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Plant nutrient management for enhanced productivity in intensive grain production systems of the United States and Asia

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Abstract

Are present nutrient management recommendations for the world's major cereal cropping systems adequate to sustain the productivity gains required to meet food demand while also assuring acceptable standards of environmental quality? To address this question, the current nutrient management approaches and their scientific basis in large-scale, mechanized maize (*Zea mays* L.)-based cropping systems of the USA and more labor-intensive, small-scale irrigated rice (*Oryza sativa* L.) production systems in Asia were evaluated. The principal challenges in both systems are similar: (1) there is no compelling evidence for significant increases in the genetic yield potential in both systems during the past 30 years, (2) farm yields are presently about 40–65% of the attainable yield potential, and (3) nutrient management mostly relies on approaches that do not account for the dynamic nature of crop response to the environment. Because average farm yield levels of 70–80% of the attainable yield potential are necessary to meet expected food demand in the next 30 years, research must seek to develop nutrient management approaches that optimize profit, preserve soil quality, and protect natural resources in systems that consistently produce at these high yield levels. Achieving these goals will require novel strategies for more precise plant nutrient management tailored to the technologies, dynamics and spatial scales relevant to each system. Significant advances in soil chemistry, crop physiology, plant nutrition, molecular biology, and information technology must be combined in this effort. Future field-oriented plant nutrition research must be of a more strategic, interdisciplinary, and quantitative nature. Systems approaches at micro- to meso-scales are required for gaining a more quantitative understanding of crop response to nutrients based on interactions among the essential crop nutrient requirements and on response to dynamic environmental conditions.

Abbreviations: PFP_N – partial factor productivity of applied N (kg grain per kg N applied); RE_N – apparent recovery efficiency of applied N (kg increase in N uptake per kg N applied); SSNM – site-specific nutrient management

Introduction

Increases in future food production will largely come from today's most intensively used agricultural land, but these systems must also meet stricter environmental standards. Hence, an ecological intensification (Cassman, 1999) of cereal production systems is justified by concerns about food security, the availability of adequate land and water resources (Young, 1999), and protection of natural resources. It appears feasible because of the existence of large gaps in yield, profitability, and nutrient efficiency that can be exploited with greater precision of soil and crop management (Cassman, 1999). The absolute increase in demand for cereals during 1997–2020 will be as large (about 650 million metric tons) as the increase in demand during the preceding 23 years even though annual relative growth rates in world cereal demand are expected to decline to about 1% per year (Rosegrant et al., 2001). There is considerable uncertainty in such estimates, but a yield increase of 20–30% over a period of 20 years represents a significant challenge. For tropical areas, average rice yields would have to increase to

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about 80% of the climate-adjusted yield potential of presently available germplasm (Dobermann, 2000).

The first objective of this paper is to compare nutrient management practices in two of the world's most important cereal production systems: rainfed and irrigated maize-based cropping systems in the north-central USA and irrigated rice systems in south and southeast Asia. Secondly, we review plant nutrition issues that are relevant for raising yields to levels that may provide an optimal combination of minimal environmental impact, greatest profit, and sustainable food production for both systems. Specific questions addressed include: (i) What is the potential for significant improvements in nutrient use efficiency through germplasm improvement and how will other trends in crop genetic improvement affect nutrient management? (ii) Is current scientific knowledge of crop response to nutrients and environmental conditions sufficiently robust to make significant improvements in nutrient use efficiency? (iii) How can farmers better account for spatial and temporal variation in indigenous nutrient supply and crop nutrient demand? (iv) Can productivity be raised further without significant negative environmental impacts?

