BETTER CROPS
WITH PLANT FOOD

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Advancing the Science of

Ecological Intensification

for Maize-Based Cropping Systems

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BETTER CROPS WITH PLANT FOOD

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Our cover: Looking through a field of maize.
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CONTENTS

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Fertilizer Industry Round Table

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Ecological Intensification of Maize-Based Cropping Systems

By Kenneth G. Cassman

Ecological intensification (EI) is the process of improving both yields and environmental performance of crop production with a focus on precise management of all production factors and maintenance or improvement of soil quality.

Innovation and adoption of EI practices will be facilitated by use of "big data" that farmers themselves generate, coupled with a robust spatial framework to identify cohort fields that respond similarly to these innovations.

Maize and soybean research plots at IPNI Global Maize Project site in Mato Grosso, Brazil.

The terms ecological intensification (EI) and sustainable intensification (SI) were first coined in the late 1990s (Cassman et al., 1999; Pretty, 1997). A unifying objective supporting each of these concepts is the need to increase crop yields per unit land, time, and consumable resources used in food production. Whereas EI was originally seen as essential to achieve the dual goals of meeting projected food demand on existing farm land while minimizing negative impacts on environmental quality and conserving natural resources, SI was originally concerned mostly with "regenerative", low input agricultural options as the means to reduce negative impacts of agriculture on ecosystem services. Since then, general understanding of SI has come closer to that of EI in terms of the underpinning objective of producing enough food to supply a climax human population of 9.5 to 11 billion people without degrading the environment or exhausting the natural resource base upon which agriculture depends. The primary difference between the two is that SI includes economic and social dimensions of sustainability whereas EI focuses on biophysical aspects.

Why is Ecological Intensification Important for Maize Systems?

Ecological intensification is especially relevant for addressing global concerns about conservation of biodiversity and mitigating climate change because conversion of natural ecosystems to farmland has devastating impact on both (Burney et al., 2010; Laurance et al., 2014). For example, since 2002 crop production area has been increasing at the fastest pace in all of human history in response to rapid growth in demand for livestock products, grain, and oilseed crops. During the 2002 to 2014 period, harvested crop area increased by more than 13 million (M) ha annually (32 M Ac/yr), and increased production of maize and soybean accounted for 52% of this total (**Figure 1**). Because projected demand for maize and soybean in coming decades is not expected to slow, the explicit goal of accelerating yield gains in maize and soybean on existing farmland is an essential component of efforts towards wildlife conservation and climate change mitigation.

But if accelerating yield gains leads to amplification of negative environmental impact, beyond current levels that already are of concern, the path to food security is not sustainable. Therefore, progress towards EI requires simultaneous improvements in *both* yields and environmental performance. In most cases the productivity and environmental dimensions cannot be investigated separately because few "trade-off free" options exist. There are many management options that can increase crop yields while also resulting in greater negative environmental impact, and many that can reduce environmental impact with a yield penalty. For example, converting from

Abbreviations and notes: N = nitrogen.

conventional tillage to no-till often results in substantial reduction in erosion and improved soil quality. In wetter regions of the U.S. Corn Belt, however, no-till makes it more difficult to achieve timely sowing and gives less uniform plant stands that reduce crop yields and decrease yield stability.

How to Achieve Ecological Intensification

The original vision of EI identified three key elements: (1) closing the exploitable yield gap, (2) improving soil quality, and (3) precision agriculture (Cassman, 1999). The *exploitable* yield gap for a given field or region is defined as the difference between the current yield level and 75 to 85% of the yield potential (either rain-fed or irrigated) for that field or region as can be simulated with a well validated crop model (van Ittersum et al., 2013). Variation in the exploitable *ceiling yield* (i.e., 75 to 85% of the yield potential) reflects the degree of risk associated with use of additional inputs needed to move yields up the response curve beyond 75% of the potential yield, and the ratio of commodity price to input costs (Lobell et al., 2009). For crops in which ripening grain is located at the top of the canopy with high center of gravity, such as rice and wheat, applying sufficient N to achieve 85% of yield potential can often result in lodging and reduced grain yields and quality. For these crops, the exploitable ceiling yield may be at the lower end of the 75 to 85% range. In contrast, maize ears are located in the middle of the stalk and have relatively low center of gravity, which means less susceptibility to lodging and the exploitable yield ceiling is likely closer to 85% as suggested by a recent study based on famer-reported data (Grassini et al., 2011a). Other risks typically associated with management that seeks to push yields to the high end of the exploitable ceiling yield range include greater disease and insect pressure that occurs in lush canopies.

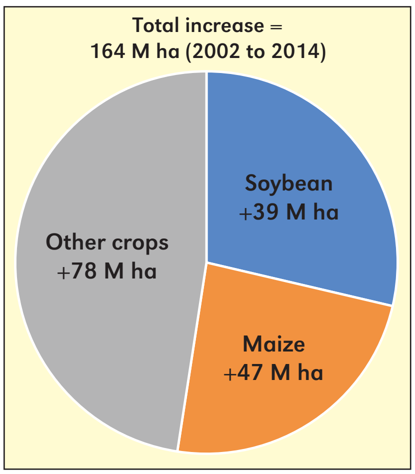

Figure 1. Global increase in harvested staple food crop area from 2002 to 2014, including cereals, oilseed, pulses, root, and tuber crops in million hectares (M ha). Source: FAOSTAT http://www.fao.org/faostat/en/#data/QC

Improving soil quality is the second cornerstone of ecological intensification. For this purpose, soil quality is defined by those soil properties that have greatest impact on crop yields and input use efficiencies. These include soil chemical properties that determine nutrient supply capacity, stimulate or constrain root growth and plant health; biological properties that govern microbial and faunal populations that decompose crop residues and organic matter to release N, P, and S, suppress pathogens and insect pests, fix atmospheric N_2, and symbionts that help acquire P and other nutrients; physical properties that govern aeration, water infiltration rate and storage capacity, root extension, and rooting depth.

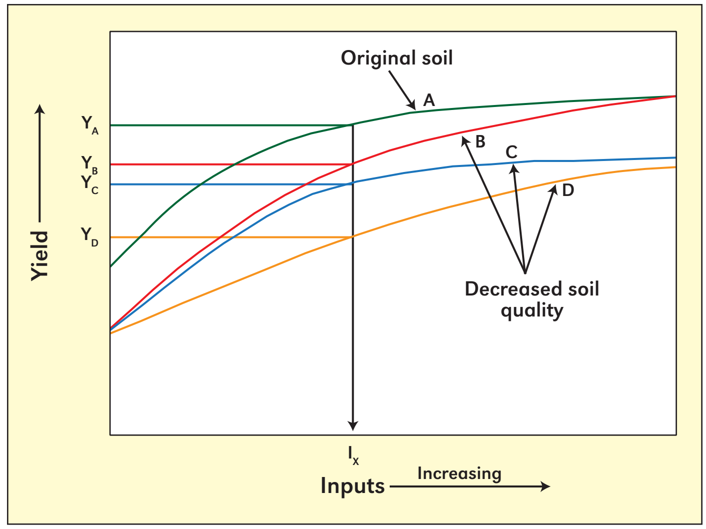

Figure 2. Conceptual framework illustrating the relationship between crop yields and input requirements as influenced by soil quality. A decrease in soil quality from an initial state (curve A) can result in the need for greater inputs of energy, nutrients, water, seed, and pest control measures to achieve the same yield. The slope and asymptote of the shifted response (shown by curves B, C, and D) depend on the type of soil degradation and result in reduced input use efficiency, yield potential, or both. (Cassman, 1999).

An underpinning assumption is that a change in soil quality affects the relationship between yield and input requirements (**Figure 2**). A reduction in soil quality means that increased external inputs are needed to overcome this degradation. Conversely, an increase in soil quality reduces input requirements and thus increases input use efficiency. For example, a management system that leads to an increase in soil organic matter can also bring greater N supply from mineralization and a smaller requirement for applied N, thus increasing the yield per unit of applied N. Likewise, a reduction in soil organic matter can lead to greater requirements for applied N per unit of yield.

Precision agriculture, in a broad sense, is the third cornerstone. In large commercial production fields, it involves variable-rate, or zone management of inputs such as seed, fertilizer, lime, irrigation, and pesticides. In small fields typical of crop production in many developing countries of Africa and Asia, it involves field-specific management with a focus on precise timing and quantities of applied inputs on a field by field basis rather than by routine, blanket recommendations across a district or county.

Metrics for Measuring Progress Towards Ecological Intensification

The conceptual framework of **Figure 2** leads to a focus on yield and input use efficiencies as the basis for monitoring progress towards EI. Thus, for any point in time, the goal is to move average yields up while also improving the ratio of outputs to inputs for nutrients, water, and energy. Some have criticized this focus as being too narrow for two reasons. The first argues that a focus on yield and output/input ratios does not give enough emphasis to the "*ecological*" dimensions of EI with the goal of better leveraging internal resources, as opposed to use of purchased inputs of external origin, through attention to management of microbial, floral, or faunal components of the agroecosystem. At the end of the day, however, such systems must also be shown to result in higher yields and greater input use efficiency or they would not meet the definition of EI. *Indeed, EI is agnostic with regard to farming methods and approaches to achieve the dual goals of increasing yields while decreasing negative environmental impact so long as the approach is also economically viable and socially acceptable.*

A second concern with the conceptual framework of **Figure 2** is that a focus on soil properties influencing crop performance is too myopic and ignores other important ecosystem services that soils provide, such as: (1) habitat for an enormous host of biota including bacteria, fungi, protozoa, nematodes, worms, insects, arachnids, and such, (2) water storage to capture rainfall and reduce runoff and flooding, (3) pollutant filtering and detoxification to protect water quality, and (4) regulation of atmospheric composition through release, capture, or retention of carbon dioxide, methane, and nitrous oxides—each a powerful greenhouse gas. However, it is difficult to conceive of a soil property, that if improved for its capacity to contribute to higher yield and input use efficiency, would not also maintain or improve each of these four ecosystem services. Hence a focus on yield and input use efficiencies as the metrics for monitoring progress towards EI is not likely to result in unintentional degradation of the broader array of ecosystem services that soils provide.

The Path Forward

At issue is how to accelerate innovation and adoption of technologies and cropping systems that support EI of maize-based systems. For the high-yield, large-scale, mechanized systems of the U.S., Brazil, and Argentina, the challenge is how to efficiently identify the suite of management practices that perform best under the location-specific conditions of a given field or zone within a field. The number of production factors that must be considered is large, including variety or hybrid, seeding rate, sowing date, tillage method, nutrient quantities-formulation-amounts-placement-timing, weed, insect pest, and disease control measures, use of organic nutrients, lime, and other soil amendments, and crop rotation. The sad fact is that conventional, replicated field experiments are a poor vehicle for evaluating and fine-tuning multiple, interacting factors because of the time and cost requirements of such work. For example, to identify the most appropriate seeding rate, N fertilizer amount and timing, and tillage method for maize in a specific region would require a multi-factor experimental design, with at least four replications of each treatment at each location, and four to six locations over several years. And the results of such a study would be biased by the other management factors selected as the "background" management approach (e.g., sowing date, pest control, variety or hybrid used, crop rotation, and cover crop options).

Given this complexity, there is growing excitement for use of "big data", which includes high spatial resolution data for long-term historical daily climate records coupled with real-time data on current and short-term weather forecasts, yield records and immediate soil and plant status with regard to water and nutrient status, and plant health. To be effective however, big data needs a robust analytical framework to sift through all the noise and identify the driving variables and best combination of practices for a given situation on a particular field.

Unfortunately, to date, I am not aware of successful use of a big data approach to foster EI *at scale*. In contrast, smaller steps towards use of a big data approach show substantial promise. One example from Nebraska used farmer-reported data, from hundreds of pivot-irrigated maize fields, on yield, sowing date, irrigation amount, hybrid maturity, tillage method, crop rotation, and N fertilizer rate to identify the optimal combination of management factors for highest yield, water, and N fertilizer use efficiencies (Grassini et al., 2011a,b).

Also needed is a robust spatial framework for identifying the "*technology extrapolation domain*" (TED) for a given field to facilitate use of results from field studies and farmer-reported data across landscapes with variable soils and climate. A TED is defined as a region in which soil type and climate are of sufficient uniformity that a specific technology, management practice, or cropping system would behave similarly within that zone. The Global Yield Gap Atlas (www.yieldgap.org) has developed such a spatial framework based on the most sensitive variables governing rain-fed crop performance: temperature regime, water balance, and water holding capacity in the rootable soil depth, which is largely determined by soil texture and depth to which roots can grow without physical or chemical impediments (van Wart et al., 2013; Grassini et al., 2017).

By unlocking the power of big data and use of a robust spatial framework to accelerate technology innovation and adoption, I have every confidence it will be possible to meet expected maize demand, and expected demand for other food crops for that matter, without a large expansion of crop production area or degrading environmental quality. But it will require a ruthless focus of research and development investments funded by both the public and private sectors on the dual EI objectives of higher yields and reduction of negative environmental impact. BC

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Exploring Maize Intensification with the Global Yield Gap Atlas

By Patricio Grassini, Kenneth G. Cassman, and Martin van Ittersum

The Global Yield Gap Atlas (www.yieldgap.org) provides estimates of yield potential, yield gap, and water productivity for maize and eight other major food crops.

Maize yield gaps range from 80% in Sub-Saharan Africa and India to 15% in irrigated and favorable rain-fed environments in USA and Europe. The Atlas can help identify regions with greatest potential for sustainable maize intensification.

The global community must find a way to provide food and water security for a population expected to reach 9.7 billion by 2050. Global carrying capacity for food production and our ability to protect carbon-rich and biodiverse natural ecosystems from conversion to cropland ultimately depends on achieving maximum possible yields on every hectare of currently used arable land and achieving this goal with sustainable use of available water resources. **Yield potential** is the maximum attainable yield as determined by climate and soil in absence of nutrient deficiencies and biotic stresses. **Water productivity** is the efficiency with which water is converted to food. Yet for most major crop-producing regions of the world, including data-rich regions such as the U.S. Corn Belt and Europe, there were, until recently, no reliable data on yield potential and water productivity. These two parameters are critical benchmarks in agricultural areas where rain-fed and irrigated agriculture is under pressure. With good crop and water management practices, farmers should be able to attain about 80% of the site-specific yield potential and water productivity (**Figure 1**).

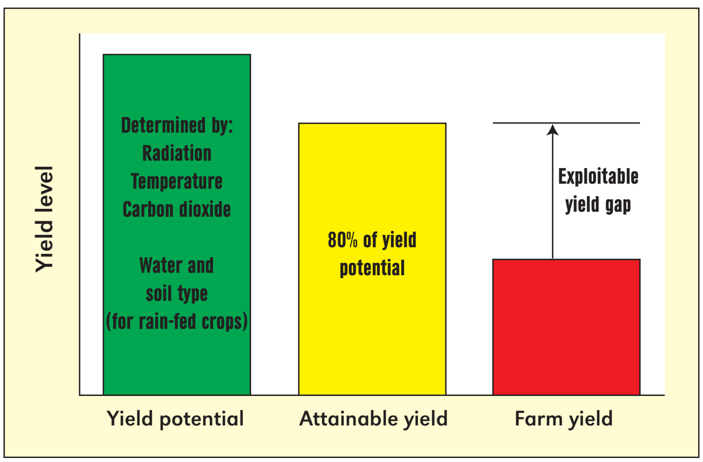

Figure 1. Crop yield potential (either irrigated or rain-fed), attainable yield, and on-farm yield. Adapted from van Ittersum et al. (2013).

In 2011, researchers from University of Nebraska-Lincoln (USA) and Wageningen University (The Netherlands) began the development of the Global Yield Gap Atlas (GYGA), with the goal of establishing improved methods for estimating the yield gap -- the difference between current average on-farm yield and yield potential -- and water productivity on every hectare of existing crop land worldwide. The first phase of the project (2012-2015) focused on cereal crops. Recently, the crop list has been extended to include soybean, sugarcane, and potatoes. The country-crop combinations included in the Atlas so far account for 60%, 58%, and 35% of the global rice, maize, and wheat production, respectively (**Figure 2**).

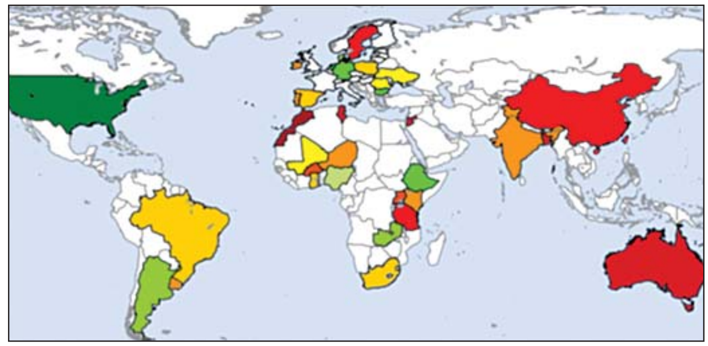

Figure 2. Current coverage of the Global Yield Gap Atlas (www.yieldgap.org). The Atlas currently covers nine crops (maize, rice, wheat, sorghum, millet, soybean, sugarcane, barley, and potatoes) and 42 countries.

GYGA is an international project that requires "boots-on-the-ground effort" because it is based on local data from each of the world's major crop production countries. Essential data include soil properties that govern plant-available water holding capacity in the soil profile to maximum rooting depth, long-term weather records, and planting and harvest dates of major crops in existing cropping systems. A standard protocol for assessing yield potential, yield gaps, and water productivity based on a strong agronomic foundation was developed (**Figure 3**) and applied in a bottom-up process that uses local experts and networks to provide knowledge about crop management and productivity and existing soil and climate databases.

These data are used with the most appropriate crop simulation models and a geographic information system and scaling method to produce detailed maps with associated databases displayed. All maps and underlying data are accessible through an interactive web-based platform suitable for expert and non-expert users (www.yieldgap.org). To the extent that intellectual property restrictions allow, all data used in building the Atlas are made publicly available as a resource for scientists, policy makers, agri-business, and others. In other words, GYGA provides a web-based platform for estimating yield potential, yield gaps, and water productivity that is transparent, accessible, reproducible, geospatially explicit, agronomically robust, and applied in a consistent manner throughout the world.

Table 1 provides a summary of maize average yield potential, on-farm yield, and yield gaps estimated across the maize producing countries included in the Atlas. Yield potential was simulated for each cropping system based on long-term weather data and local soil and cropping system data. Estimates of yield potential shown here represent national averages, calculated

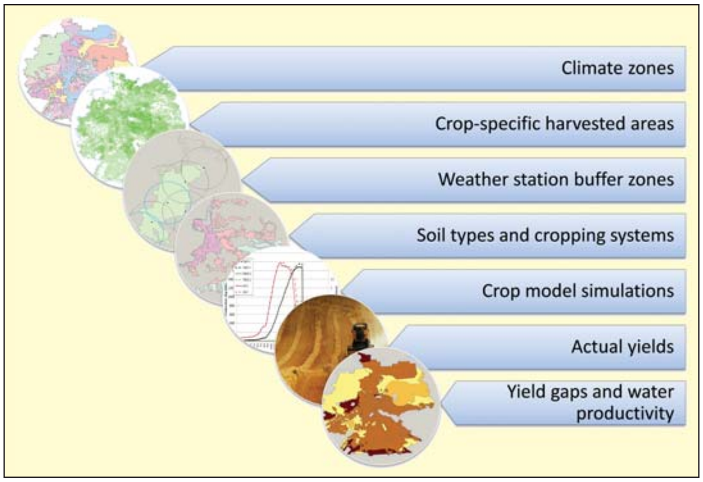

Figure 3. Protocol developed by the Global Yield Gap Atlas to estimate yield potential, yield gaps, and water productivity. Briefly, sites located within the major crop producing areas within a country are selected and local weather, soil, current yields, and cropping system data are used as basis to simulate yield potential and estimate yield gaps and water productivity. Figure developed by Dr. René Schils, regional coordinator for GYGA-Europe. Detailed description of the GYGA methodology can be found in Grassini et al. (2015) and van Bussel et al. (2015).

