Introduction

A unique feature of the International Plant Nutrition Colloquium is the range in scale of the sub-disciplines represented, from nanometers to global. Perhaps never in history has the Colloquium's capacity to exploit this cross-cutting of scales been more important than it is today.

Nutritional, environmental and economic challenges we face at a global scale may well have a significant part of their resolution at the molecular level of genetics and nanotechnology. But that resolution can never be realized if the consequences of a molecular change are not understood at each step in up-scaling that change to the ecosystem level and beyond.

This paper has two linked objectives. The first is to present the pursuit of high agricultural productivity and nutrient use efficiency (NUE) as a singular goal and the only means of accomplishing either component globally. The second objective is to offer three concepts that may facilitate cooperation among the diverse groups present at the Colloquium that are needed to accomplish the required productivity and efficiency improvements.

Productivity and Efficiency as One

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

Dr. Norman Borlaug recently called for a second "Green Revolution" that would be a more extensive rebellion against world hunger. He has expressed hope that the U.S. Food Security Act of 2009 could help lead the way. Sen. Richard Lugar, cosponsor of the bill, described the bill as a "more focused effort on our part to join with other nations to increase yields, create economic opportunities for the rural poor and broaden agricultural knowledge." (TAMU, 2009).

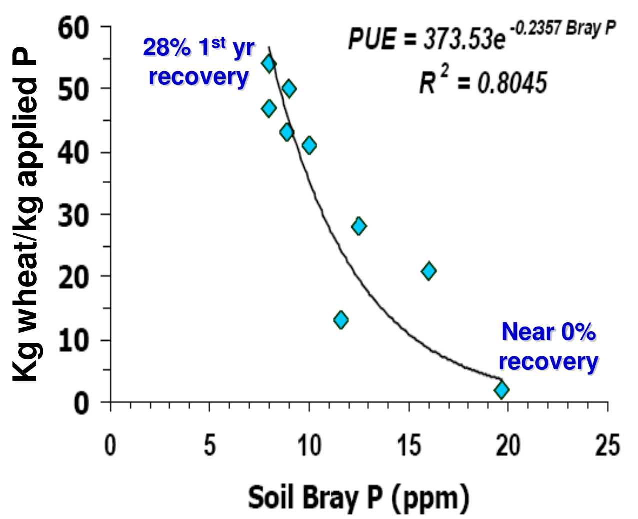
Earlier this year the U.S. Secretary of Agriculture stated "So we have to figure out how to do more with what we have. And that means an investment by USDA in concert with the private sector and land grant universities in figuring out how we can be more productive; how we can use less natural resources to produce these crops (USDA, 2009)."

The need for simultaneous increase of productivity and efficiency has clearly caught the attention of private industry. Monsanto (2008) has announced its commitment to develop by 2030 seeds that can double crop yields and reduce by one-third the amount of key resources, e.g., nitrogen and water, required to grow crops. Dupont (2009) has stated that thanks to its global research efforts, Pioneer is on track to increase corn and soybean yields by 40% by 2018, more than doubling the current annual rate of gain.

As in the past, future yield increases will not likely be solely due to genetic improvement but due to changes in several interacting production factors. For example, evaluation of the grain yields of corn hybrids released in the U.S. Corn Belt by Pioneer Hi-Bred International from 1930 to 2007 by year of hybrid release shows an annual rate of yield increase of only 0.014 t/ha at 10,000 plants/ha, but 0.107 t/ha at 79,000 plants/ha (Hammer et al., 2009). Similarly, adjustments in nutrient management practices as changes in genetics, plant density, and other cultural practices occur must be considered, with or without genetic alterations specifically targeting NUE. With the greater nutrient levels contained in higher yielding crops, and potentially more nutrient inputs necessary to replace the increased harvest removal, more nutrients will be at risk of loss from the system. So, the challenge of increasing both productivity and NUE increases. These factors have spurred efforts by the fertilizer industry to develop a family of enhanced efficiency fertilizers designed to more effectively deliver nutrients to crop plants while minimizing loss to the environment.

Simultaneous pursuit of higher productivity and NUE requires caution in how NUE is being measured. Methods of NUE determination and their interpretation were recently reviewed by Dobermann (2007). He also summarized the current status of NUE for major crops around the world, pointing out that single year average recovery efficiency for N in farmer's fields is often less than 40% but that the best managers operated at much higher efficiencies. Dobermann used a six-year study in Nebraska on irrigated continuous maize managed at recommended and intensive levels of plant density and fertilization to illustrate how NUE expressions can be easily misinterpreted. In this study comparing a higher yielding, intensively managed system to the recommended system for the region, partial factor productivity (PFP; grain produced per unit of N applied) indicated that the intensive system was considerably less N efficient than the recommended system. Because fertilizer N contributed to the buildup of soil organic matter in the intensive system, when the change in soil N was taken into account, the two systems had nearly the same system level N efficiency. Dobermann pointed out that over time, this increased soil N supply should eventually reduce the need for fertilizer N, resulting in an increase in PFP. Such effects are particularly noteworthy for researchers striving to increase productivity with more intensive methods where new practices are being implemented that differ from the history for the research plot area or farm field. If cultural practice changes are such that soil organic matter is no longer in steady state, temporary net nutrient immobilization or mineralization can impact apparent NUE.