Nutrient management in intensive maize systems in the USA

Rainfed and irrigated systems in which maize (*Zea mays L.*) is grown either in rotation with soybean (*Glycine max* L.) or as a continuous monocrop are the predominant cropping systems in North America. About 30 million ha of maize are harvested annually for grain in the USA, of which eleven states in the Corn Belt produce more than 210 million t or 35% of global maize supply (Table 1). Environmental conditions in this region are favorable, soils are deep and fertile, input use is relatively high, and farms are large. Individual fields are typically >50 ha and maize is produced in highly mechanized systems with an average labor input of only 6 h ha^{-1} per crop. During the past 35 years, average maize yields have increased linearly at a rate of 109 kg ha^{-1} per year (Figure 1), mainly due to the adoption of improved crop management technologies and genetic improvement of maize hybrids that complements these management practices (Duvick and Cassman, 1999). Average maize yields now approach 9 Mg ha^{-1}, but progressive farmers routinely harvest 11–13 Mg ha^{-1}. Despite this steady yield gain, however, present maize yields are only about 40–50% of the estimated climate-adjusted genetic yield potential of current maize hybrids and there is little compelling evidence that yield potential has increased significantly in the past 30 years (Duvick and Cassman, 1999).

Fertilizer recommendations are based on soil testing in about half of the maize area. The use of anhydrous ammonia and fluid N fertilizers as the primary N sources is another unique feature of maize systems in the USA, which account for 80% of global anhydrous ammonia consumption and 67% of nitrogen solutions (IFA, 2000). Fertilizer rates used on maize are typically within ranges of 94–185 kg N ha^{-1}, 10–34 kg P ha^{-1}, and 0–86 kg K ha^{-1} (Table 2) but large differences exist among states and among farms within each state (Padgitt et al., 2000). For example, average K use in the top 11 maize states ranges from 10 kg K ha^{-1} in Nebraska to 120 kg K ha^{-1} in Indiana, average N use from 100 kg N ha^{-1} in Wisconsin to 180 kg N ha^{-1} in Illinois (Figure 2). Regional relationships between grain yield and fertilizer rate tend to be inconsistent because fertilizer management decisions are largely made before planting and are not adjusted during the growing season in response to climatic conditions (N) or are based on long-term management programs (P, K). For example, in the U.S. Corn Belt positive correlations were observed between grain yield and rates of N, P, and K applied to maize in 2000, whereas no such relationship was observed in 1999 although the average maize yield was similar in both years (Figure 2).

Commercial fertilizer use rose sharply in the 1960s and 1970s in response to the adoption of responsive maize hybrids and favorable economic forces (Uri, 1998). However, maize yield increases since 1980 were achieved with stagnating fertilizer-N use and declining rates of P and K, leading to significant increases in the partial factor productivity (PFP, kg grain per kg nutrient applied) of these macronutrients (Figure 1). Average grain output per unit N applied increased from 41 kg kg^{-1} in 1980 to 58 kg kg^{-1} in 2000. Three factors have probably contributed to the improvement in N fertilizer efficiency: (i) increased yields and more vigorous crop growth associated with increased stress tolerance of modern hybrids (Duvick and Cassman, 1999), (ii) improved management of production factors other than N such as conservation tillage, seed quality and higher plant densities, and (iii) improved N management. Improvements in N management include some reductions in fall-applied N fertilizer with a shift to applications in spring or at