Table 1. Yield potential, on-farm yield, and yield gap (expressed as % of yield potential) for selected maize producing countries included in the Global Yield Gap Atlas. Source: www.yieldgap.org

Region/country	Water regime	On-farm yield, t/ha[5]	Yield potential, t/ha	Yield gap, %
West Africa[1]	Rain-fed	1.7	10.0	83
India	Rain-fed	1.6	9.3	83
East Africa[2]	Rain-fed	1.8	8.0	78
Brazil	Rain-fed	4.7	8.7	54
East Europe[3]	Rain-fed	4.5	8.7	48
Bangladesh	Irrigated	5.7	10.1	43
Argentina	Rain-fed	6.8	11.6	42
South Europe[4]	Irrigated	10.2	14.8	31
USA	Rain-fed	9.7	12.4	22
USA	Irrigated	11.8	14.0	16
Germany	Rain-fed	9.7	11.0	12

[1]Includes Ghana, Mali, Burkina Faso, and Nigeria.
[2]Includes Ethiopia, Uganda, Kenya, Tanzania and Zambia.
[3]Includes Bulgaria, Ukraine, Hungary, Poland, and Romania.
[4]Includes Spain and Portugal.
[5]Actual yields estimated based on most recent available statistics in the last 10 years.

based on the area where maize is currently grown in each country and using many years of weather data to account for weather variability. Likewise, the yield potential estimate here is based on current crop sequences and dominant management practices such as planting date, plant density, and cultivar maturity. For the purpose of this summary, some countries were aggregated into regions given the similarity of their yield gaps and yield potential. Average yield potential ranges from 14.8 to 8 t/ha across countries/regions, reflecting differences in water supply (irrigated *versus* rain-fed), length of crop growing season as determined by annual patterns of temperature and rainfall, and crop intensity (one *versus* multiple crops planted in the same piece of land in a 12-month period). However, a common feature is the existence of a yield gap, though the size of this gap is highly variable across countries (from 15 to 80%).

Figure 4 illustrates the range of yield gaps by looking at three maize producing regions with contrasting level of intensification: irrigated maize in the United States, rain-fed maize in Argentina, and rain-fed maize in Sub-Saharan Africa. Variation

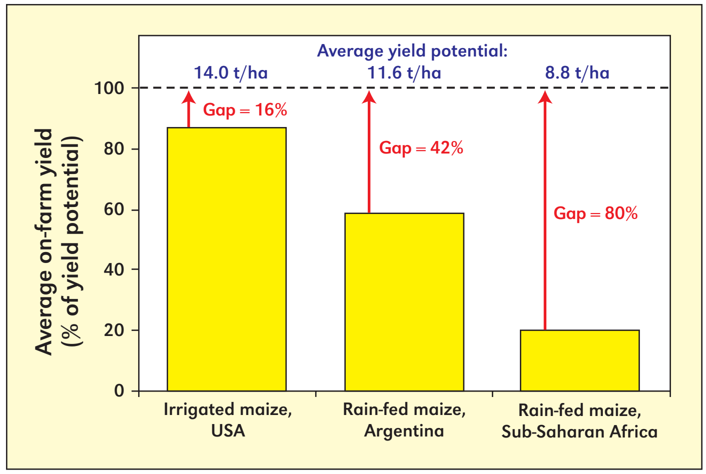

Figure 4. Average on-farm yield, expressed as a percentage of the yield potential, for three cropping systems with different level of intensification: irrigated maize in USA and rain-fed maize in Argentina and Sub-Saharan Africa. Values above bars indicate average yield potential, which was calculated using crop simulation models based on long-term weather data (solar radiation, temperature, and precipitation) and local soil and management data. Size of the yield gaps is shown with the red upward arrows. Sources: Global Yield Gap Atlas (www.yieldgap.org) and Aramburu et al. (2015).

in the size of yield gap reflects not only differences in access to information and inputs, but also differences in risk level in relation to weather variability. In the case of irrigated maize in U.S., access to irrigation water compensates for weather variability and associated risk, allowing crop producers to optimize farm management and achieve a small yield gap. Rain-fed producers in Argentina face large uncertainty about weather conditions in the season ahead, which in turn creates uncertainty about the appropriate level of inputs. If they apply input levels in excess of the amount needed for maximum profit in a year when yield potential is below average due to unfavorable weather, they will likely achieve a small yield gap but with smaller profit. On the other hand, if farmers are too conservative and under-invest in inputs in a year with high yield potential due to favorable weather, they will miss the possibility of achieving a large profit and will have a large yield gap. As a result, the yield gap for rain-fed maize in Argentina is larger than for irrigated maize in USA. Still, the maize yield gap in Argentina is relatively small compared to rain-fed maize in Sub-Saharan Africa. A key difference is that Argentine farmers have better access to inputs and information than Sub-Saharan African farmers.

The Atlas enables farmers, governments, policy makers, foundations, NGOs, the private sector, and others to identify regions with greatest potential for investment in agricultural development and technology transfer and to monitor impact over time. And the Atlas can be used to assess the feasibility of a country or region to achieve food self-sufficiency through crop intensification and, if this cannot be achieved, for assessing how much extra land clearing or food import will be needed to meet future demand for food. A number of studies have been published on these topics using the GYGA approach (Aramburu et al., 2015; van Oort et al., 2015; Espe et al., 2016, Marin et al., 2016, van Ittersum et al., 2016; Timsina et al., 2016).

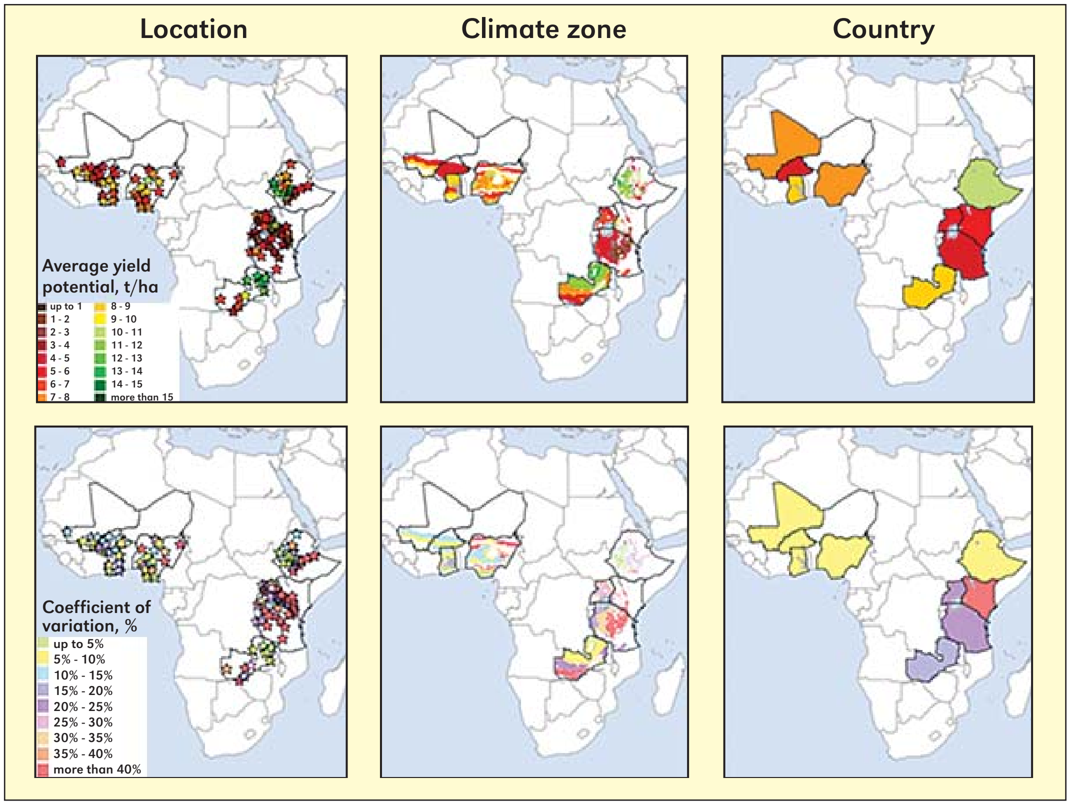

Figure 5. Estimates of yield potential (top) and its year-to-year variability (bottom) for rain-fed maize in nine countries in Sub-Saharan Africa at three spatial scales: location (left), climate zone (middle), and country (right). Source: Global Yield Gap Atlas (www.yieldgap.org).

Accurate estimates of yield potential (and its year-to-year variability) are also critical at the field level to improve current crop and input management (e.g., estimation of fertilizer nutrient requirements and probability of obtaining a profitable response) and also at larger (region and country) scales to inform investments and policy in agriculture. An example of yield potential and its variability is shown for rain-fed maize at three different spatial scales across nine countries in Sub-Saharan Africa (**Figure 5**).

Future developments of the Atlas include estimation of nutrient gaps and delineation of extrapolation domains for technology transfer and ex-post and ex-ante impact analysis. We believe that the spatial framework developed by the Atlas can be used to make agronomic research more efficient by providing an objective way to design field trials to maximize area coverage in relation to number of experimental sites and monitor the impact of policy and technologies over time and space. The Atlas can also be used as a foundation for studies aiming to explain and mitigate yield gaps and investigate impact of climate change, land use, and environmental footprint of agriculture, and as a platform for in-season yield forecasting.

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Ecological Intensification and 4R Nutrient Stewardship: Measuring Impacts

By Rob Norton, Cliff Snyder, Fernando García, and T. Scott Murrell

The impacts of improved management can be assessed through common production and nutrient balance measures.

However, the assessment of the sustainability of ecological intensification (EI) requires that these measurements be linked to changes in soil nutrient status and to farm level profitability.

The effective, productive, and efficient use of fertilizers is fundamental to feeding the global population, with around half of current food production made possible by balanced crop nutrient input. At the same time, there are parts of the world where fertilizers are under-used so that food security is threatened and soil fertility degraded, or where they are overused to the point of contributing to environmental pollution (e.g., N, P).

Farmers and their advisers turn to science to help define and then refine the ways inputs are used to produce adequate, good quality food, ensure minimal environmental impact, and maintain the soil resource. The IPNI Global Maize Project (GMP) provides data from over 20 sites that can be used to compare typical farmer practice (FP) to what scientists and local agronomists believe to be improved practices aimed at sustainably improving yields and meeting the standards for environmental quality—a goal termed Ecological Intensification (EI). These EI practices differ from region to region but include strategies for better cultivars, balanced nutrition, and improved soil and crop management. The initial EI treatments in the GMP were estimates of an ideal set of practices for accomplishing the objectives of EI at a given site. However, the long-term aspect of the GMP provides opportunities for the local agronomy team to make adjustments in the practices as observations and measurements suggest and to accommodate improved technologies or genetics as needed during the experiment.

Table 1. Four metrics commonly used to describe nutrient use efficiency (NUE) and some typical values for those indicators with reference to N in particular.

NUE metric	Calculated from	Typical values for N (maize or wheat, after Dobermann, 2007)
Partial Factor Productivity *PFP: kg grain/kg fertilizer*	Y/F	40-80
Partial Nutrient Balance *PNB: kg nutrient removed/kg fertilizer*	R/F	<1.0 = more supplied than removed >1.0 = more removed than supplied
Agronomic Efficiency *AE: kg grain increase/kg fertilizer*	$(Y-Y_0)/F$	10-30
Recovery Efficiency *RE: kg nutrient increase/kg fertilizer*	$(U-U_0)/F$	0.5 (whole-plant) 0.3 (grain only)

Y = crop yield with applied nutrients; Y_0 = crop yield with no applied nutrients; F = fertilizer applied; U = crop nutrient uptake into harvested portion with applied nutrients, U_0 = crop nutrient uptake with no applied nutrients.

Crop yield is a key measure of the response of any system to changed management practices, but this response can be considered in concert with selected nutrient use efficiency (NUE) metrics. System efficiency and effectiveness can be defined in many ways and a selection of these is shown in **Table 1**. Deciding on the most appropriate indicator will depend on the types of data available and the purposes to which they will be put.

Agronomic efficiency (AE) quantifies the yield gained or lost per rate of nutrient applied. It is directly related to the profitability of the nutrient application: the greater the AE, the greater the profitability.

Recovery efficiency (RE) estimates the proportion of the nutrient applied that is taken up by the crop. For a given set of conditions, some or all crop nutrient uptake needs will be met by the supply of nutrients in the soil. When the soil is unable to meet these needs, the shortfall must be made up by a nutrient application. Recovery efficiency quantifies how efficiently that application makes up the shortfall (Stanford, 1973). Higher recovery efficiencies mean the fertilizer is accessed and used more efficiently by the crop. There are many factors that affect RE, such as more efficient genotypes for nutrient uptake, the quantity of nutrients already present in the soil, and the degree to which nutrients transfer among soil pools.

Both RE and AE require a nil fertilizer application treatment to estimate the extra yield or nutrient uptake resulting from the added fertilizer. Such measures are normally only available on research plots (at research stations or on-farm), which limits their usefulness in non-research settings; however, there are two NUE indicators that are well-suited to evaluations at a field, farm, or regional level: partial factor productivity (PFP) and partial nutrient balance (PNB).

Partial factor productivity compares yield to the quantity of fertilizer applied. It answers the question *"How productive is this cropping system in comparison to its nutrient input?"* It will usually decline with increased nutrient inputs because of the principle of diminishing returns, although at rates well below the optimum rate, linear yield responses can occur.

Partial nutrient balance compares the quantity of nutrient being taken out of the field to the amount of nutrient applied. A ratio is used to quantify PNB; however, it can also be converted to mass balance (net kg or lb of nutrient removed or added), termed nutrient balance intensity.

System level PNB only indicates the fate of nutrients removed in harvested produce. It does not consider other

Abbreviations and notes: N = nitrogen; P = phosphorus; K = potassium. IPNI Project GBL-GM17

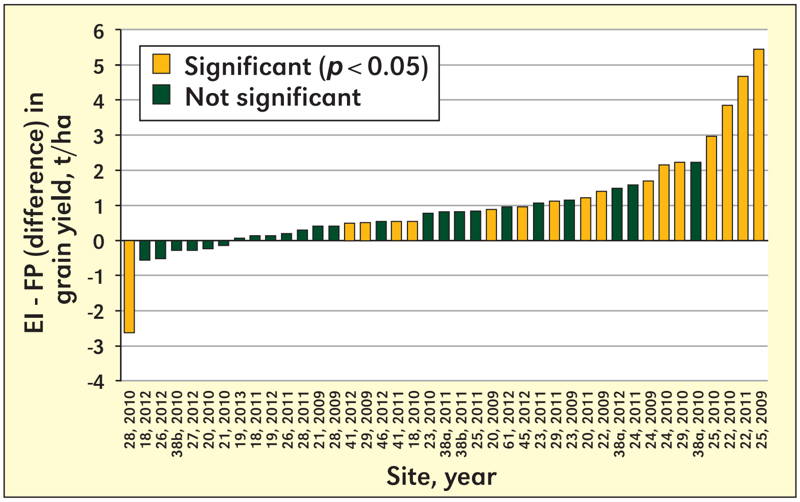

Figure 1. The difference in grain yield between Ecological Intensification (EI) and Farmer Practice (FP) for 41 sites in the Global Maize Project.

transfer processes, and so does not necessarily indicate the risk or amount of nutrient losses to the environment. Further, none of these indicators reference soil health or soil nutrient levels, so are incomplete in their description of sustainability impacts. More discussion on selecting appropriate nutrient performance indicators can be found in Fixen et al. (2015) and Norton et al. (2015).

In this paper, we discuss the impacts of the EI management treatments on the specific nutrient use efficiency (NUE) indicators listed in **Table 1**. The experimental designs implemented in the GMP make it possible to quantify all four indicators only for N. For P and K, only PNB is presented.

Effective Use of Nutrients

Raising grain yield (t/ha) is one of the main objectives of improved management, with the ultimate purpose of increasing the profitability of maize production. Here, we simply express it as the yield gain due to EI. Of the 41 site-years compiled to date for the GMP, 16 site-years showed a statistically significant increase (p<0.05) in yield of EI over FP, while only one site-year produced lower yields with the EI compared to the FP. The lower yield was at Celaya, Mexico, 2010, where very high N rates were used. At the other site-years, there were no statistically significant differences between EI and FP. **Figure 1** shows the yield differences between FP and EI across all 41 site-years.

Productive Use of Nutrients

Even though yields may increase as a result of EI, the relative role of nutrients in contribution to this increase can be assessed with reference to the PFP. PFP is a simple production efficiency metric that can be easily calculated from smallholder farmer's fields to whole nations where there are reliable records of yield and nutrient inputs. PFP is only applicable where a single product (e.g., maize, milk, canola) is the output of the system, so is of lesser value in assessing efficiencies of mixed farming systems that produce a range of products.

PFP does not consider the contribution of soil reserves to crop yield, and because of the typical shape of a yield response curve to nutrients, PFP will usually be largest for the first unit or units of fertilizer and then decline as additional nutrient is supplied. Therefore, a very high PFP indicates that the system is operating at lower yields than when the PFP is lower, and/or that a large proportion of crop N is supplied from soil N. A very low PFP value indicates that there has been little yield response to the fertilizer applied, and this may be a consequence of high inherent soil fertility, or due to other factors limiting yield such as pests, disease, or adverse weather.

Figure 2 is a summary of the PFP values for maize in response to N applications at the GMP sites. There were seven site-years when the PFP_N for the FP treatments was 100 kg grain/kg N or more, compared to a typical value of 40 to 80 kg grain/kg N (Dobermann, 2007). So, while this indicates a large return of grain for fertilizer N supplied, it suggests that these sites were at the lower end of the yield response curve. In 24 site-years, EI treatments lowered the PFP_N, although some values were already low—indicating that those low PFP_N sites were less responsive sites than where PFP_N for the FP treatments was higher.