Figure 1. Influence of soil fertility on agronomic efficiency of P fertilizer in wheat experiments in Argentina (Garcia, 2004).



Nutrients such as P and K that readily accumulate in plant available forms in most soils pose special challenges in studies pursuing simultaneous increases in productivity and NUE. **Figure 1** which summarizes P studies on wheat in Argentina illustrates the challenge. The lower the soil fertility level, the higher was agronomic efficiency ((treatment yield- control yield)/nutrient rate). At the lowest soil P levels, P recovery efficiency (by the difference method) was 28% and declined to near zero as soil P approached non-yield-limiting levels. So, neither agronomic efficiency nor recovery efficiency by the difference method offers direct indication of whether P efficiency is appropriate for the system. The same is true for K. In a recent global review of the efficiency of soil and fertilizer P use, the authors indicated preference for calculating recovery efficiency by the balance method where P in the crop is divided by P applied (Syers et al., 2008). They concluded that for many soils that are in the critical soil P range (where crop yields are maximized), application of P at rates similar to what is removed in the crop will maintain those soil levels, indicating very high P recovery efficiency, often approaching 90%. This approach does require continual measurement of soil fertility status which is often not possible in developing countries.

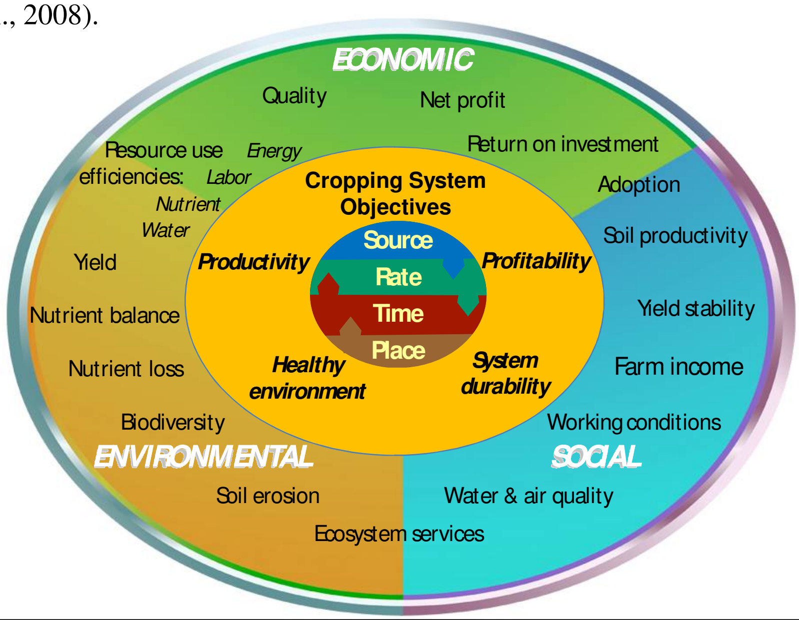
Facilitating Cooperation in Pursuit of Productivity and Efficiency Improvement

It has been estimated that the world will need twice as much food within 30 years (Glenn et al., 2008). That is equivalent to maintaining a proportional rate of increase of over 2.4% over that 30-year period. Sustainably meeting such demand is a huge challenge and will require close cooperation and understanding among disciplines, across geographies, and between public and private sectors. Three concepts are offered here that may facilitate cooperation among the groups needed to accomplish the required productivity and efficiency improvements.

The 4R Nutrient Stewardship Framework

For plant nutrition science to work well across disciplines, whether basic or applied, and across geographies, a common framework for viewing goals, practices, and performance is likely helpful. **Figure 2** is a schematic representation of the 4R nutrient stewardship framework which is intended to serve that purpose.

Figure 2. The 4R nutrient stewardship framework (after Bruulsema et al., 2008).



At its core are the 4Rs – application of the right nutrient source at the right rate, right time, and right place. Best management practices are the in-field manifestation of these 4 rights. The 4 Rs are shown within a cropping system circle because they integrate with agronomic BMPs selected to achieve crop management objectives. Those farm-level crop management objectives contribute toward the larger economic, social and environmental goals of sustainable development.

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

Mainstreaming of Simulation Models

Defining the gap between current and potential yields is a useful step towards maximizing productivity and efficiency. FAO recently published a set of such estimates for six corn-producing countries **(Figure 3)**. Their evaluation showed a yield gap varying from nearly 5 t/ha in India to zero for the U.S. However, such estimates should not be taken too literally relative to specific locations. For example, if one compares the Nebraska irrigated corn yields for the intensively managed treatments discussed earlier to the county average farmer yields for the same time-period, a difference of 4 to 5 t/ha is observed **(Table 1)**, suggesting that a yield gap exists in at least some areas of the U.S. as well.

Figure 3. Potential for corn yield increase (FAO, 2008).