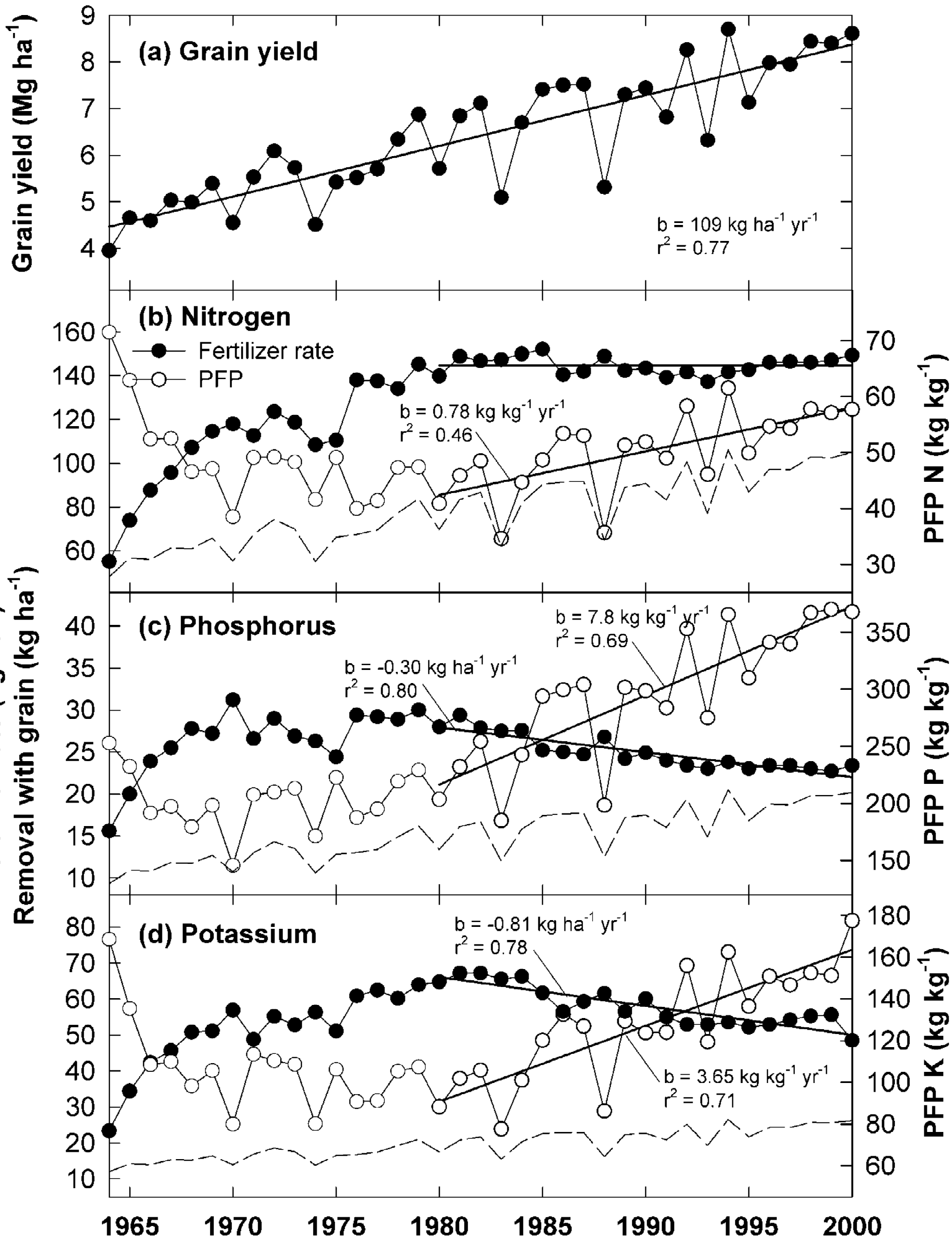

Figure 1. Trends in grain yield, fertilizer use (filled circles), partial factor productivity of fertilizer nutrients (open circles, PFP = kg grain yield per kg nutrient applied), and nutrient removal with grain (dashed line, kg element ha^{-1}) in maize grown in the USA. Trend lines were fitted to the period from 1980 to 2000. Yield data: Mean annual maize yields, National Agricultural Statistics Service, USDA http://www.usda.gov/nass; Fertilizer data: Mean N, P, and K amounts applied to maize, USDA Annual Cropping Practices Surveys of more than 2000 farms representing 80–90% of the maize area, http://www.ers.usda.gov. Nutrient removal with grain was calculated by assuming average concentration of 1.4% N, 0.27% P, and 0.35% K in grain.

planting, greater use of split N fertilizer applications rather than a single large N application, and development and extension of N fertilizer recommendations that give N 'credits' for manure, legume rotations, and residual soil nitrate (Shapiro et al., 2001). In addition, nitrification or urease inhibitors are used on

Table 1. Comparison of intensive rice and maize systems. Values shown refer to the main grain crop in the cropping system, i.e., maize for the USA and rice for Asia