Efficient Removal of Nutrients

Partial Nutrient Balance reflects only one of several transfer processes that operate with crop nutrients. A PNB of 1 indicates that the same amount of nutrient (e.g., N, P, or K) was removed in the grain as was supplied as fertilizer. If the value is more than 1, more nutrient is being removed than is being applied, so that soil reserves are likely being depleted. Alternatively, if the value is less than 1, more nutrient is being applied than is being removed. This ratio does not indicate the fate of the extra nutrients, nor if the "surplus" is likely to be ecologically damaging or benign. Where low soil nutrient status is present, PNB less than 1 could indicate improvement in the inherent soil fertility; but where PNB is very low, there may be a higher risk of loss to the environment. Interpreting the PNB values

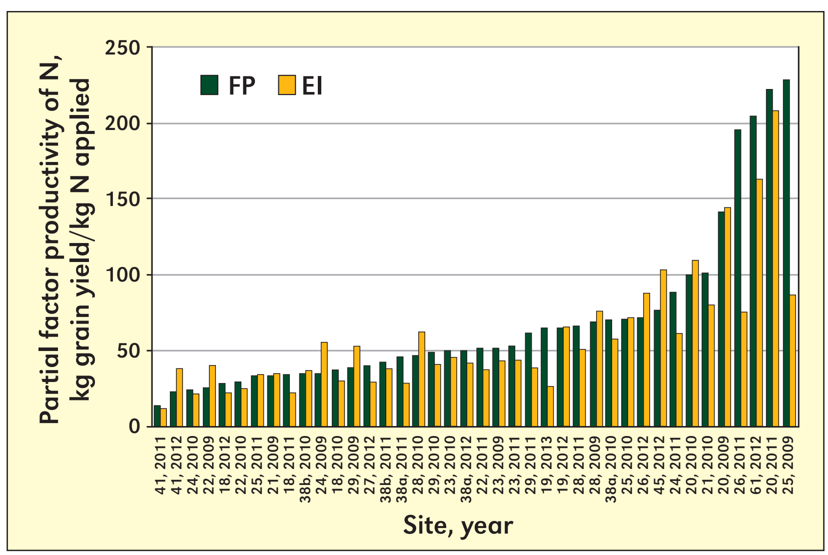

Figure 2. The partial factor productivity for N (PFP_N) for Ecological Intensification (EI) and Farmer Practice (FP) compared over 17 of the sites in the Global Maize Project where PFP_N values were statistically different between the practices.

Table 2. Changes in PNB for N, P, and K with Ecological Intensification (EI) compared to Farmer Practice (FP) at the Global Maize Project sites for different yield responses. Not all nutrient removals were measured at all sites.

Yield	PNB_N Better	PNB_N Same	PNB_N Worse	PNB_P Better	PNB_P Same	PNB_P Worse	PNB_K Better	PNB_K Same	PNB_K Worse
EI > FP	6	4	3	8	1	-	5	2	-
EI = FP	5	12	4	3	13	3	2	7	7
EI < FP	-	-	1	-	1	-	-	1	-
Totals		35			29			24	

requires reference to soil test values or indigenous nutrient supplies over several seasons or years to assess the true effect on soil reserves.

PNB_N was calculated for 35 site-years in the GMP. PNB_N was not significantly different between FP and EI in 16 site-years. **Figure 3** shows the PNB_N for EI and FP at 19 site-years where there were significant differences between the two management systems, with the Y-axis reset to a PNB of 1. In terms of balancing nutrient input and output, moving higher or lower is not necessarily better or worse, but raising low values and lowering high values can be environmentally and sustainably significant. Of the statistically significant effects, at six site-years PNB_N values above 1.25 under FP were lowered in the EI treatment. At another four site-years, PNB_N less than 0.75 under FP was raised with EI. Across all 19 site-years with statistically significant treatment effects, 14 saw reductions in PNB_N with the EI treatment; however, at five of these, the decline was relatively small (<0.15), even though statistically different. The impact of the low PNB_N will depend on the antecedent soil N status and the susceptibility of the N to environmental losses. Low PNB_N where soil test levels are low could result in soil fertility improvement or higher N losses where there is susceptibility.

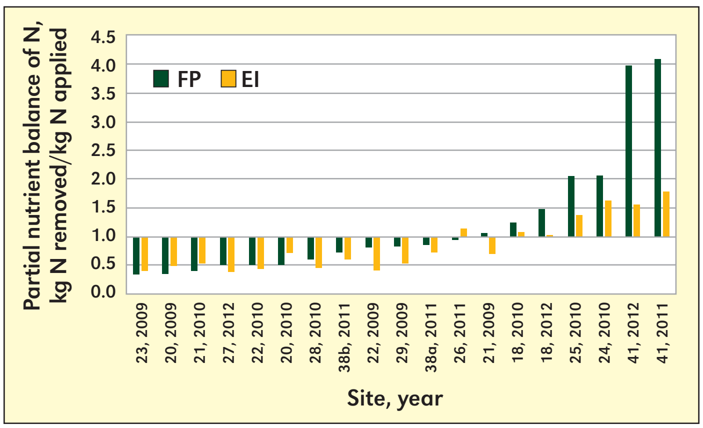

Figure 3. Comparison between Ecological Intensification (EI) and Farmer Practice (FP) in terms of partial nutrient balance for N for 19 sites in the Global Maize Project where the balances were statistically different between the practices.

Nutrient Efficiency Interactions

Because of the interactions among nutrients, management, and the environment, improved production system(s) performance cannot be adequately assessed by a single measure. Higher yields often mean more nutrient is removed, so that PNB can decline as the crop removes more nutrient from the soil. As a result of the higher yield, PFP can increase but at the expense of soil reserves. **Table 2** summarizes the changes in PNB for N, P, and K between the EI and FP treatments, at different yield responses from the GMP sites where nutrient removal was measured. PNB was considered to improve (better) where a low PNB (PNB<0.8) was raised, or a high PNB (>1) was lowered. In these metrics, the goal would be to maintain or improve yield while improving or maintaining PNB (green shading), and from the GMP, this has been achieved at 27 site-years for N, 25 site-years for P, and 16 site-years for K. The sites in cells colored yellow or orange require additional consideration of the management practices to either improve yield or PNB.

The impact of changes in PNB should not be considered without an assessment of the changes in soil reserves of the nutrients. If the soil nutrient reserves are at optimum levels, then the target PNB may be near unity. If soil nutrient reserves are adequate or plentiful, it may be appropriate to exploit those fertility reserves, so a PNB>1 may be appropriate. Conversely, if soil fertility is depleted, extra nutrient(s) may be required to increase nutrient reserves by applying more nutrient than is removed (PNB<1).

These performance indicators of sustainable plant nutrition from the IPNI Global Maize Project underscore the importance of tracking crop yields, PNB, and PFP linked to soil nutrient supplies. In addition, it is important to understand the economic costs and benefits for the farmer, since farmer profitability must also be improved or maintained for both short- and long-term success. BC

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Opportunities for Ecological Intensification Approaches when Yield Gaps Are Narrow

By T. Scott Murrell, Jeffrey A. Coulter, Vladimir Nosov, John Sawyer, Daniel Barker, Olga Biryukova, and Jeffrey Vetsch

Four sites in the IPNI Global Maize Project located in areas thought to have narrow exploitable yield gaps demonstrate that management practices assembled to achieve ecological intensification produced comparable or greater maize yields than those achieved with standard farmer practices.

There are many maize growing areas in the world where farmers have been steadily increasing management intensity, already producing what are considered high yields in their respective regions. The difference between attainable yield and yields under current farmer practices (FP), or the exploitable yield gap, is believed to be narrow in these areas. We present data from four IPNI Global Maize Project research sites located in such areas. In each location, a management system was constructed in an attempt to achieve the goals of ecological intensification (EI). The achievements of those approaches, as well as their challenges, are presented.

Iowa, United States

This rain-fed site was established in 2011 on a Mollisol near Ames, Iowa, USA. Maize and soybean were grown in rotation on the same experimental areas over time, with each crop present each year. Phosphorus and K were applied according to soil test interpretations in both EI and FP treatments (Mallarino et al., 2013; Sawyer et al., 2011).

The EI system incorporated several changes compared to the FP system. Strip-till maize and no-till soybean were used in the EI system instead of more intensive, full-width conventional tillage in the FP (i.e., spring disk/field cultivate for maize and fall chisel plow-spring disk/field cultivate for soybean). Over the 2011 to 2016 duration of the experiment, the EI treatment used maize seeding rates 19 to 27% higher than the FP, with rates ranging from 84,000 to 100,000 seeds/ha. Planting dates were the same for both treatments except for 2012, when EI was planted 28 days later. Target soybean populations in EI were also 50% higher: 370,000 seeds/ha compared to 250,000 seeds/ha for FP. In the EI treatment only, S as calcium sulfate was applied at a rate of 17 kg S/ha before maize in the crop rotation.

Nitrogen fertilizer rates for EI were generally lower (14 to 17% lower in four of the experimental years, equivalent in one year and 18% higher in another year). The yearly rate of N in FP was the upper end of the profitable N rate range calculated by the Corn Nitrogen Rate Calculator (http://cnrc.agron.iastate.edu), using yearly N fertilizer and corn prices from the Estimated Costs of Crop Production in Iowa (Ag Decision Maker, File A1-20, FM 1712 http://www.extension.iastate.edu/agdm/crops/html/a1-20.html). In the EI, N was split-applied, with ammonium nitrate broadcast pre-plant, followed by side-dressed (V5 maize growth stage) UAN banded 10 cm below the surface, with bands applied midway between every-other 76 cm maize row. Maize canopy sensing at the V10 maize growth stage was conducted each year to monitor EI treatments and direct any late N application. However, only in the third and fourth years of the experiment was there a mid-vegetative stage application of either urea with a urease inhibitor or ammonium nitrate. In the FP, anhydrous ammonia was applied spring pre-plant, in 20 cm deep bands midway between each row. For each system, there was also a treatment with no N application.

Abbreviations and Notes: N = nitrogen; P = phosphorus; K = potassium; S = sulfur; Mo = molybdenum; Zn = zinc; ATS = ammonium thiosulfate; KCl = potassium chloride; UAN = urea ammonium nitrate. IPNI Projects USA-GM26, RUS-GM41, USA-GM51, USA-GM-65

Analyzed across 2011 to 2016 (**Table 1**), the two management systems did not differ in average maize grain yield when fertilized with N; however, maize in the EI system did accumulate a lower quantity of N. When no N fertilizer was applied, grain yield and N uptake in the EI system were lower than those in the FP. For the efficiency metrics, the EI system had a greater agronomic efficiency of N (AE_N), producing 35 kg dry matter (DM)/ha per 1 kg N/ha applied. The FP system produced 10 kg DM/ha less per 1 kg N/ha applied. The greater AE_N of EI is a function of: 1) the lower unfertilized yields in EI, 2) the lower N application rates in EI, and 3) the greater

Table 1. A comparison of ecological intensification (EI) and farmer practice (FP) management systems at Ames, Iowa for dry matter (DM) grain yield, total N uptake, agronomic efficiency of N (AE_N), average partial factor productivity (PFP), average partial nutrient balance (PNB), and average recovery efficiency of N (RE_N).

Treatment	Average DM grain yield†, kg DM/ha	Total N uptake, kg N/ha	Average AE_N, kg/kg	Average PFP --- kg/kg ---	Average PNB	Average RE_N, %
EI-N	10,650 a	187 b	35 a	73 a	0.85 a	70.7 a
FP-N	11,020 a	199 a	25 b	69 a	0.79 a	62.1 a
EI-N0	5,470 c	84 d	–	–	–	–
FP-N0	6,950 b	99 c	–	–	–	–

All measurements were analyzed over six years (2011 to 2016).
†Adjusted to 15.5% moisture, average yields with N application are: EI = 12,607 kg/ha (201 bu/A) and FP = 13,046 kg/ha (208 bu/A).
‡Within a column, averages with different letters are statistically different (p≤0.05).

Achievements:
The EI system was able to sustain maize yield and increase AE_N while reducing tillage and reducing the overall N rate, which was split across an additional application.

Challenges:
Results may point to a reduced ability of the soil under EI to supply N for maize uptake, a greater reliance on applied fertilizer N for optimal yield, and, if fertilizer N application rates are reduced, a greater chance for soil N resource depletion in FP.

grain yield response to N in EI. No differences existed between EI and FP for the other efficiency metrics: partial factor productivity (PFP), partial nutrient balance (PNB), or recovery efficiency of N (RE_N).

Rostov Oblast, Southern Russia

This study began in 2011 in the District of Tselina in Rostov Oblast, Southern Russia. The clay loam soil at this low rainfall research location is classified as an ordinary Chernozem (Voronic Chernozem Pachic in WRB, 2006) – a soil sharing many characteristics with the Mollisol order in the USDA Soil Taxonomy. Normal weather patterns result in low rainfall and high temperatures during pollination. At the start of the experiment, the calcareous soil tested medium in P, very high in exchangeable K, a basic pH (7.9), and an organic matter content of 2.9%. Soil tests were taken to a depth of 20 cm. Maize and soybean were initially planted in 2011 after winter wheat and were thereafter grown in rotation with soybean from 2011 to 2014. In 2014, the soybean crop was heavily infected with the soybean mosaic virus (SMV) and was destroyed in July. No yield measurements were taken that year. Starting in 2015, chickpea became the rotational crop.

Like other Global Maize locations, two management systems were compared: FP and EI. Within each management system, N response was tested in sub-plots without N (N1) and with N (N2), resulting in four treatments: FP-N1, FP-N2, EI-N1, and EI-N2 (**Table 2**). Both maize and the rotational crop (soybean and chickpea) were fertilized. From 2011 to 2013, the same maize hybrids were used for both management systems. New, shorter season hybrids have been planted in EI since 2014 and in FP since 2016.

Soybean was the rotational crop in 2011-2014. Chickpea was the rotational crop from 2015-2016. Seed treatments included Zn, Mo, and in the first soybean season and each chickpea season, a *rhizobium* inoculant.

Maize fertilization practices for FP were selected from those used in large scale farms and agricultural enterprises near the study location. In the FP-N1 treatment, MAP was broadcast before planting at a rate supplying 9 kg N/ha and 40 kg P_2O_5/ha. In FP-N2, ammonium nitrate, also broadcast pre-plant, was added to supply a total of 30 kg N/ha and 40 kg P_2O_5/ha.

Maize fertilization practices for EI were determined from accompanying, controlled studies. These studies demonstrated that higher N and P rates as well as K addition were needed, even though soil test K levels were high. The rate of K was split across two applications. Fertilization in EI was done at two to three different times. In EI-N1, MAP and KCl were broadcast before planting to supply 12 kg N/ha, 50 kg P_2O_5/ha, and 20 kg K_2O/ha. In EI-N2, ammonium nitrate was added to supply an additional 38 kg N/ha. At planting, in both EI-N1 and EI-N2, a Zn seed treatment was used along with an application of MAP and KCl banded 2 cm to the side of the seed row, at rates of 5 kg N/ha, 20 kg P_2O_5/ha, and 20 kg K_2O/ha. In only EI-N2, an additional 30 kg N/ha was side-dressed as ammonium nitrate at maize growth stage V3 to V5.

Soybean fertilization practices in 2011 to 2014 also differed among treatments. Fertilizers were broadcast before planting in all treatments. The FP-N1 treatment applied MAP at 9 kg N/ha and 40 kg P_2O_5/ha, and the FP-N2 applied an additional 11 kg N/ha as ammonium nitrate. In EI-N1, MAP and KCl were applied at rates supplying 10 kg N/ha, 45 kg P_2O_5/ha, and 30 kg K_2O/ha. The EI-N2 treatment added an additional 20 kg N/ha. In the first soybean season, a *rhizobium* inoculant was applied to the seed in both EI-N1 and EI-N2. In all soybean seasons, Mo was added as a seed treatment in both EI-N1 and EI-N2.

Table 2. Fertilizer treatments applied to maize, soybean, and chickpea for farmer practice (FP) and ecological intensification (EI) management systems without (N1) or with (N2) supplemental nitrogen at Rostov Oblast, Southern Russia.

	Fertilizer timing	N	P_2O_5	K_2O	Seed treatment
		------- kg/ha	-------		
		Maize			
FP-N1†	Pre-plant	9	40	–	–
FP-N2	Pre-plant	30	40	–	–
EI-N1	Pre-plant	12	50	20	–
	At planting	5	20	20	Zn
EI-N2	Pre-plant	50	50	20	–
	At planting	5	20	20	Zn
	V3 to V5 stage	30	–	–	–
		Soybean			
FP-N1	Pre-plant	9	40	–	–
FP-N2	Pre-plant	20	40	–	–
EI-N1	Pre-plant	10	45	30	–
	At planting	–	–	–	Mo/inoculant
EI-N2	Pre-plant	30	45	30	–
	At planting	–	–	–	Mo/inoculant
		Chickpea			
FP-N1	Pre-plant	6	26	–	–
FP-N2	Pre-plant	24	26	–	–
EI-N1	Pre-plant	12	52	30	–
	At planting	–	–	–	Mo/inoculant
EI-N2	Pre-plant	24	52	30	–
	At planting	–	–	–	Mo/inoculant

†Nitrogen in the N1 treatments resulted from the application of monoammonium phosphate to meet crop requirements.

After the failure of the soybean crop in 2014 from SMV, chickpea became the rotational crop. Fertilizers were broadcast before planting chickpea in all treatments like for soybean. The FP-N1 treatment applied MAP at 6 kg N/ha and 26 kg P_2O_5/ha, and the FP-N2 applied an additional 18 kg N/ha as ammonium nitrate. In EI-N1, MAP and KCl were applied at rates supplying 12 kg N/ha, 52 kg P_2O_5/ha, and 30 kg K_2O/ha. The EI-N2 treatment added an additional 12 kg N/ha. In both chickpea seasons, a rhizobium inoculant and seed treatment with Mo were used in both EI-N1 and EI-N2.

The highest average grain yield of maize of 5,750 kg DM/ha was obtained through a locally adapted EI management strategy that included: balanced application of N, P, and K; split N applications; use of a P, K, and Zn at planting; and during the last three years of the study, new shorter-season hybrids (**Table 3**). The average improvement of EI over FP was 9%. Maize responded only slightly to added N in both the EI and FP management systems. The average yield increase due to N was 6%. Adequate nitrate-N levels in the soil may explain this low response. These results demonstrated the need to

Table 3. Average maize yield (2011-2016), soybean yield (2011-13), soybean protein content (2011-13), soybean oil content (2011-13) and chickpea yield (2015-16) for farmer practice (FP) and ecological intensification (EI) management systems without (N1) or with (N2) supplemental N at Rostov Oblast, Southern Russia.

Treatment	Average maize yield, kg DM/ha	Average soybean yield, kg DM/ha	Average soybean protein content, %	Average soybean oil content, kg oil/ha	Average chickpea yield, kg DM/ha
FP-N1	5,000	1,360	40.1	248	1,910
FP-N2	5,280	1,460	42.4	260	2,210
EI-N1	5,420	1,610	43.4	309	2,290
EI-N2	5,750	1,700	45.6	328	2,420

Only the means for dry matter (DM) yield from the chickpea treatments (FP-N1 and EI-N2) are statistically different at $p \leq 0.05$.

determine the best N rates to apply in this region, and those experiments have been initiated.

The highest average grain yield of soybean of 1,700 kg DM/ha was also obtained through EI management including balanced application of N, P, and K fertilizers, Mo seed treatment, and inoculation (in the first season). The improvement over FP (N9P40) reached 25%. The yield response to additional N over the low N treatment, for both the EI and FP management, ranged from 6 to 7% and was not significant during all seasons. Improvements in seed protein were obtained with both EI and FP management treatments that provided extra N fertilizer. In addition, soybean oil output was also slightly increased due to higher yield obtained with extra N.

Based on the two-season data, chickpea performs noticeably better than soybean in the low rainfall experimental location. Again, the highest average yield of chickpea of 2,420 kg DM/ha was obtained through EI management including balanced application of N, P, and K fertilizers, Mo seed treatment, and inoculation each season. The improvement over FP (N6P26) reached 27%. The yield response to additional N over the low N treatment under the EI and FP management ranged from 6 to 15%, respectively, and was significant during both seasons.

Achievements:
The EI system increased maize yield by 9%, soybean yield by 25%, and chickpea yield by 27%. The EI system also increased soybean protein content and oil production. Ecological intensification approaches were developed not only for maize but also for each of the rotational crops, resulting in greater overall system productivity.

Challenges:
Nitrogen management requires further refining. The soil is providing more N than expected, resulting in low responses to added N. Interpretations of K soil test concentrations may need to be reexamined, since accompanying studies indicated responses to K where none were predicted.