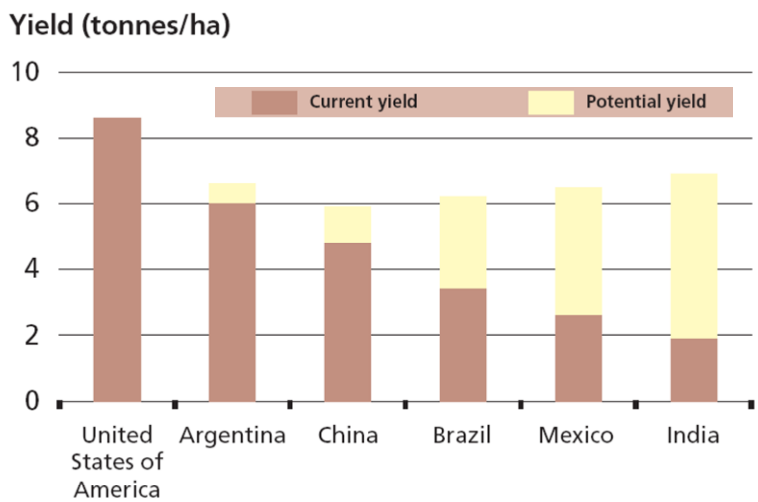


Table 1. A comparison of long-term average maize yields in an intensive management study to local average farmer yields (Experimental data from Adviento-Borbe et al., 2007).

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

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

Global Data Networks

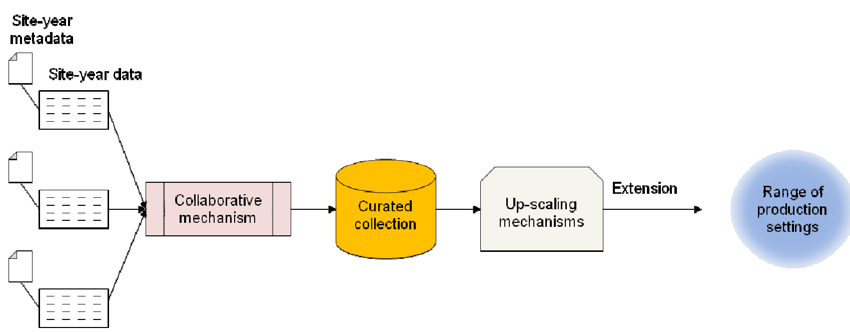
In its recent synthesis report, The International Assessment of Agricultural Knowledge, Science and Technology for Development stated that the main challenge for agricultural knowledge, science and technology (AKST) is to increase the productivity of agriculture in a sustainable manner (IAASTD, 2009).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

In her plenary lecture at the 2008 annual meeting of the American Association for the Advancement of Science, Dr. Nina Fedoroff, Administrator of USAID, said that the only alternative to higher food prices and progressive deforestation is to use contemporary science, including molecular modification, to increase the productivity of the land we already farm and decrease its water demands (Fedoroff, 2008). She went on to say that our research universities and institutes, working together with the business sector and using contemporary electronic resources, have a unique opportunity to accelerate the “flattening” of the world.

The “flattening” term used by Dr. Fedoroff is derived from Thomas Friedman’s book in which he presented three eras of globalization (Friedman, 2005). In the third era, the one we are in today, the change agent is the individual with the power to collaborate and compute globally, enabled by fiber optics and software. It is this technology that allows a soil testing laboratory in the Midwest U.S. to have its data management and programming done in Bangalore.

Can this flattening technology be put to better use in pursuing our productivity and NUE goals? The National Academy of Sciences (2009) now tells beginning scientists that researchers have a responsibility to devise ways to share their data in the best ways possible, mentioning repositories of astronomical images, protein sequences, archaeological data, cell lines, reagents, and transgenic animals as examples. To address unmet communication needs of collaborating scientists, Purdue researchers developed the Network for Computational Nanotechnology (NCN). An outcome of this network was nanoHUB (http://www.nanohub.org). This on-line community of over 90,000 annual users provides web access to the tools scientists need to collaborate on modeling, research, and educational efforts in nanotechnology. Is there need for a “Nutrohub”, a global plant nutrition research and education community? Such a community could have numerous groups, each with its own focus, but sharing communication and computing tools. Groups could develop integrated data management processes such as the one illustrated in **Figure 4,** developed for IPNI’s Global Maize project.

Figure 4. A conceptual model of the process of developing and testing field data across large geographic scales (Murrell, 2008).



Summary

Arguably, the single most important challenge for the field of plant nutrition is to contribute all it can to improving global productivity while at the same time increasing resource use efficiency. The global character of the demand for agricultural products and many of the most critical environmental issues creates a tight linkage between improving productivity and minimizing environmental impact. Sustainably meeting this challenge will require close cooperation and understanding among disciplines, across geographies, and between public and private sectors and a commitment to gathering data through repeated measures over longer time spans (8 to 10 or more years) than are typically used in most agronomic studies today (~ 3 years). Three concepts are offered that may facilitate this needed interaction.

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

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