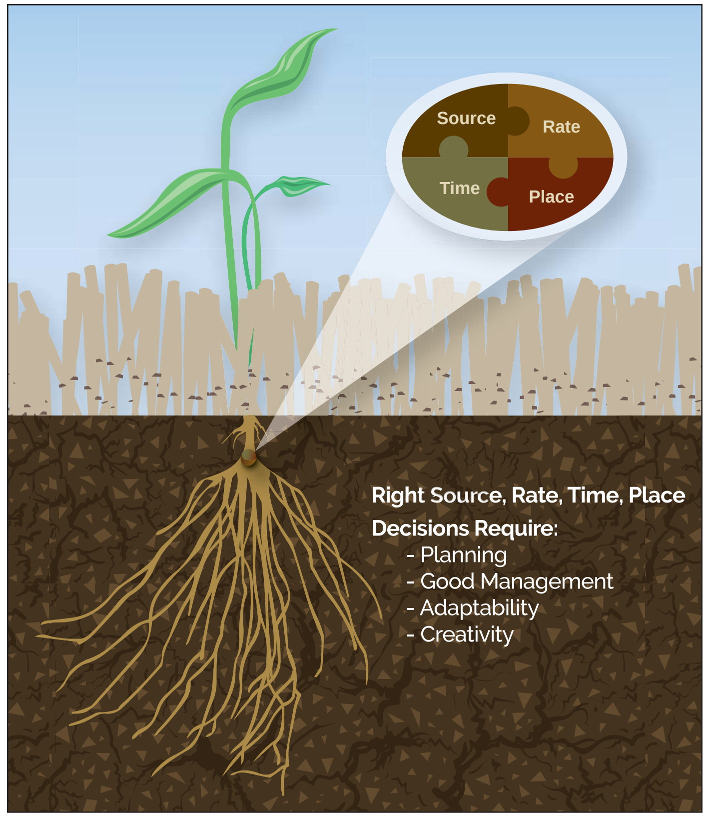


Figure 1. Wheat grain yield (bu/A) at the economical optimum N fertilization rate (US$/A) derived from the long-term winter wheat fertility study located near Lahoma, Oklahoma. Economical optimum calculated as (Yield x 6.00) – (N-rate x 0.60). Nitrogen rates evaluated ranged from 0 to 100 in increments of 20. Only plots received balanced P and K rates were evaluated (from unpublished data).



The science of 4R Nutrient Stewardship supports the implementation of precision agriculture through an integration of our knowledge of factors controlling nutrient supply.

Ideally, the right time to apply nutrients will correspond with plant uptake and occur over the entire growing cycle of the crop to ensure that the applied nutrients are neither lost to the environment nor bound organically or chemically in plant unavailable forms. Much like the case for accurate rate delivery, improvements in machinery have allowed producers to be more flexible with nutrient timing by affording them the ability to cover ground more quickly and over taller crops. Applicators have been engineered with tool bars to coulter inject while having six foot of clearance, while high clearance sprayers equipped with drop nozzles can pass through a corn field at tasseling. Variable rate irrigation is a technology that has enhanced the science of fertilizer timing by giving producers the ability to spoon feed nutrients to the crop throughout the growing season. Many producers have found that by using fertigation they are able to fine-tune their fertilizer rate, timing, and placement to improve nutrient use efficiency.

The right place can also have implications on the efficiency of nutrients applied. For immobile nutrients such as P and many of the secondary nutrients, the placement of the fertilizer in bands greatly increases the fertilizer use efficiency by improving root interception and slowing the rate in which the nutrient becomes plant unavailable through chemical reactions. The placement of the fertilizer below the surface reduces losses from runoff, volatilization, and immobilization in crop residue. In the past, no-till producers were challenged by fertilizer application as the majority of the equipment available to incorporate fertilizer caused significant soil disturbance. However, the introduction of low disturbance applicators have allowed no-till producers to incorporate fertilizer with little loss of surface residue. These same applicators can also be used to incorporate top-dress N in wheat without damaging the crop, thus giving growers yet another option for merging the right time and the right place.

By implementing 4R Nutrient Stewardship practices, producers are able to maximize yields, optimize fertilizer efficiency and minimize environmental impacts. The implementation of 4R Nutrient Stewardship requires significant planning, good management, ability to adopt new ideas, and a bit of creativeness. Many of the PA technologies available today aid in our goal to be the best stewards of the land. A successful PA program must be based on sound agronomic science, such as the fundamental principles that guide 4R Nutrient Stewardship. BC

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Soil's Year in the Sun

They say everyone gets their 15 minutes of fame …their moment in the sun. This year, 2015, has been declared by the General Assembly of the United Nations as the International Year of Soils, a credit that seems long overdue.

A year seems hardly enough time to celebrate the fundamental contribution of soil, which is a resource so essential to the development and support of life on this planet of ours. For society at large, we are of course, where we are today because of the quality of our soils. Soils have fostered life, fed billions, and they have protected our environments. How we manage our soils has been an integral part of our great successes…and failures. We've depended on farmers and their daily relationship with soil for thousands of years.

So it has taken a few thousand of years for us to organize ourselves to the point where we can dedicate an entire year to celebrating soils. Yes, it's about time, but perhaps the timing is perfect. We have a great opportunity to promote our science of agronomy to those who might be examining for the first time with fresh, inquiring eyes, how agricultural production is accomplished today. In fact, this is one of the primary goals of the UN declaration, to "raise awareness among society and decision makers about the profound importance of soil for human life."

Activities related to the International Year of Soils are going to keep the contribution of soils in the forefront of our minds this year. Our experience in the field provides us with lots of good stories to highlight from across the globe, which can demonstrate the effectiveness of the many regionally-adapted techniques farmers use to manage and improve their soils.

So when 2015 is over and soil's time in this limelight is done, what should you do next as a manager of soil? Lets try to keep the ball rolling and maintain these new connections we've gained through this international effort. Lets keep them tuned-in on what is happening now, or is about to happen, down on the farm.

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