Minnesota, United States

There are two research sites in this project. In 2013, an experiment was established on a rain-fed, tile-drained clay loam Mollisol in south-central Minnesota, USA, near Waseca. In 2014, a second experiment was established on an irrigated loamy sand Mollisol in central Minnesota near Becker. Maize is produced continuously in each experiment. Each experiment compared FP to EI management systems, developed in consultation with researchers, crop advisers, and farmers.

Each experiment used a disk-rip tillage system and received a pre-plant application of S at 17 and 22 kg S/ha at Waseca and Becker, respectively. At both locations, a solution of N (5 kg N/ha) and P (18 kg P_2O_5/ha) was applied in-furrow during planting.

Compared to the FP system, EI had 40% of maize stover harvested after grain harvest and before fall tillage, in combination with a longer-season hybrid and a 14% greater planting density (101,000 seeds/ha).

Two nutrient management approaches (standard and advanced) were evaluated within both the EI and FP systems. Standard nutrient management followed university guidelines for nutrient management (Kaiser, 2011). The advanced nutrient management treatment had P and K applied at rates of removal by grain.

Nitrogen management with standard and advanced approaches differed between the two sites. These applications were in addition to the N applied in the furrow at planting. At Waseca, the standard approach had 180 kg N/ha applied preplant as urea. The advanced approach utilized split-application of N. Urea was applied pre-plant at 152 kg N/ha. At planting, a solution of ammonium thiosulfate (ATS) and UAN was applied in a band placed on the surface 5 cm to the side of the row at 27 kg N/ha. The final 45 kg N/ha was sidedressed at the six leaf-collar maize stage as UAN injected midway between the 76-cm rows.

At Becker, the coarse-textured soil warranted in-season split application of N with both nutrient management approaches. The standard approach used sidedressed applications of urea at early (two and six leaf-collar) maize stages (45 and 185 kg N/ha, respectively). The advanced approach applied 27 kg N/ha in a band on the surface 5 cm to the side of the row at planting, using a solution of ATS and UAN, as at Waseca. Subsequent urea applications were made at the six leaf-collar, twelve leaf-collar, and tasseling maize stages at 78, 85, and 39 kg N/ha, respectively.

Results from 2013 to 2016 at Waseca and 2014 to 2016 at Becker are summarized in **Table 4**. In a region with a long history of intensive maize production and high yields, substantial yield increases were possible at both locations with improved agronomic and nutrient management practices. At both locations, advanced nutrient management combined with the EI management system (EI/advanced) produced greatest maize grain yield; however, the standard nutrient approach combined with the EI system (EI/standard) produced the greatest improvement in economic net return. The EI/standard combination improved net return in three of four years at Waseca and in all three years at Becker. It also had the greatest AE_N and RE_N at Waseca and the second-greatest AE_N and RE_N at Becker.

Moving to an advanced nutrient management approach without other agronomic changes (the FP/advanced combination) was not as consistently or overall profitable at either site as changing agronomic practices and staying with standard nutrient management (the EI/standard combination). At Waseca, the FP/advanced combination produced yields equivalent to the EI/standard combination. Compared to the FP/standard combination, the FP/advanced combination improved RE_N, but did not improve AE_N and consistently reduced net return. At Becker, the FP/advanced combination increased net return in two of three years, but had less overall net return compared to the EI/standard combination. It did, however, increase RE_N with similar yield and AE_N compared to the EI/standard combination.

Table 4. Comparison of ecological intensification (EI) and farmer practice (FP) management systems at Waseca and Becker, MN, USA for dry matter (DM) grain yield, average agronomic efficiency of N (AE_N), average recovery efficiency of N (RE_N), changes in net return due to management treatments, and the number of years when management changes were profitable.

Agronomic management	Fertilizer management	Average dry matter grain yield, kg DM/ha	Average AE_N, kg/kg	Average RE_N†, kg/kg	Average change in net return from management changes, US$/ha	Number of years when management changes were profitable
Waseca						
FP	Standard	9,550 c	62 bc	0.40 c	–	–
	Advanced	10,410 b	57 c	0.46 b	79	0 of 4
EI	Standard	10,730 b	71 a	0.53 a	69	3 of 4
	Advanced	11,690 a	66 ab	0.50 ab	-20	1 of 4
Becker						
FP	Standard	9,170 c	80 c	0.42 c	–	–
	Advanced	10,090 b	92 b	0.58 a	92	2 of 3
EI	Standard	10,460 b	93 b	0.50 b	116	3 of 3
	Advanced	11,750 a	101 a	0.59 a	101	3 of 3

Averages are for 2013-16 at Waseca and for 2014-16 at Becker. Within a column for a given location, means followed by the same letter are not significantly different ($p \leq 0.05$).

No one combination of agronomic and nutrient management produced the greatest performance across all metrics of cropping system performance. At both locations, the EI/standard combination was most profitable while the EI/advanced combination had the highest yield and N use efficiencies. Results from this study demonstrate potential for improvement in corn yield and N use efficiency in environments where customary practices produce high grain yield (>9 t DM/ha). Weather and crop responses are dynamic over time. Additional years of research will provide greater understanding of where, when, and to what extent advanced nutrient and agronomic management approaches can narrow yield gaps while limiting economic risk and enhancing environmental stewardship.

Achievements:

At both locations, EI increased yield much more than expected, indicating that the exploitable yield gap may be greater than previously thought. At the Waseca location, EI based on changes in agronomic practices, but not nutrient practices, produced the most consistent economic net returns, the greatest overall profitability, and the highest AE_N and RE_N. At the Becker location, located on an irrigated sand, EI using both changes in agronomic and nutrient management practices produced the greatest yield, AE_N, and RE_N, and was consistently profitable; however, it did not produce the greatest overall profitability. Greatest profitability combined EI agronomic practices with traditional nutrient management.

Challenges:

Advanced nutrient management adds significant expenditures in both FP and EI management systems. There is a need to fine-tune the combinations of N, P, and K to create more consistent as well as greater overall profitability in the advanced nutrient management system.

Summary

Three research sites in the states of Iowa and Minnesota in the USA, as well as one research site in Southern Russia demonstrate that EI produces maize yields comparable to or exceeding those obtained in FP; however, achievement of other goals such as increased nutrient use efficiency has not always occurred. All four sites are combining what are thought to be improvements to nutrient management with improvements to other agronomic practices. Such integration is vital to achieving other goals beyond just yield increases. Several achievements have occurred, but many challenges remain. BC

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Ecological Intensification Management When Yield Gaps are Wide

By Fernando García, T. Satyanarayana, and Shamie Zingore

Regions with wide yield gaps in maize commonly lack adequate adoption of high-yielding hybrids and crop protection, they are susceptible to water deficits, and have inadequate soil and/or nutrient management practices.

Kenyan research highlights the need to tailor sources of fertilizer in order to account for the multiple nutrient deficiencies associated with low inherent soil fertility.

South Asian and Argentinean studies highlight a need for improved residue management, hybrid selection, planting time, plant population, row spacing, and NPS fertilization management.

Potential yields of maize have increased worldwide as a result of advances in breeding, crop protection, and improved management of soil, water, and nutrients. However, several regions show wide gaps between actual and attainable yields. **Table 1** compares actual yields (Y_A) for maize in several countries to two estimates of yield potential: 1) the yield possible when water availability is limiting (water-limited yield potential, Y_W) and 2) the yield possible with no water limitations (yield potential, Y_P). **Table 1** also provides two estimates of the yield gap calculated by the difference between the ratio of Y_A with either Y_W or Y_P and 80% (the percent of Y_W or Y_P that is realistically attainable). See discussion provided by Grassini et al. in this issue of *Better Crops* for a more detailed explaination on yield gaps.

Table 1. Average actual yield (Y_A), water-limited yield potential (Y_W), yield potential (Y_P), and yield gaps (Y_G) with Y_W and Y_P for maize in different countries.

Country	Average actual yield, Y_A	Water-limited yield potential, Y_W	Yield potential, Y_P	---- Yield gaps, Yg ---- $(0.8 - Y_A/Y_W) \times 100$	$(0.8 - Y_A/Y_P) \times 100$
	---------- t/ha ----------			------- % -------	
Argentina	6.8	11.6	13.8	21	31
Brazil	4.7	8.7	12.5	26	42
Bulgaria	5.9	7.3	13.0	-1	35
Burkina Faso	1.5	6.3	10.3	56	65
Ethiopia	2.2	12.5	16.1	62	66
Germany	9.7	11.0	12.8	-8	4
Ghana	1.7	8.6	14.8	60	69
India	1.6	9.3	12.6	63	67
Kenya	1.9	7.1	14.7	53	67
Mali	1.9	9.7	14.6	60	67
Nigeria	1.6	10.8	14.2	65	69
Poland	6.1	10.5	12.5	22	31
Romania	3.4	9.0	12.2	42	52
Tanzania	1.2	5.4	13.8	58	71
Uganda	1.6	6.9	13.7	57	68
Ukraine	4.7	8.2	12.3	23	42
USA	9.7	12.3	14.0	1	11
Zambia	2.3	11.3	16.9	60	66

Source: http://www.yieldgap.org

What are the causes of these wide yield gaps? Studies have shown that the main causes are: lack of adoption of high-yielding hybrids, inadequate crop protection, water deficits, and inadequate soil and nutrient management practices (Dass et al., 2008; Timsina et al., 2010; van Ittersum et al., 2013; Aramburu Merlos et al., 2015). For example, an analysis of simulated, attainable, and actual maize yields in major maize growing ecologies across South Asia revealed wide management yield gaps ranging from 16 to 57% (**Figure 1**; Saharawat et al., 2010). These gaps were ascribed mainly to low yielding genotypes, poor crop establishment due to random broadcasting of the seed, and inadequate and inappropriate fertilizer nutrient applications that leaves 15 to 45% of the maize area unfertilized and the remainder with imbalanced nutrient applications.

The Global Maize Project (GMP) led by IPNI in collaboration with many research institutions in different countries has shown gaps between actual and attainable yields varying from 0 to 30% (at 80% of Y_W). In these experiments, Y_G could not be attributed to a single factor, but rather to the interaction of the several factors related to the management of resource and input technologies.

Abbreviations and notes: N = nitrogen; P = phosphorus; K = potassium; S = sulfur; Mg = magnesium; B = boron; Mo = molybdenum; Zn = zinc. IPNI Projects KEN-GM46, KEN-GM61, IND-GM22, IND-GM-35, ARG-GM-24, ARG-GM-25.

Sub-Saharan Africa

Maize is the dominant food and cereal crop in sub-Saharan Africa (SSA) and accounts for 28% of the cereal area and 36% of the cereal production (FAO Statistics). Maize production has increased by 500% between 1961 and 2014, mainly due to area expansion, with less than 30% of the increase attributable to productivity, as maize yields have remained less than 2 t/ha on average (**Figure 2**). Despite many areas with high potential for maize production, low yields achieved by smallholder farmers in SSA are associated with complex constraints, including variable and unreliable rainfall, poor soil fertility, low use of fertilizer, limited use of improved seed varieties, and low investments in infrastructure that constrain access to input and output markets. Poor soil fertility conditions and low fertilizer use are recognized as some of the main yield-limiting factors. The use of mineral fertilizers in most countries in SSA has been

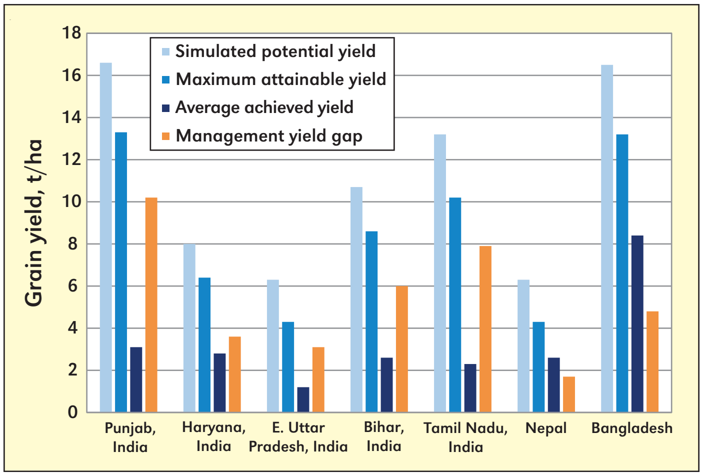


Figure 1. Potential, attainable, and actual yields and management yield gaps under different ecologies across South Asia (Saharawat et al., 2010).

mainly promoted through blanket N+P recommendations that are based on agro-ecological zones.

Increased use and proper management of fertilizer provides the most important step to increased maize productivity in SSA. As investments are being accelerated to help smallholder farmers to increase fertilizer use, parallel efforts are also required to ensure balanced fertilizer use to optimize productivity, fertilizer use efficiency, and minimize nutrient losses.

Maize trials conducted as part of the GMP in Eastern and Central Kenya showed the strong influence of agro-ecological conditions and balanced nutrient application on maize yields (**Figure 2**). Maximum attainable yields achieved with fertilizer over three seasons were higher (8 t/ha) at the Muguga sub-humid site compared with semi-arid Kambiyamwe (5 t/ha). Under farm conditions, yields were very low at both sites (<2.5 t/ha), as a consequence of poor agronomic practices and very low fertilizer application rates. Control yields with no fertilizer applied in on-station trials were higher than on-farm yields, suggesting the capacity to improve yields with improved maize varieties and optimal plant spacing.

In Muguga, yield across all treatments were >5 t/ha. This is more that 500% higher than the current maize yield average in smallholder farming systems in sub-humid zones in central Kenya, indicating a large yield gap between current and attainable yields. Balanced nutrient management (use of N+P+K+S+Zn+B) in the first year resulted in a 2% increase in grain yield over the current N+P recommendation. Second and third years of the balanced treatment increased productivity by 8% and 12% over N+P, respectively. Similar effects of balanced fertilizer application were observed in Kambiyamawe, despite lower yields due to moisture constraints.

The results from the GMP in Kenya highlight the need to change the blanket recommendations and tailor sources of fertilizer to account for the multiple nutrient deficiencies associated with low inherent soil fertility and long-term N+P application. There is growing recognition of the need to address K, secondary, and micronutrients in maize production. Soil mapping programs in Ethiopia and other countries have established high occurrence of S, Zn, and B deficiency, while significant maize responses to S, Zn, B, Mg, and Mo have been observed across the continent. Efforts are also underway in many countries (e.g., Malawi, Kenya, Ethiopia, Rwanda, and Tanzania) to support the development of fertilizer blends containing K, secondary, and micronutrients and make them available at larger scales.

South Asia

A study comparing attainable (Y_W) and actual (Y_A) yields across the major maize growing ecologies reported that the present average Y_A at farmers' fields is only about 50% of the Y_W, which could be increased through adoption of improved technology (Dass et al., 2008). Maize and maize-based systems, extract large amounts of mineral nutrients from the soil due to large grain and stover yields. Proper nutrient management of exhaustive maize-based systems should aim to supply fertilizers adequate to meet the demand of the component crops and applied in ways that minimize loss and maximize the efficiency of use (Jat et al., 2013). Productivity of maize in India has not increased significantly in the recent past. In a situation of plateauing yield levels and growing environmental concerns, practicing Ecological Intensification (EI) could help achieve greater production with minimal environmental impacts of agricultural production systems.

The GMP in India compared EI with farmers' fertilizer practice (FP) at two locations, one at the University of Agri-

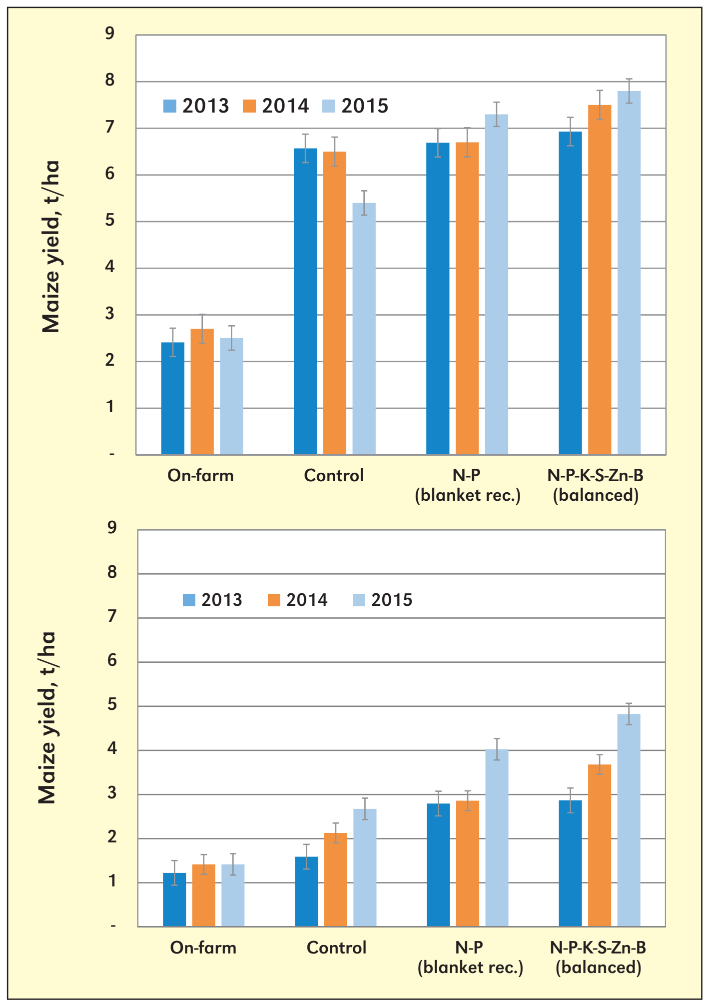
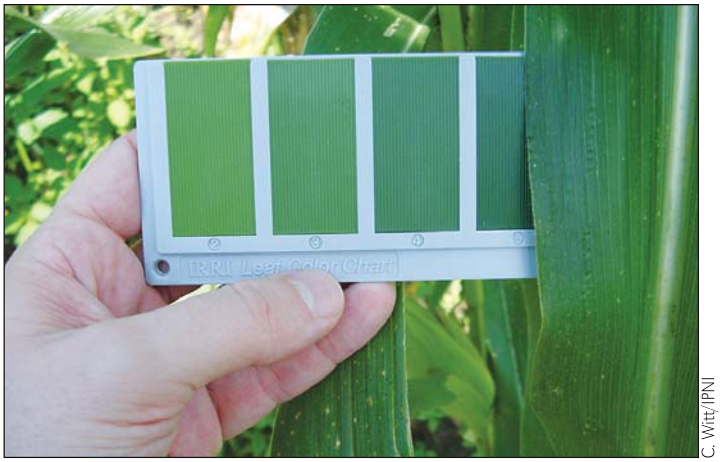


Figure 2. Maize grain yields over three cropping seasons of the Global Maize Project at Muguga in central Kenya (top) and Kambiyamwe in eastern Kenya (bottom). Bars indicate standard errors of the mean.



4-Panel Leaf Color Chart for real time crop N status assessment.

cultural Sciences Dharwad, Karnataka, and the other at Birsa Agricultural University, Ranchi, Jharkhand. EI considered application of the right rates of N, P_2O_5, and K_2O for maize production, involving all the limiting secondary and micronutrients. 4R nutrient management was combined with other best management practices such as planting time, planted population, hybrid selection, residue management, etc.

Maize was planted during the sixth consecutive monsoon season in a Vertisol at the experimental station of the University of Agricultural Sciences, Dharwad, Karnataka. EI recorded a significantly higher yield (6.5 t/ha), which was 26% higher than FP and consistent with the results obtained in the last five years (**Table 2**). The higher grain yield under EI may be attributed to higher crop uptake of N (162 kg/ha), P (72 kg/ha), and K (53 kg/ha), which were 19, 20, and 26% higher than the FP, respectively. A net return of US$1,080/ha was obtained with EI, which was 22% higher than that obtained with FP (US$883/ha). The other metrics considered for evaluating the performance of EI point to enhanced nutrient use efficiency. Partial Factor Productivity for N (PFP_N), was higher in EI (18.7) than FP (17.1). Agronomic efficiency (AE_N) was also higher under EI (35.7) than with FP (9.1).

Table 2. Effect of Ecological Intensification (EI) versus Farmer Practice (FP) on maize yield at Dharwad (India).

	Grain yield						
	2009	2010	2011	2012	2013	2014	Mean
Treatments	----------	----------	----------	t/ha	----------	----------	----------
EI	4.5	4.1	3.9	6.4	6.8	6.5	5.4
FP	3.4	3.3	2.9	5.4	5.6	5.5	4.3
EI - FP	1.2	0.8	1.1	1.1	1.2	1.1	1.1*

*Significant at $p<0.05$

Long-term evaluation of EI within a maize-wheat rotation in Ranchi, Jharkhand with red and lateritic soil produced a six-year average grain yield of 6.2 t/ha—amounting to 123% more than the FP average (**Figure 3**). This EI research effectively determined the right rates and timings for N application to optimize both yield and profitability of this maize-wheat cropping system. Applying 240 and 150 kg N/ha (in maize and wheat respectively) split between three applications based on Leaf Color Chart-based N assessment proved to be most beneficial (Biradar et al., 2012).

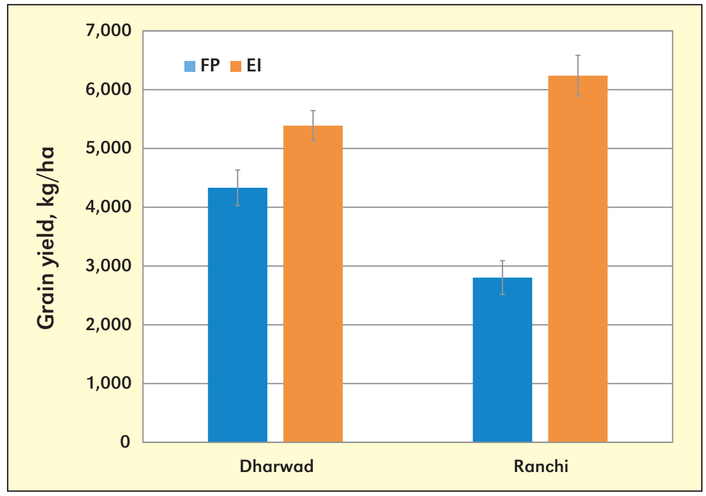


Figure 3. Average grain yields of maize under farmers' practice (FP) and ecological intensification (EI) at the Global Maize Project sites in India. The data represents an average of six years (2009-14). Vertical bars show standard errors of the means.

Argentina

Comprehensive estimations of gaps (at 80% of Y_W) find 20% differences between current and attainable maize yields at the country level, with regional variations between 9% and 49% (Aramburu Merlos et al., 2015). This wide regional variability of Y_G has been attributed to differences in cropping history and technology adoption by farmers (nutrient use, control of insects, pests, and diseases).

Attainable yields were positively related to the variation in water supply, however yield gaps were larger under conditions of less restricted water availability. In dry years, water is the most limiting factor for crop production, and Y_G is relatively small. In years when water is less limiting, higher Y_G might be related to risk aversion behavior by farmers, which reduces the chances of achieving higher yields in these favorable years by inducing a level of management, and nutrient application, based on yields commonly reached with normal or moderately adverse weather conditions.

Unstable political and economic conditions further reinforce risk aversion by farmers who have been reluctant to adopt proven technologies such as high plant populations, early planting dates, and fertilization, despite the abundant information generated through research. Aramburu Merlos et al. (2015) partially attribute the estimated Y_G for maize to N deficiencies and decreasing soil P availability as a result of long-term negative P balances.

Data from six years of the GMP at Argentina found that improved soil and crop management increased grain yields by 22% at the Balcarce site and by 43% at the Paraná site (**Figure 4**). Differences in management between FP and EI were related to hybrid, plant population, row spacing, and NPS fertilization management (**Table 3**). These improved practices have been adopted from results of previous research (Barbieri et al., 2008; Calviño et al., 2003; Caviglia et al., 2004; Sainz Rozas et al., 1997). The EI treatment has also shown positive impacts in water and N use efficiency (Caviglia et al., 2012; Picone et al., 2013; Cafaro La Menza et al., 2014; Maltese et al., 2015), and in net returns.

Nutrient requirements and response in maize have been

Table 3. Main crop management practices for Farmer Practice and Ecological Intensification at the Global Maize Project sites in Argentina.

Management factor	Farmer Practice	Ecological Intensification
Cultivar	Most common hybrid (RoundReady®)	High yielding and stable (RoundReady® and Bt)
Population, seeds/m^2	6 to 6.5	8 to 8.5
Row spacing, m	0.7	0.525
N fertilization	Fixed rate (regional average); Urea applied at planting	Soil test-based rates; UAN applied at V6
P fertilization	30% less	Buildup to 20 ppm
S fertilization	None	5 kg/ha

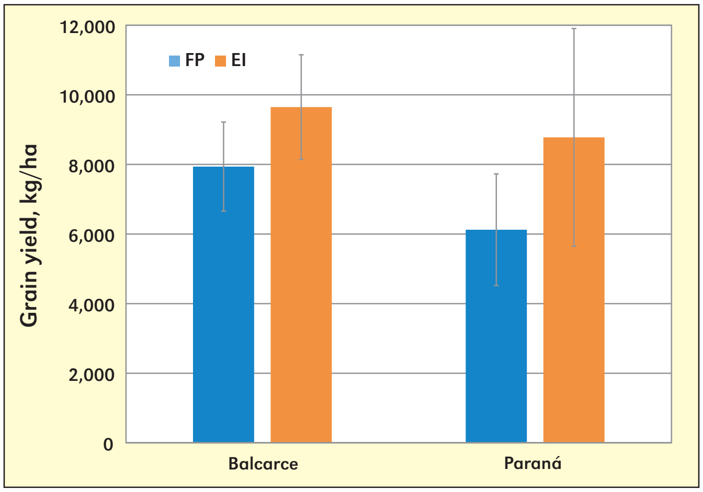


Figure 4. Average grain yields of maize under farmer's practice (FP) and ecological intensification (EI) treatments at the Balcarce and Paraná sites of the IPNI Global Maize project at Argentina. Averages for six growing seasons (2009-14) under a maize-wheat/double cropped soybean rotation. Vertical error bars are standard deviations of the means.

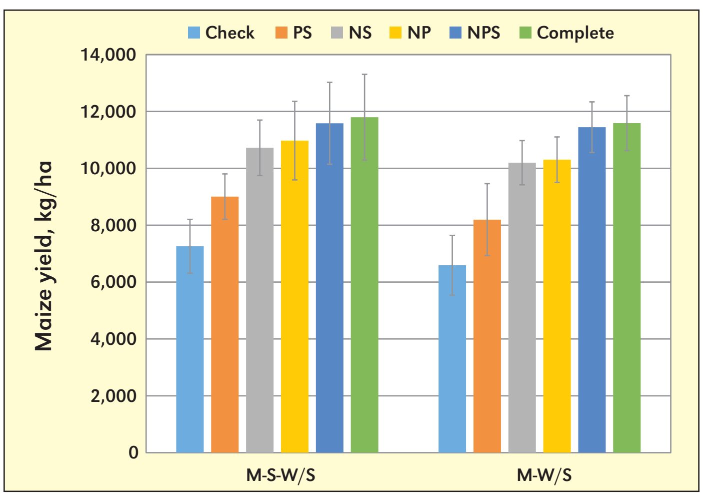


Figure 5. Average maize grain yields under maize-soybean-wheat/double cropped soybean (M-S-W/S) and maize-wheat/double cropped soybean (M-W/S) rotations in long-term fertilization experiments in the central Pampas of Argentina. Averages for five and seven growing seasons (2000 to 2014) for M-S-W/S and M-W/S, respectively. Vertical error bars are standard deviations of the means. Source: CREA Southern Santa Fe-IPNI-ASP.

extensively demonstrated through field experimentation and widely reported in the literature. As an example of the impact on yields, on-farm research in the central Pampas of Argentina has shown that 4R nutrient management could increase maize grain yields by 24 to 76% compared to unfertilized treatments (**Figure 5**).

Summary

Wide yield gaps in maize are still common in several regions of the world. Knowledge and information is available to reduce these wide gaps. 4R nutrient management is a key set of practices among the several management practices involved in getting higher yields. Extension work, public policies, and improved economic and political scenarios could greatly contribute to sustainably narrowing the maize yield gap. BC

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Ecological Intensification to Increase Nutrient Use Efficiency while Maintaining Yield Levels: An Example from China

By Rongrong Zhao and Ping He

Results from an ecological intensification (EI) study conducted in a spring maize cropping system in Jilin found significantly greater grain yield in three of five years and higher nutrient use efficiency for all years under EI.

Researchers anticipate that widespread adoption of EI practices will bring sustained benefits to maize cropping systems in northeast China.

China is facing the challenges of maintaining both food security and sustainable agricultural development under the great pressure of its growing population. As one of the most important cereal crops in China, maize plays a significant role in expanding the overall grain production capacity.

The attainable yield for maize in northeast China could be as large as 16.8 t/ha through high input of nutrients, water, labor, and other cropping system improvements such as crop straw recycling, no-tillage, and application of organic manure (Fan et al., 2011). The cost of this high yield is the high input of fertilizer, pesticides, and higher environmental risks including the degradation of land and freshwater, greenhouse gas emissions, and the loss of biodiversity. Attaining high grain production while minimizing its environmental cost is an important goal for China. High fertilizer consumption and low nutrient use efficiency have raised concerns by both scientists and the fertilizer industry.

Between 2009 and 2013, a long-term field trial based on the EI concept was conducted in Gongzhuling, Jilin Province. Two main treatments were defined in the project to directly compare Farmer's Practice (FP) with EI (**Table 1**). Farmer's Practice used higher fertilizer application rates, which were not split across the growing season. Lower planting populations of local varieties are also common practice in northeastern China.

Crop Yield and Yield Gap

Among five years, grain yields for the EI treatment in 2010, 2012, and 2013 were not significantly different from FP; however, the grain yields of EI in 2009 and 2011 were significantly higher than FP treatment (p<0.01; **Figure 1**). The average grain yield of EI (180 N) and FP (250 N) treatments were 11.8 t/ha and 11.4 t/ha, respectively, which were less than the 12 t/ha of average irrigated maize grain yield in Nebraska and Southeast Asia, but higher than the 10.4 t/ha of average spring maize grain yield in northeast China

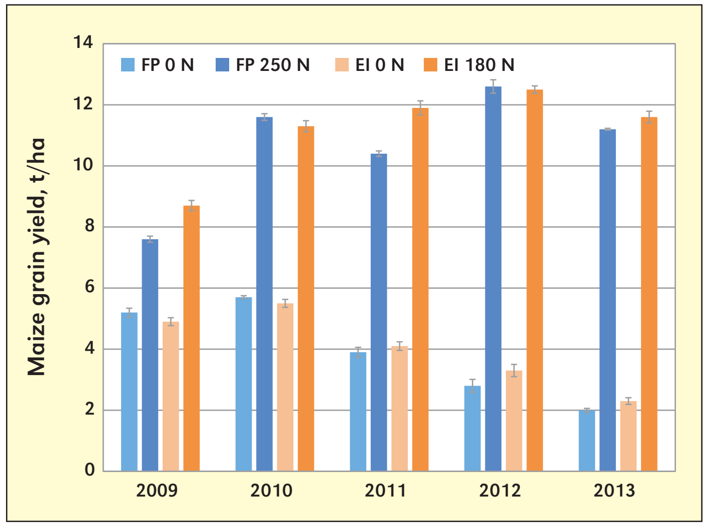

Figure 1. Maize grain yield (15.5% moisture content) at Gongzhuling city, Jilin Province (2009 to 2013). Error bars indicate standard errors of the mean.

(**Figure 1**). The water-limited potential yields (Y_W) of the EI treatment simulated by the Hybrid-Maize model ranged from 10.6 to 15.9 t/ha during 2009 to 2013 (**Table 2**). The mean grain yield of irrigated maize in Nebraska was 11 t/ha, while the experimental-field grain yield of irrigated maize was 13.8 t/ha (Setiyono et al., 2010). The average simulation of Y_W was 14.3 t/ha across five years, with averaged yields of 11.2 t/ha and 10.7 t/ha in EI and FP treatment, which reached 78 and 75% of the simulated Y_W, respectively. Using 85% Y_W as an exploitable level, the calculations of 85% Y_W with a range of 9.0 to 13.5 t/ha from 2009 to 2013 are shown in **Table 2**. The mean Y_G varied from 0.3 to 1.6 t/ha for EI 180 kg N/ha treatment, meanwhile, the mean Y_G ranged from 0.5 to 3.1 t/ha for the FP 250 kg N/ha treatment (**Table 2**). This means that agricultural technology or nutrient management could be the limiting factor when the potential yield ceiling exists.

Table 1. Treatments used in field trials in Gongzhuling, Jilin Province.

	Fertilizer applied[1], kg/ha					
Treatment	N	P_2O_5	K_2O	N Timing[2]	Hybrid	Population
EI	180	70	90	1/4 basal: 2009-2013	Pioneer 335	65,000/ha
				2-way: 2009-2011		
				3-way: 2012-2013		
FP	250	145	100	All basal	Local variety	50,000/ha

[1] In 2009, 30 kg S/ha and 5 kg Zn/ha were applied in EI based on soil test results.
[2] Basal = planting day; For EI, 2-way = planting day + tasseling stage, 3-way = planting day + heading stage + tasseling stage.

Nutrient Use Efficiency

As integrative indices that quantify total economic output relative to the utilization of all nutrient resources in the system, agronomic efficiency (AE), partial factor productivity (PFP), recovery efficiency (RE), and partial nutrient

Abbreviations and notes: N = Nitrogen; P = phosphorus; K = potassium; S = sulfur; Zn = zinc. IPNI Project CHN-GM20.

He Ping/IPNI Image

Dr. He Ping comparing maize growth response to EI treatments at the Jilin Global Maize Research Site.

balance (PNB) are useful measures of nutrient use efficiency (NUE). Definitions of these metrics are provided by Norton et al. in this issue of *Better Crops*.

Agronomic efficiency of N (AE_N) in EI ranged from 20.6 to 51.8 kg/kg during the five years of study (**Table 3**) with the average being 39.7 kg/kg. Correspondingly, AE_N in FP ranged from 9.5 to 39.3 kg/kg with an average of 26.9 kg/kg, which was 32% lower than EI. Partial factor productivity of N (PFP_N) in EI ranged from 48.1 to 69.7 kg/kg with an average of 62 kg/kg. The PFP_N in FP varied from 30.3 to 50.2 kg/kg with an average of 42.5 kg/kg, which was 31% lower than EI. Recovery efficiency of N (RE_N) in EI ranged from 0.29 to 0.88 kg/kg with the average value being 0.66 kg/kg. The RE_N in FP ranged between 0.21 to 0.64 kg/kg with the average values being 0.50 kg/kg, which was 24% lower than EI. The partial nutrient balance of N (PNB_N) ranged between 0.50 to 0.73 kg/kg in EI and from 0.36 to 0.56 kg/kg in FP. The average PNB_N was 0.65 kg/kg in EI, which was 31% higher than FP, which had an average value of 0.45 kg/kg.

Conclusions

The use of EI practices represents a more sustainable and economic way of employing knowledge and technologies in agriculture development than current farmer practices and aims to address food and environmental security. In our study, optimized planting density, fertilizer N rate and application timing were implemented to improve corn grain yield, and likely reduce any negative impacts on the environment during 2009 to 2013 in Jilin. Compared with FP, the EI treatment maintained crop grain yield, and improved nutrient use efficiency. BC

Table 2. Yield gap based on rain-fed yield potential (Y_W), calculated using Hybrid-Maize, ecological intensification (EI), and farmers' practice (FP) and the modeled yield for Jilin from 2009 to 2013.

	--- Observed yield ---		Y_W[a]	$85\%Y_W$[b]	Yield gap, $0.85Y_W$-EI	Yield gap, $0.85Y_W$-FP
	---------- t/ha ----------					
	Ecological Intensification	Farmers' Practice				
2009	8.7	7.6	10.6	9.0	0.3	1.4
2010	11.3	11.6	14.2	12.1	0.8	0.5
2011	11.9	10.4	15.9	13.5	1.6	3.1
2012	12.5	12.6	15.7	13.3	0.8	0.7
2013	11.6	11.2	15.0	12.8	1.2	1.6
Mean	11.2	10.7	14.3	12.1	0.9	1.5

[a] Potential yield of maize based on rain-fed conditions by using Hybrid Maize Model
[b] 85% of Y_W is the exploitable yield ceiling.

Table 3. Effects of the ecological intensification on agronomic N use efficiency (AE_N), partial factor productivity of applied N (PFP_N), recovery efficiency of N (RE_N), and partial nutrient balance of N (PNB_N) in maize from 2009 to 2013.

Year	Cultivation systems	AE_N, kg/kg	PFP_N, kg/kg	RE_N, kg/kg	PNB_N, kg/kg
2009	EI	20.6 a	48.1 a	0.28 a	0.50 a
	FP	9.5 b	30.3 b	0.21 a	0.36 b
2010	EI	32.0 a	62.7 a	0.63 a	0.73 a
	FP	23.0 b	46.1 b	0.42 b	0.44 b
2011	EI	43.0 a	64.8 a	0.71 a	0.68 a
	FP	26.1 b	41.6 b	0.64 b	0.56 a
2012	EI	51.1 a	69.7 a	0.80 a	0.71 a
	FP	39.3 b	50.2 b	0.62 a	0.50 b
2013	EI	51.8 a	64.6 a	0.88 a	0.65 a
	FP	36.6 b	44.5 b	0.63 b	0.42 b

Letters differing within a year indicate a statistically significant difference (Tukey-HSD) between EI and FP treatments.

Acknowledgments

This research was supported by the Global Maize Project (GMP), International Plant Nutrition Institute (IPNI), and CAAS-IPNI Joint Lab for Plant Nutrition Innovation Research. We would like to thank the scientists from Academy of Agricultural Sciences of Jilin. We are also grateful for the patience and help offered by the farmers in our study.

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Ecological Intensification When Maize is Not the Primary Crop

By Eros Francisco

Today in Brazil, the most common way to grow maize is as a 2nd crop after soybean harvest.

This cropping system evolution has also brought research, since the year 2000, on most beneficial cover crop species that can fit as intercrop with maize.

Such cropping system intensification raises questions about needed adjustments to N management for both high yield and improved soil quality

Maize has traditionally been grown worldwide as a primary crop during the summer to provide grain for both human and animal nutrition. In temperate regions, no other crop is grown after the maize harvest in the fall, but in some tropical or subtropical regions of the world maize can be grown throughout the entire season with minimal limitation, and be a secondary crop within a cropping system.

In Brazil, the amount of land devoted to growing maize in the summer (1st crop) was about 92% of the total area planted to maize until the year 2000. Generally, in the southern region, maize was seeded early in the spring and harvested by the end of the summer when a winter crop (wheat, oat, or barley) was sowed. In recent decades, farmers of the Midwest region began to grow maize more intensively in the fall, as a 2nd crop following soybean harvest. Today, the land planted to 1st crop maize is only 60% of its historic high of the mid 1980s (**Figure 1**). In the 2016 season, 2nd crop maize occupied 66% of the total 15.9 million (M) ha planted to maize, and represented 62% of Brazil's total maize production (66.7 M t; Conab, 2016). Francisco et al. (2014) have described the latest changes that have occurred in Brazilian soybean cropping systems to result in this shift to growing maize as a 2nd crop.

Commonly, farmers have grown 2nd crop maize alone, but recent crop and soil management research is revealing benefits of intercropping maize with cover crops, either legumes or grasses. Some benefits are related to soil quality, such as better aggregation, increased soil organic carbon and water holding capacity, more N availability via indigenous fixation with legumes, and others. Cropping system benefits include higher nutrient cycling, better weed control, land use intensification, nematode control, and so on. But for many farmers, the most beneficial outcome of intercropping maize with grasses is to have a pasture for grazing after maize harvest, which has allowed them to integrate grain and beef production in the same area.

The Global Maize Project (GMP) has two sites in Brazil. Field trials have been carried out for more than six years and are located in the states of Paraná and Mato Grosso, which well represent regional cropping systems where maize is not the primary

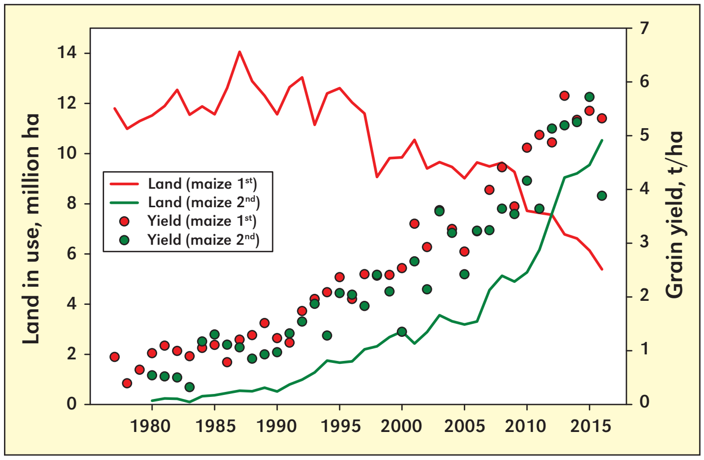

Figure 1. Historical use of land and yield of 1st and 2nd maize crops in Brazil. Source: Conab (2016).

crop. **Table 1** summarizes the components of both studies. In the south region (Paraná), the crop rotation is generally composed of wheat or black oat in the winter and soybean or maize in the summer, whereas in the Midwest region (Mato Grosso) maize is grown in the fall as a 2nd crop after soybean harvest.

The alternative under evaluation, proposed as the ecological intensification (EI) in each region, was to introduce legumes

Abbreviations and notes: N = nitrogen; C = carbon. IPNI Project GM-18; GM-19.

Table 1. Treatments under evaluation with maize in the states of Paraná and Mato Grosso, Brazil.

#	Description	Crop sequence† Spring/summer	Fall/winter	N applied to maize, kg N/ha
	Paraná			
1	Farmer practice	Soybean (1) Maize (2)	Wheat (1) Black oat (2)	0, 70, 140, 210
2	Farmer practice + silage production	Soybean (1) Maize (2)	Barley (1) White oat (2)	
3	Ecological intensification	Soybean (1) Maize (2)	Black oat (1) Forage pea†† (2)	
	Mato Grosso			
1	Farmer practice	Soybean	Maize	0, 35, 70, 110
2	Farmer practice + cover crop	Soybean	Maize+*Brachiaria*†††	
3	Ecological intensification	Soybean (1) Soybean (2) Maize+*Brachiaria* (3)	Maize+*Brachiaria* (1) Sunn hemp†††† (2) *Brachiaria* (3)	

† Number in parenthesis represent year in the crop sequence.
†† *Pisum sativum* subsp. *arvense* (L.) Asch. and Graebn. ††† *Brachiaria ruziziensis* Germ. and C.M. Evrard.
†††† *Crotalaria spectabilis* Roth and *Crotalaria ochroleuca* G. Don.

Table 2. Grain yield, N removal, and performance indicators of maize in response to the ecological intensification of the cropping system in two regions of Brazil.

#	Description	Grain yield t/ha	N removal kg/ha	PNB† kg/kg	PFP†† kg/kg
	Paraná				
1	FP	11.05 b	144 b	0.96	99 b
2	FP+Silage	10.98 b	143 b	0.97	99 b
3	EI	12.15 a	169 a	1.13	108 a
msd§		(0.44)	(19.5)	(0.65)	(5.2)
	Mato Grosso				
1	FP	7.40	116	2.20	133
2	FP+CC	7.14	113	2.12	129
3	EI	6.96	109	2.08	128
msd		(0.72)	(19.5)	(0.37)	(15.4)

† Partial nutrient balance: kg nutrient removed/kg nutrient applied. †† Partial factor productivity: kg grain/kg nutrient applied. § Minimum significant difference. Means represent the average of all N tested rates (0, 70, 140, and 210 kg N/ha in Paraná and 0, 35, 70, and 105 kg N/ha in Mato Grosso), and followed by the same letters do not differ by Tukey test (p<0.1).

into the system to increase N availability via biological fixation and serve as a positive factor for N use efficiency, as well as to intercrop a type of grass with maize to add more crop residue for the purpose of increasing soil C content. Also, adjustments in N supply were required to fulfil the cropping system demands, so a response curve of N rates was added as a split plot factor. All other nutrients were equally and adequately applied.

Yield and Nutrient Use Efficiency

The insertion of forage pea into the EI cropping system in Paraná significantly increased grain yield of maize by more than 1 t/ha, as compared to the farmer practice (FP) system (**Table 2**). It also supported higher N removal and benefited N use efficiency of the system. EI produced higher partial factor productivity (PFP; 108 kg grain/kg N applied), which represented a 9% increase compared to FP. The amount of N removed in EI was higher, as well as the partial N balance (PNB), indicating that the system is adequately supplying N to the crop. The intermediate system tested (FP plus silage production) performed similarly to FP.

Another positive effect of EI was noted in maize yield response to N application. **Figure 2** presents maize yield and N performance indicators in response to N rates among cropping systems in Paraná. No response of yield to N applied was observed in EI, while a significant and positive response to N rates was shown in FP. On average, grain yields obtained with 140 kg N/ha and 210 kg N/ha were equal and higher than observed with 70 kg N/ha and control (no N applied), while PFP and PNB performed differently in each rate showing decreasing values with increasing N rates. Due to the high amount of N supplied by forage pea fixation, maize yield in EI was significantly higher for the control (2.6 t grain/ha greater) and at the lowest N rate tested (1.8 t grain/ha greater), as compared to FP, respectively.

On the contrary, growing a legume crop (sunn hemp) in

Aerial view of Global Maize Project site in Mato Grosso, Brazil.

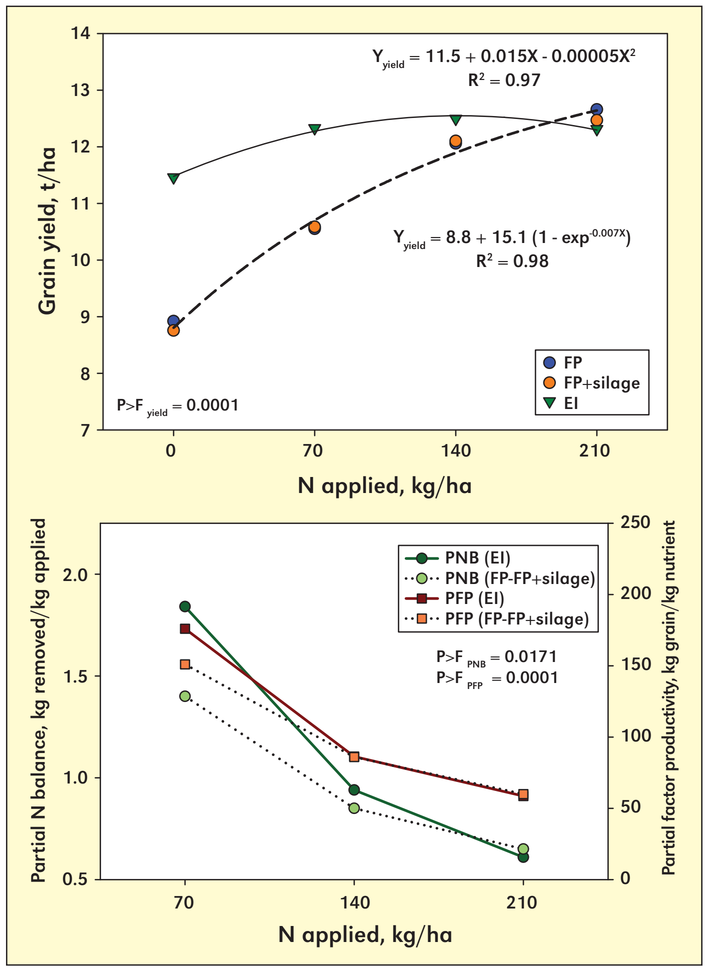

Figure 2. Maize yield (upper) and nutrient performance indicators (lower) in response to N rates in Paraná, Brazil, according to cropping systems: farmer practices (PF), farmer practices plus silage production (FP+silage), and ecological intensification (EI). Partial nutrient balance (PNB): kg N removed/kg N applied. Partial factor productivity (PFP): kg grain/kg N applied. Average of 4 years.

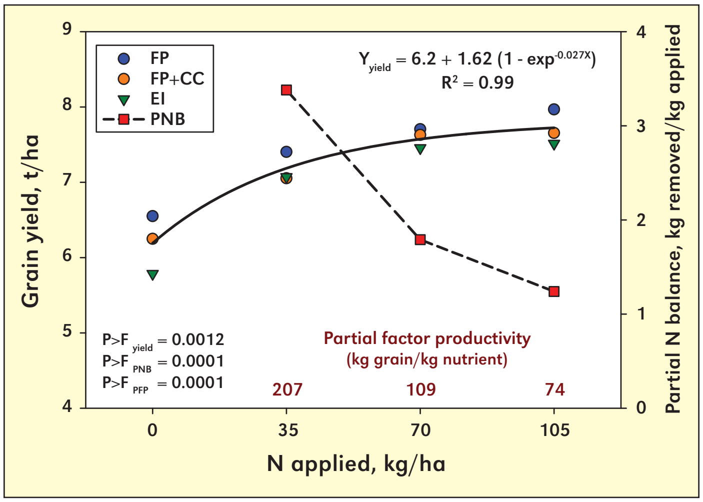

Figure 3. Maize yield and nutrient performance indicators in response to N rates in Mato Grosso, Brazil, according to cropping systems: farmer practices (PF), farmer practices plus cover crop (FP+CC), and ecological intensification (EI). Average of 6 years.

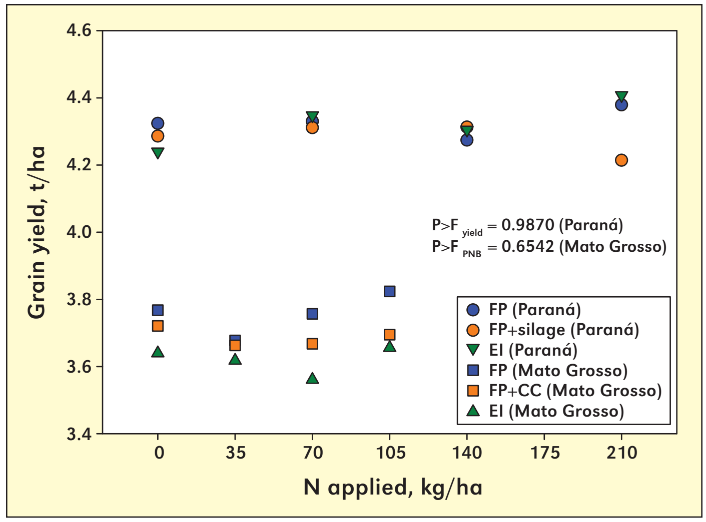

Figure 4. Soybean yield in response to N rates previously applied to maize in Paraná and Mato Grosso, Brazil, according to the cropping systems: farmer practices (PF), farmer practices plus silage production (FF+silage), farmer practices plus cover crop (FP+CC), and ecological intensification (EI). Average of 4 years in Paraná and 6 years in Mato Grosso.

the fall following soybean harvest as part of the EI treatment in Mato Grosso showed no benefit to maize yield, as in Paraná (**Table 2**). Despite no statistical significance, maize yield of EI consistently trended lower than FP, as well as the amount of N removed and the value of performance indicators. After six years of study, average maize yield of EI trended 0.5 t grain/ha lower than FP. Two possible reasons have been provided to explain this potential difference: 1) competition of *Brachiaria* grass intercropped with maize for water and nutrients, or 2) N immobilization by the higher amount of biomass added to the soil. Regarding the first reason, research results are showing that intercropping grasses with maize can reduce grain yield in a large range depending on the type of grass, time of seeding, use of herbicide, and weather conditions (Borghi and Crusciol, 2007; Ceccon et al., 2013). In this case, the reduction in maize yield caused by the association with *Brachiaria* grass was 0.26 t grain/ha on average (FP vs. FP+CC), which could not be overcome by growing sunn hemp for extra N in EI.

Figure 3 presents maize yield and N performance indicators in response to N rates among cropping systems in Mato Grosso. A significant response of all parameters to N rates was observed. All rates of N applied performed equally to increase grain yield as compared to control (no N application), while PFP and PNB performed differently in each rate showing decreasing values with increasing N rates. Grain yield was increased 16%, 23%, and 24%, respectively, with 35, 70, and 105 kg N/ha, as compared to control (no N applied).

Soybean grain yield was not affected by the cropping system nor by the rate of N previously applied to maize in both studies (**Figure 4**). In Paraná, grain yield of FP and EI showed a slight positive trend of increase with higher N rates, as compared to FP+silage, but no statistical difference was observed. In Mato Grosso, soybean grain yield of each cropping system was numerically higher with increasing N rates in the first three years of the study, but this trend was inverted later on, likely in response to higher maize grain yields observed with new hybrid. Also, soybean yield of EI was a bit less than FP indicating that more N may be required in the system to deal with higher amounts of C added via crop residues.

Summary

The use of performance indicators is an adequate way to compare the efficiency of different cropping systems in supplying crop nutrients. Values of PFP and PNB observed in Paraná showed that N use efficiency in EI was much higher than in FP, representing a possibility of saving resources while increasing grain yield. On the other hand, the performance of EI in Mato Grosso was not as expected and further investigation is necessary to understand the interaction of growing factors.

The weather conditions of fall/winter, such as precipitation and temperature, are crucial for growing cover crops that can positively affect the cropping systems. In regions where precipitation is accumulated in the summer time and short rains occur in the rest of season, like in Mato Grosso, the benefits of EI via use of cover crops can be suppressed.

Nitrogen is a key nutrient for high yielding maize, as shown in both studies, but its efficient use must be pursued in EI systems. The results presented above indicate that lower rates of N can be applied in Paraná when farmers decide to adopt EI. BC

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The Role of Precision Agriculture in Closing Maize Yield Gaps

By Steve Phillips and Kaushik Majumdar

The specific set of agricultural technologies needed to address our goals for global food security will vary amongst regions, but precision agriculture (PA) has often been identified as a key component in developing high-production, high-efficiency systems.

Precision agriculture is often associated with technology or other data-gathering methods to make site-specific decisions regarding farm management. However, it has evolved into more than just tools and technology, it is an approach to whole-farm management that recognizes and incorporates spatial and temporal variability into the decision-making process for producers with varying levels of access to technology.

The key component of PA in many regions is a global navigation satellite system such as the Global Positioning System (GPS). The satellites are used for precise navigation of equipment and geo-referenced positioning to collect high-resolution information from crops and soils. GPS-based manual guidance technologies have been popular for a decade or so in several countries, but in recent years, more producers and custom applicators have switched to automated guidance. A recent survey conducted in the Midwest USA, indicated that over 80% of custom applicators are using automated guidance (Erickson and Widmar, 2015). Other highly adopted automated technologies are GPS-enabled sprayer section control with nearly 75% of custom applicators offering this service and harvest monitors (nearly 60% usage among farmers).

Precision maize planting using automated guidance and planter section control.

Automated guidance results in greater accuracy of each pass across the field during planting, fertilization, and pesticide application resulting in optimization of inputs and a reduction in field time by approximately 17% (Watson and Lowenberg-DeBouer, 2004).

In maize production, the elimination of skips and multiple seed drops within the row greatly improves the stand establishment and results in increased yield and profitability. Wade and Douglas (1990) reported that uneven plant distribution can reduce grain yield up to 30%, while Doerge et al. (2002) similarly reported that individual plant yields were maximized when plants were within 5 to 7 cm of equidistant spacing. Mechanized planters that can deliver precisely spaced, single seeds are ubiquitous in developed farming systems, but socio-economic barriers in many developing countries have limited the opportunities for adoption of this technology and much of the maize is planted by hand. Even in these conditions, precision seeding (equidistant spacing) has been shown to increase yield by an average of 1,130 kg/ha compared with the farmer practice (Chim et al., 2014).

Adoption of these automated types of technologies that don't depend on site-specific information to extract value has been rapid and steady, while adoption of others that require agronomic calibration (such as variable-rate technology) have been slower growing. However, the adoption of these services has been increasing at a faster rate the past few years as prescription methodology has improved (Erickson and Widmar, 2015). One of the site-specific technologies that is growing rapidly in popularity for maize production is variable rate seeding. Most of these applications are map-based, with management zones created using soil sampling data, crop yield history, and other soil and crop information collected using remote or proximal sensing. It is well documented that areas within fields possess different characteristics that affect crop performance and should be managed accordingly. The basic objective is to increase seeding rate in those areas where yield potential is higher and plant fewer seeds in areas of lower yield potential. A study in Virginia that is part of the IPNI Global Maize project (IPNI, 2017a) is evaluating the effect of variable rate seeding on maize yield. In 2015 and 2016 a comparison

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

Table 1. Maize grain yield (t/ha) following variable or fixed seeding rates. IPNI, 2017a.		
	2015	2016
Variable rate	15.6 a	12.5 a
Fixed rate	14.6 b	11.9 b

Variable rate = seeding rates ranged from 59,280 to 79,040 seeds/ha; Fixed rate = seeding rate was 71,630 seeds/ha. Means within a column followed the same letter are not significantly different at $p<0.10$.

was made between maize grain yield from a crop planted at a single seeding rate of 71,630 seeds/ha and one that was variably seeded at rates ranging from 59,280 to 79,040 seeds/ha based on soil types and historical yield maps. In both years, the variable rate treatment yielded significantly more grain than the single seeding rate (**Table 1**).

In the USA, variable rate fertilization is the most common site-specific PA technology with nearly 70% of dealerships offering the service and nearly 50% of the market area utilizing the technology (Erickson and Widmar, 2015). Similar to variable rate seeding prescriptions, fertilizer management zones are established on a variety of parameters that may include soil fertility, soil physical characteristics, yield, and other information. The redistribution of fertilizer in the field is intended to improve nutrient use efficiency (NUE) by minimizing over-application while simultaneously increasing rates to areas of the field with higher than average yield potential. While some studies have shown variable rate technology to result in reduced average fertilizer rates and higher NUE (Thomason et al., 2011), the practice does not necessarily mean that overall fertilizer input will be reduced. **Figure 1** illustrates variable rate P and K application maps for a field in Virginia. These figures are both examples of variable rate nutrient applications that did not result in any change in total fertilizer applied compared with the recommendation that would have followed a random composite soil sampling. The difference is that in the case of a single rate application of P, only 60% of the field would have received the correct rate while 20% would have been under fertilized by approximately 17%, and 20% of the field would have received 28% more P than was required. The result for a single fertilizer rate of K would have been more accurate with about 70% of the field receiving K within 4% of the recommended rate, while 25% would have been over fertilized, and only 5% under fertilized.

Another technology used to make variable-rate nutrient applications, particularly for N, is crop canopy sensors. There are several commercially available crop sensors that have been widely researched and the technology is becoming an accepted practice for determining in-season crop N needs in several countries around the world. Melchiori (2010) reported increased partial factor productivity (PFP; kg grain/kg N) in maize using sensor-based N rates compared to a standard fixed rate. Their work covered seven growing seasons in Argentina and evaluated the ability of the sensor to determine optimum

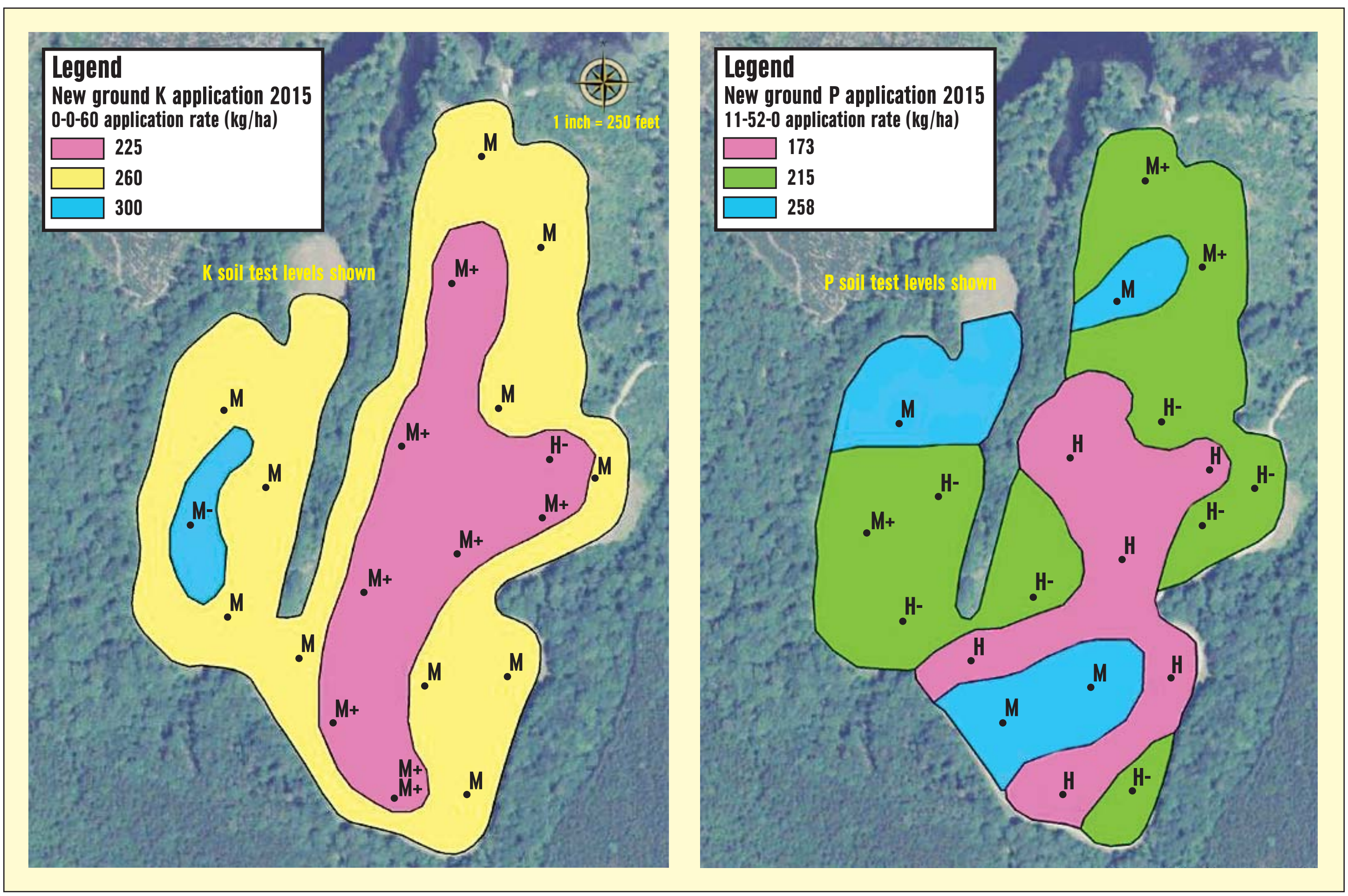

Figure 1. Variable rate phosphorus (P) and potassium (K) application maps, based on agronomic interpretation of multiple soil tests taken with a field. M = moderate; H = high. Thomason et al., 2011.

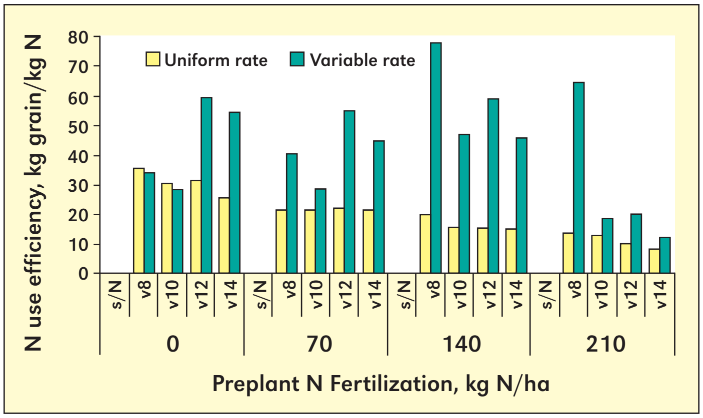

Figure 2. Nitrogen use efficiency (partial factor productivity for N) in maize following N fertilization between V8 and V14 using sensor-based variable rates or uniform fixed rates at varying levels of preplant N fertilization. Melchiori, 2010.

sidedress N rates for maize across a range of growth stages and preplant N rates. Similar to other published studies, they found no difference in grain yield between the methods, but a higher PFP when using the sensor-based system (**Figure 2**).

Relative to economic benefits, some PA tools can save on labor costs (i.e., autoguidance), some can reduce input costs (i.e., automatic section control), and some result in better management for higher yield (i.e., variable rate seeding and fertilization). Griffin and Lowenberg-DeBoer (2005) published a review of 234 studies where PA was found to be profitable in 68% of the cases. Nearly 40% of the studies were done on maize with 73% reporting economic benefits. Silva et al. (2007) also reported on the economic value of PA for maize and found that on average PA was more costly than traditional farming but resulted in higher yields and subsequently higher revenues.

It is a common belief that the value of PA can only be realized in the large-scale, high-profitability farming systems found in developed nations. Thus, PA technologies have often been viewed as irrelevant to smallholder systems because of lower profitability, lack of education and training opportunities, and grower resistance. For some specific technologies, this may be true, but several precision nutrient management strategies exist and are being used successfully in smallholder systems including leaf color charts, omission plots, handheld crop sensors, and web-based decision support software packages.

One PA tool developed specifically for smallholders is the Nutrient Expert® (NE) decision support software (IPNI, 2017b). Nutrient Expert enables crop advisors to develop fertilizer recommendations that are tailored to a specific field or growing environment, taking into account important factors affecting nutrient management recommendations and uses a systematic approach of capturing information to develop location-specific recommendations. Nutrient Expert does not require a lot of data nor very detailed information as in the case of many sophisticated nutrient decision support tools, which can overwhelm the user. It allows the users to draw the required information from their own experience, the farmers' knowledge of the local region, and the farmers' practices. The tool can use experimental data, but it can also estimate the required site-specific parameters using existing site information.

Field testing of NE with farmers in Asia has demonstrated yield gains in grain crops by as much as 1.3 t/ha and increased profits of over US$200/ha. Depending on the local situation, the increased production and profitability occurs in different manners. For example, data from over 400 sites in India show a significant decrease in applied P fertilizer and a simultaneous increase in K resulting in increased grain yield due to improved nutrient balance (**Table 2**). Trials in Indonesia demonstrated a need for increased K fertilizer rates, which resulted in significant grain yield increases (**Table 2**). A third example is in the Philippines where recommended increased rates of P and K over the local farmer's practice resulted in a significant increase in fertilizer cost, but the yield increase led to greater profitability for the farmer (**Table 2**).

Table 2. Nutrient Expert® (NE) performance on maize production in Asia. The baseline for comparison is the standard farmer practice (FP). IPNI, 2017b

	Effect of Nutrient Expert® (NE – FP)		
Parameter	India (n = 412)	Indonesia (n = 26)	Philippines (n = 190)
Grain yield, t/ha	+1.3***	+0.9***	+1.1***
Fertilizer N, kg/ha	-6	-12	+3
Fertilizer P_2O_5, kg/ha	-16***	-5	+18***
Fertilizer K_2O, kg/ha	+22***	+15***	+18***
Fertilizer cost, US$/ha	-1	+16	+37***
Gross profit, US$/ha	+256***	+234***	+267***

*** denotes a significant difference at *p*<0.01.

Summary

Closing maize yield gaps to meet the food production needs for a growing population will require continuous improvement in agricultural system performance and will depend on a combination of technology, agronomy, and management developments. Precision agriculture tools and management strategies can help create the information-driven, evidence-based agricultural systems needed to meet the challenges of the future. BC

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Educating Farmers and Crop Advisers About Ecological Intensification

By T. Satyanarayana, Vladimir Nosov, Sudarshan Dutta, and Kaushik Majumdar

Currently, cereal yields in India and southern Russia are only at 40 to 65% of their potential, mostly because of management practices that do not consider the crop's dynamic response to the environment.

Ecological intensification (EI) systems developed here have proven to be beneficial in terms of yield and profitability, while improving nutrient use efficiency.

Education on EI adoption is widely needed, and some of the methods of educating the region's farmers and crop advisers about the benefits of EI are outlined in this article.

(Clockwise starting top left) IPNI Lecture Program for Undergraduate Students at Kuban State Agrarian University, Krasnodar, Russia. Fertilizer industry agronomists visiting the EI experiment in Tselina, Rostov. Farmers of Ranchi, Jharkhand observing the benefits of EI practices on improved maize yields. Research scholars pursuing studies on EI at the University of Agricultural Sciences, Dharwad, India.

In India

Maize is considered the third most important food crop among the cereals in India and contributes nearly 9% of the national food basket (Dass et al., 2012). Maize yields in India need to increase significantly to meet the country's growing food, feed, and industrial needs of a population with a current annual growth rate of 3 to 4%. Increasing maize production in India is associated with other challenges such as better resource use efficiency, cropping sustainability, and safety to the environment and ecosystems. Under such circumstances, the principles of ecological intensification (EI) can help to create new management systems that could improve upon current farmer practices.

In India, agriculture is done mostly by smallholder farmers, that operate under a wide range of soil, climate, and socio-economic conditions. Farmers often over or under use fertilizer nutrients or apply them in an imbalanced manner, at an inappropriate time, or by an incorrect method. Such practices result in low crop productivity with less economic return and often leave a large environmental footprint for fertilizer. Developing EI practices and promoting large scale dissemination of such practices to farmers could offer an improved crop management strategy to intensify maize production, improve input use efficiency, and ensure environmental protection.

Abbreviations and notes: N = nitrogen; P = phosphorus; K = potassium; Zn = zinc. IPNI Project RUS-GM41; IND-GM22, IND-GM-35.

In Russia

Maize production in Russia is growing as farmers respond to high domestic demand from the livestock and poultry industry. Russia has achieved self-sufficiency in maize production recently and has become a net exporter. Maize area increased about 1.6 times between 2011 and 2015. However, the average maize yield in Russia during the last five years (2011-15) was only about 4.4 t/ha. The current nutrient use in maize is only 55 kg N, 22 kg P_2O_5, and 13 kg K_2O/ha (ROSSTAT, 2016), which is quite inadequate and unbalanced to sustain higher maize yields in the region. Also, yields in the southern region

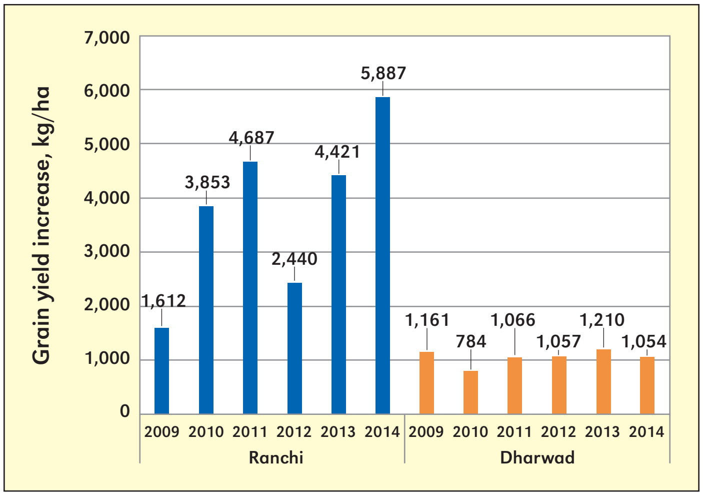

Figure 1. Maize grain yield increase for Ecological Intensification over farmer practice (EI-FP) in Ranchi, Jharkhand and Dharwad, Karnataka across six years. The average grain yield increase was 2,440 kg/ha.

are commonly affected by hot and dry periods in July that limit maize pollination and grain formation.

In Russia, the agricultural producers are categorized into three general types: 1) agricultural enterprises (joint stock companies, subsidiaries of agro-holdings), 2) commercial farmers, and 3) subsistence farmers. In the Rostov region in 2015, they represented 67, 31, and 2% of the crop area, respectively. Rostov is one of the regions with a high proportion of commercial farmers. These commercial farmers, however, have generally less knowledge of nutrient management options for intensive production systems, and hence produce lower crop yields compared to agricultural enterprises (Nazarenko et al., 2011). Education of this category of producers about EI management systems is widely needed.

Critical Practices

Ecological intensification integrates the best management practices that contribute to increasing crop yields over existing farmer practices in a sustainable way.

In India, nutrient management was the major intervention under EI, where 4R Nutrient Stewardship, the principle of applying the right source of nutrients at the right rate, the right time and in the right place, was followed to achieve higher maize yields. The EI treatment for summer maize received 180 kg N, 90 kg P_2O_5 and 100 kg K_2O/ha, along with secondary and micronutrients, which were supplied through appropriate sources, at the right physiological stages, and placement method. Right nutrient management was also combined with many other best crop management practices such as choice of high yielding genotype (promising hybrids of the region), ideal planting time, optimum planted population, residue management, crop rotation with legume etc. Similarly, EI management in southern Russia considered balanced application of NPK fertilizers, splitting the N rate, and application of starter PK fertilizers. Right nutrient management was combined with optimum planting time and seed treatment with Zn.

In India, long-term evaluation of the EI system (2009-10 to 2014-15) over farmer practice (FP) at Ranchi, reported a significantly higher mean grain yield of maize (6.3 t/ha), which is 163% higher than FP. Similarly in Dharwad, the EI system resulted in significantly higher maize yield (5.4 t/ha), which was higher than FP by 24%. The difference in maize grain yield between EI and FP was significant at both the locations across six consecutive maize seasons (2009-10 to 2014-15). The magnitude of yield difference between EI and FP was higher at Ranchi than at Dharwad (**Figure 1**). The soils of Ranchi were red and lateritic in nature, relatively low in soil fertility, acidic (pH 5.1), and low in organic C (0.43%). The soils of Dharwad were Vertisols, relatively high in native fertility, with neutral soil pH (7.2), and medium organic C (0.56%). The comparison of fertilizer use between Ranchi and Dharwad revealed that N, P_2O_5, and K_2O use by farmers in Ranchi was only 53, 5, and 3 kg/ha, whereas in Dharwad, it was 115, 52, and 45 kg/ha, respectively. Relatively poor soil fertility coupled with inadequate rates of nutrient application by farmers was evident in Ranchi, which resulted in significantly improving the maize yield with the EI practice. However, such a widespread yield improvement with EI was not evident at Dharwad, as the native soil fertility was high compared to Ranchi and the farmers were already practicing improved crop management practices including higher nutrient application rates. Averaged over six years, EI management system improved maize grain yields by an average of 2,440 kg/ha compared to current FP.

The goal of EI management is to boost yields while improving nutrient use efficiency (an indicator for evaluating environmental quality). Partial factor productivity (PFP; kg grain/kg fertilizer N) was higher in FP than EI at both Ranchi and Dharwad. However, under EI in Ranchi, PFP did increase from 15 to 19 kg grain/kg N over six years, thus EI is helping to

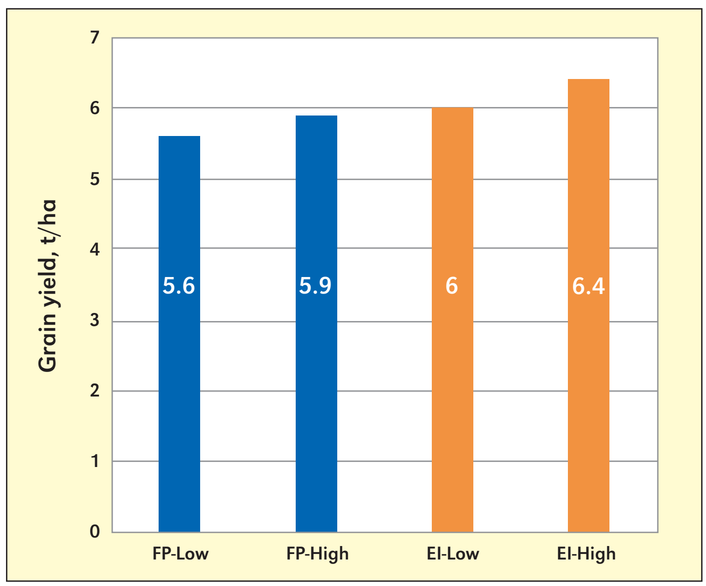

Figure 2. Effect of different levels of nutrient management according to farmer practice (FP) and ecological intensification (EI) on maize grain yield in Tselina, Rostov region, Russia (5-year average: 2011-15; Nosov et al., 2016). Treatment details (kg/ha): FP-Low = N9 P40 applied in spring before planting; FP-High = N30 P40 applied in spring before planting; EI-Low = N17 P70 K40 split between a pre-plant (N12 P50 K20) and planting (N5 P20 K20) application placed 2 cm to the side of the seed; EI-High = N85 P70 K40 split between a pre-plant (N50 P50 K20) and planting (N5 P20 K20) application placed 2 cm to the side of the seed, and N30 side-dressed at the V3 to V5 stage.

improve nutrient use efficiency while also improving yields by 1.5 t/ha (data not shown). Also, the agronomic efficiency (AE) for N at Ranchi was higher under EI (27.5 kg grain increase/kg N) compared to FP (19.9 kg/kg).

In southern Russia, the highest maize yield of 6.4 t/ha (5-year average) was obtained through EI management, with an average improvement of 9% over FP (**Figure 2**).

Promotion of EI practices to farmers and extension agronomists is needed to increase on-farm maize production. Large-scale dissemination of such concepts provide the opportunity to bridge existing yield gaps and increase farm profitability in an environmentally sustainable manner.

Some of the following activities helped in educating farmers and crop advisers on EI:

- *Regular field visits and discussions at the experimental locations involving project cooperators, fertilizer industry agronomists, neighboring farmers, and undergraduate and postgraduate students.* All stakeholder groups pursuing research on EI systems are exposed to the benefits and challenges of practicing EI and helped in generating knowledge on the concept of EI.
- *State agricultural university farmer fairs (Krishi Mela) in India held in conjunction with tours of EI research sites.* This forum attracts large numbers of participants and has educated farmers, crop agronomists, and extension officers on EI since 2009.

Dr. Satyanarayana (left) delivering a presentation at the 12th Asian Maize Conference. Dr. Nosov (right) presenting the results of EI at the Science Week-2016 Conference organized by the Southern Federal University.

- *Publishing information through recognized journals and newsletters, and delivering presentations within recognized international events.* These activities help in promoting awareness on the development and impact of EI adoption over current farmer practices.
- *Reporting principles of EI management at regional meetings in southern Russia.* This initiative invites discussion from fertilizer dealers and agronomists, university students, and young scientists.
- *Establishing partnerships with stakeholders.* In southern Russia, partnerships between Southern Federal University, Rostov-on-Don, and the State Variety Evaluation Unit "Tselinskiy", N. Tselina helped in large scale dissemination of the EI concept. Seed companies extended support through the inclusion of modern maize hybrids, which further strengthened the EI practice. In turn, seed producers promoted EI-based nutrient management technologies to their dealers, retailers, and progressive growers. Similar partnerships were also established in India, involving stakeholders from the National Agricultural Research and Extension System, the State Agricultural Universities, State Departments of Agriculture, agronomists representing fertilizer and seed industries, and progressive farmers and students.

Online video available at https://www.youtube.com/watch?v=tJoMYMYVyPM&feature=youtu narrates the benefits of practicing EI to a much broader audience of farmers and crop advisers.

Summary

The concept of EI helped in developing intensive maize systems and resulted in increased maize yields by bridging the existing yield gaps. Recognizing the benefits of practicing EI, focused programs were aimed at educating farmers and crop advisers on EI. Such educational programs for the targeted audience need to be continued for large scale dissemination of the concept. In the future, publishing leaflets and other promotional material involving the concepts and benefits of EI, in regional languages, would act as education tools for farmers, crop advisers, and industry agronomists. BC

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The Global Maize Project: What Have We Learned?

By Luís Prochnow and T. Scott Murrell

Overall, average grain yield in ecological intensified (EI) systems surpassed farmer practice by nearly 1 t/ha.

If such an increase were extrapolated to all maize-growing areas of the world, an estimated 160 million (M) t of additional grain would be produced every year, representing about a 15% increase in world production.

Besides the increase in yield, improvement in nutrient use efficiency (NUE) was proved possible under EI in several circumstances.

Historically, the global average yield for maize has been increasing steadily over time. Since the 1960s, yields have been improving at a rate of 65 kg/ha/yr (**Figure 1**; FAO, 2017). In terms of the world's total maize grain production, it had been increasing at a steady rate of 10 million (M) t/yr until 2004, after which it shifted to a steeper line of 31 M t/yr (**Figure 2**). As is also shown in Figure 2, this shift in production closely follows the most recent trend line for maize harvest area expansion. Prior to 2007, global maize area had been increasing at a rate of 0.9 M ha/yr. Since 2007, maize area has been increasing at the more rapid pace of 4.7 M ha/yr. The United States, China, and Brazil have contributed to the majority of this area expansion, and in 2014 these three countries accounted for 47% of world's maize production.

These global trends clearly show that recent, rapid increases in maize production are associated more with the expansion of maize growing areas than with rapid increases in yield. One of the goals of EI, however, is to increase yields on existing lands, so there is much work yet to do.

Around the world there is a continuous debate over whether resources for research should be allocated more toward basic research or practical agronomic aspects. Those that understand the complexity of agriculture realize that both are needed. Good practice can only advance if basic aspects are understood, making new and effective techniques available for the field. In short, basic research creates the opportunities for higher yield and higher production, but the results from such research must be tested and integrated into field operations.

It seems logical that a great contribution to the reduction of yield gaps and improved efficiency in maize would come from testing the most advanced techniques made available by in-the-field research like EI, and comparing these results to what farmers are achieving. The objective question here would be: "*Is research pointing out alternatives that are better in terms of yield, efficiency, and profitability, than what farmers are presently using?*" The International Plant Nutrition Institute (IPNI) is a global organization with, among other things, a mandate to help farmers produce more with improved efficiency and greater profitably. The Global Maize Project (GMP) was implemented by IPNI to help answer the above practical question. This is facilitated by our presence in the most important agricultural regions of the world.

It is important to note that by concept the set of treatments reflecting EI and farmer practice (FP) are not fixed in time. They may change according to new possibilities coming from research (maybe added to EI) or from changes implemented in average practices used by farmers in the region (maybe added to FP). As an example, if a new maize hybrid was proven to be a great option for the region, it can be incorporated into the EI set of practices to be tested in conjunction with what else recent science suggest might be the best alternatives. As a moving set of practices, in regions where EI yields more than FP, with time, the yield gap between these two treatments would ideally narrow (**Figure 3**). This narrowing would indicate that farmers are adopting the EI management practices on their own farms. This of course would be facilitated by setting good programs to educate farmers about the benefits of EI (Satyanarayana et al., this issue).

As discussed in the different chapters of this issue of *Better Crops*, we have learned a lot with the GMP in various regions. Measuring the impacts (Norton et al., this issue) of EI and FP, and all combinations of different treatments around the globe, made it possible to have clear ideas on how to produce maize

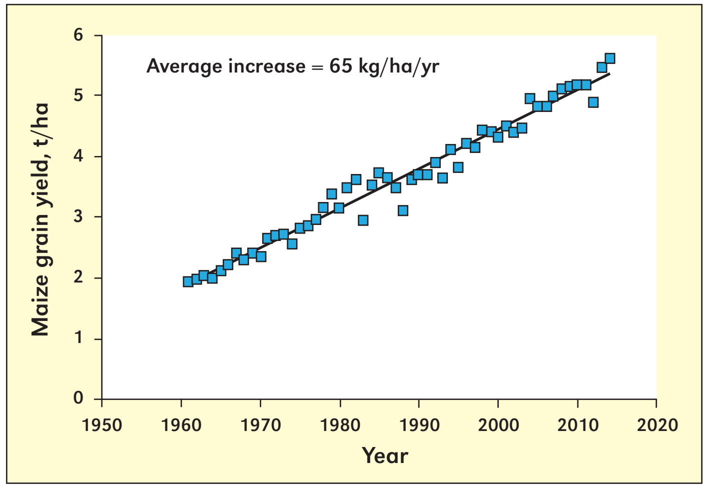


Figure 1. Trends in global average maize grain yield over time (FAO, 2017).

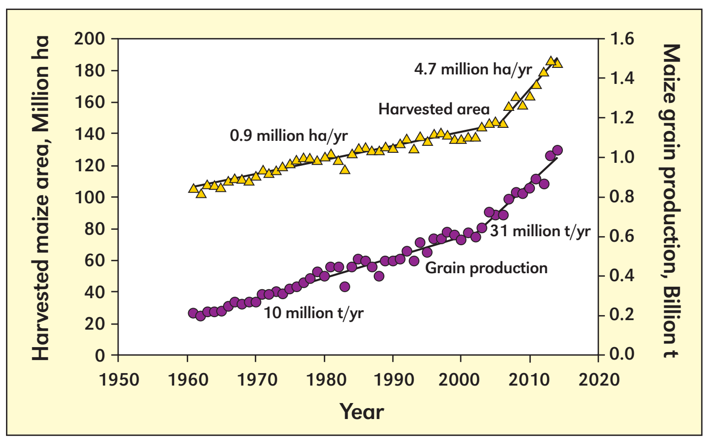


Figure 2. Trends in harvested area and total maize grain production over time (FAO, 2017).

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

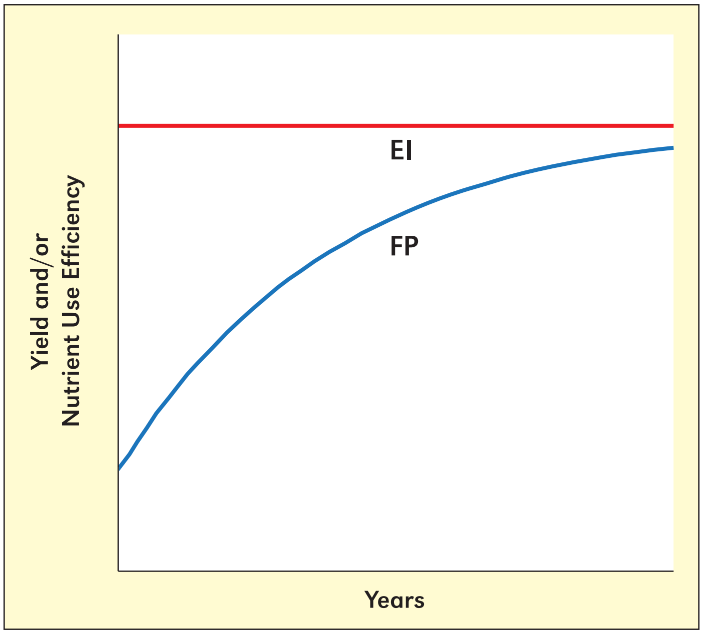


Figure 3. Conceptual goal for closing the yield and/or nutrient use efficiency gap between EI and FP, which would translate into farmers adopting the recommendations from EI.

better in regions where yield gaps are narrow (Murrell et al., this issue) or wide (García et al., this issue). For example, it was possible to see that management changes incorporated into EI practices improved net return in the majority of sites in Minnesota, USA, a region already recognized as having high yields and narrow yield gaps. Also, it was possible to confirm high yield increases in Sub-Saharan Africa, South Asia, and Argentina, regions recognized by models and yield gap analysis (Grassini et al., this issue) as having wide yield gaps. In some of these sites an improvement on nutrient use efficiency was also observed.

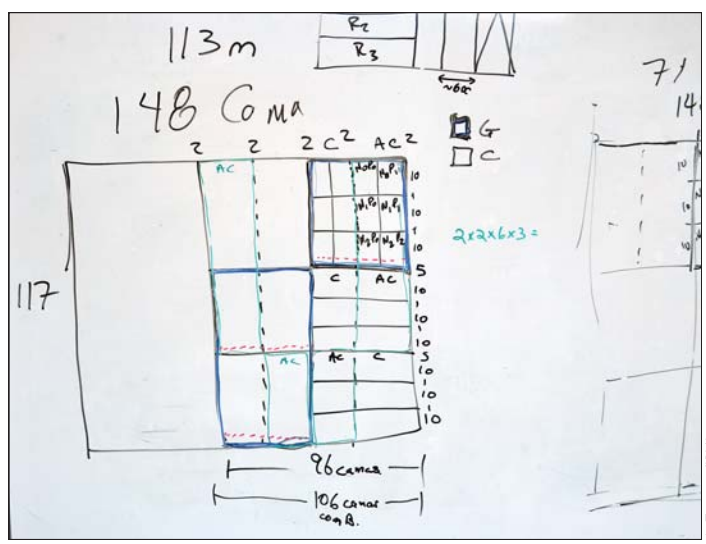
In China, the GMP found very interesting results. Optimized planting density, reduced fertilizer N rate, and better application time maintained crop grain yield and improved significantly nutrient use efficiency (Zhao and He, this issue). For example, agronomic efficiency, which measures how much grain yield has increased per unit of N applied, was 32% lower in FP than in EI. This is important information for a country needing to improve the use of nutrients in its agriculture to improve the environment and to address new legislation to be implemented in the near future.

Studies also confirmed that maize rotation with other crops can be of enormous value to some soil systems and to maize production. This was the case in Ponta Grossa, Paraná, Brazil, where the introduction of forage pea into the EI cropping system significantly increased grain yield and partial factor productivity (Francisco, this issue).

Applying precision agriculture (PA) to maize will be fundamental to seeking more production with lower environmental impact. PA tools and management strategies will help create the information-driven, evidence-based agricultural systems needed to meet its challenges (Phillips and Majumdar, this issue).

The results of the GMP and similar studies are creating an impact in different regions of the world. In a recent survey, IPNI collaborators pointed out important impacts. The following list is a compilation of that feedback:

- Forming a network of specialists through councils of maize experts discussing and deciding the type of deliverables needed in each region and how to conduct the experiments.
- The project has increased awareness of the concepts of EI (i.e., more grain with less environmental impact).
- The GMP is serving as a means to increase maize yield in different regions of the world. Although different experiments target different objectives, increasing maize yield around the world is a critical goal for ecological intensification. Overall, average grain yield increase in EI systems over FP was nearly 1 t/ha. If such an increase were extrapolated to all maize-growing areas of the world, an estimated 160 M t of additional yield would be produced every year, representing about a 15% increase in world production.
- Concepts of EI are serving as examples for researchers working with other crops, like rice, sunflower, cotton, sugarcane, and wheat. For example, scientists at Darwad and Ranchi, India, initiated work in different agro-climatic conditions following the concepts used in the GMP.
- GMP is creating a database of information that leads to improvements in fertilizer recommendations. A clear example is in Africa, where the Kenya Agricultural Research Institute is revising recommendations for maize.
- The project is serving to train students, crop consultants, and farmers around the world. Field experiments in some regions are serving as teaching tools. Field days take place in most GMP experiment sites to transfer what is being learned to those who need the information to improve farming practices. Both graduate and undergraduate students are involved and scientific work related to GMP will provide data for M.Sc. theses and Ph.D. dissertations in many different locations.
- GMP is increasing diversity in crop rotations. For example, in Mato Grosso, Brazil, soil and climatic conditions do not favor accumulation of soil organic matter. Here GMP research is looking into different cropping



A. Tasistro/IPNI

Early sketch of the layout of the Global Maize Project study conducted at the Norman E. Borlaug Experiment Station, Sonora State, México.

systems and testing their abilities to accumulate higher levels of soil organic matter to make the cropping systems more sustainable.

- GMP is facilitating expansion of maize production to some good potential areas. IPNI directors in India and Colombia pointed out this expansion. In India, collaborators claim that the area where maize is cultivated has already increased by 20% and maize is being planted instead of other less profitable crops.
- GMP is providing data that are already being used to create recommendations that are better suited to regions with high risk of insufficient rain. In Muguga, Kenya, GMP results are showing that lower rates of nutrients (about 50% of rates for maximum yields under irrigation) should be applied for higher efficiency under drought conditions, which are common in the region. Also in Kenya, results are raising awareness that more complete crop nutrition is needed, going beyond N and P to include K and micronutrients.
- The credibility of the GMP is increasing and is leading to associations with important key players at the political level. As an example, one of the IPNI directors in China pointed out that the research center in Shijiazhuang was recognized as a state agricultural environmental monitoring station.

It is evident from this survey that there are many benefits that have already emerged from this project that go beyond the specific results of the study itself.

Although we have learned a lot, more is needed. To accomplish economic, production, and environmental objectives, nutrient management will need to be better integrated with other management practices. What this project has demonstrated clearly is that changes to nutrient management practices alone are not sufficient to shift FP to EI. It takes a suite of management practice changes. Projects like the GMP, which make an effort to translate scientific findings into real farming operations, should be intensified wherever possible. The feeling is that although the GMP has proven it possible to significantly increase yields and/or NUE in different agro-ecological scenarios, one of the most important contribution of this project is highlighting that through a simple practical approach of testing what is best in science versus what farmers are actually using in the field, yield gaps can be quantified and approaches can be refined to narrow them. Once proven that a region-specific set of management practices called EI is better than FP, the project should continue to effectively transfer the technology to the field with a goal of closing that yield gap in the future. It cannot get much more practical and objective than this.

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IPNI Announces the Start of Its Annual Photo Contest

The International Plant Nutrition Institute (IPNI) is pleased to announce the start of its annual photo contest for 2017. Photo entries can be gathered throughout the remainder of the year and winners will be announced during the first quarter of 2018.

This year our contest has four categories. Our new **4R Nutrient Stewardship Category** will collect images that demonstrate the best use of crop nutrients with in-the-field examples of 4R Nutrient Stewardship—applying the Right Source at the Right Rate, Right Time, and Right Place.

> **Photo Contest Categories**
> 1. 4R Nutrient Stewardship - **New**!
> 2. Primary Nutrient Deficiencies
> 3. Secondary Nutrient Deficiencies
> 4. Micro Nutrient Deficiencies

The other three **Crop Nutrient Deficiency Categories** will collect images of nutrient deficiency in crops. Primary mineral nutrients include: nitrogen (N), phosphorus (P), and potassium (K); secondary mineral nutrients including sulfur (S), calcium (Ca), and magnesium (Mg); and micronutrients including boron (B), copper (Cu), chloride (Cl^-), iron (Fe), manganese (Mn), molybdenum (Mo), nickel (Ni), and zinc (Zn).

For additional information, please contact Gavin Sulewski, IPNI Editor, at gsulewski@ipni.net. You can also view past winners of the photo contest at http://www.ipni.net/photocontest/history BC

L. Easton

Copper Deficiency in Wheat showing pale plants and twisted bleached leaf tips.

L. Cristancho Sierra

Magnesium Deficiency in Coffee characterized by interveinal chlorosis of the older leaves and productive branches.

IPNI Image

Mid-row coulter-style liquid fertilizer bander for corn.

U. Kumar

Potassium deficiency in two-month-old Tumeric growing near Tamil Nadu University, India

IPNI Image

Rice farmers in India show their new fertilizer application plan based on a recommendation provided by Nutrient Expert®.

Maize - the agronomist's favorite crop. Farmers love to grow it and researchers love to study it. In the early planning phase of IPNI's global maize initiative late in 2007, some questioned whether there was really any meaningful science that was yet to be initiated and whether our resources would be better utilized on a less-studied crop. However, maize is the recipient of 16% of the world's fertilizer and represents 40% of global cereal production. And, IPNI scientists around the world felt we had critically important questions about best practices that were not yet answered by the existing scientific literature. There were knowledge gaps, especially at the system level where we attempt to define best practices to meet the economic, environmental and social objectives of sustainable production.

IPNI's mission is not focused on best practices of cropping systems. It's focused on the nutrient management subset (4Rs) of practices in cropping systems. But, we fully appreciate how that subset is not only interactive internally, but interacts with many other factors of the production system and that those other factors can markedly influence the performance of nutrient inputs. After many decades of disciplinary research, the science of each aspect of maize systems is rather well developed, but the science supporting how maize systems at an integrated holistic level behave remains full of uncertainty. The disciplinary science, models, and big data approaches leave us with substantial uncertainty about what the "best" set of practices actually looks like at a specific site and what the performance metrics might be for that set. The pathway of ecological intensification (EI) or sustainable intensification remains at best a fuzzy approximation.

So, the Global Maize Project was launched to establish field studies designed to provide an empirical test of what our incomplete science, filtered by local experience, approximated as the best set of practices for EI systems. How productive and efficient can maize systems become if our best knowledge and technology are all brought to bear in meeting sustainability objectives? How efficient and effective can nutrients and other inputs and resources become? And, how does the EI system compare to the systems being used by farmers in the region? It's really a final validation of the recommendations we make to farmers and a demonstration of their performance … converting the science we know to practices that farmers can use.

Paul Fixen

Dr. Paul E. Fixen
IPNI Senior Vice President and Director of Research

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