	Irrigated and rainfed maize north-central USA[1]	Intensive irrigated rice south and southeast Asia
Predominant cropping systems[2]	Single crop M-S, M-M, M-M-S, M-S-S	Double and triple crop R-R, R-W, R-R-R, R-R-M
Estimated land area (million ha)[3]	45	41
Annually harvested area (million ha)[4]	25	66
Share of global production (%)	35	58
Average grain yield (Mg ha^{-1} per crop)[5]	8.7	5.3
Annual grain production (Mg ha^{-1} $year^{-1}$)[6]	7–11	8–12
Grain yield (% of yield potential)[7]	40–50	60–65
Cropping technologies	large fields mechanized	small fields labor-intensive
Average labor use (h ha^{-1} per crop)[8]	6	115–2150

[1] Maize: top 11 maize-producing states in the Corn Belt that account for 85% of the U.S. maize and soybean production (Iowa, Illinois, Nebraska, Minnesota, Indiana, Ohio, South Dakota, Kansas, Wisconsin, Missouri, Michigan), 1999–2000 (NASS, 2001).

[2] R – rice; W – wheat; M – maize; S – soybean. Rice: two to three crops grown per year. Maize: continuous maize or 2 to 3-year crop rotations with only one crop grown per year.

[3] Estimated area occupied by the predominant cropping systems. Rice: 24 million ha double- and triple-crop continuous rice systems (Huke and Huke, 1997) and 17 million ha irrigated rice–wheat systems. Irrigated rice–wheat area was estimated to be 7.5 M ha in China, 7 M ha in India, 1.6 M ha in Pakistan, 0.75 M ha in Bangladesh, and 0.5 M ha in Nepal. These estimates were revised from previously published numbers (Ladha et al., 2000b; Timsina and Connor, 2001; Woodhead et al., 1994) by (a) taking into account recent declines in the rice and wheat areas in China by about 2–3 M ha as well as small increases in other countries (FAO, 2001) and (b) assuming that about 65% of the 10.8 M ha R–W area in India is fully irrigated (Woodhead et al., 1994). Maize: Estimated from harvested areas in different crop rotations: 4 M ha continuous maize + 2 × 13.5 M ha maize–soybean rotation + 2 × 7 M ha maize in other rotations = 45 M ha land area.

[4] Rice: Total world harvested area of irrigated rice is about 76 M ha. Of this, about 10 M ha is irrigated rice grown in temperate climate (single crop, about 9 M ha) and irrigated rice grown in cropping systems other than those included here (FAO, 2001; IRRI, 1997). Maize: Annually harvested corn area. Of this, about 4.5 M ha is continuous maize, 13.5 M ha is maize grown in annually alternating maize–soybean rotation, and 7 M ha is maize grown in other crop rotations (Padgitt et al., 2000).

[5] Average yield in 2000 based on regional production statistics (FAO, 2001; NASS, 2001). Irrigated rice yield was calculated by assuming a 56% share of the total rice area.

[6] Typical range of annual grain production. Rice: two to three crops per year, 25–75% quartile range of 205 farms (Dobermann, 2000). Maize: one crop per year, yield range achieved by most farmers.

[7] Rice: assuming an average simulated climatic yield potential of about 8.1–8.5 Mg ha^{-1} (Matthews et al., 1995). Maize: assuming a yield potential of about 18–22 Mg ha^{-1} achieved in field plots with near-optimal growth (Duvick and Cassman, 1999).

[8] Includes paid and unpaid labor. Rice: range of average labor use in seven key irrigated rice domains of south and southeast Asia (Moya et al., 2002). Maize: average of maize farms in the north-central region of the USA surveyed in 1996 (Foreman, 2001).

about 14% of the maize area (Table 2). Despite the progress made in increasing N use efficiency, recent on-farm data indicate that on average only 37% of the applied fertilizer-N is taken up by maize (Cassman et al., 2002). Management control points for N are different for irrigated and rainfed maize, but on-farm data are not available to evaluate differences in N use efficiency in more detail. Recovery efficiencies of applied N (RE_N, kg increase in plant N accumulation per kg N applied) also are highly variable because almost 80% of the N is applied before crop emergence, which makes it vulnerable to losses during the crop establishment phase before the crop can establish an active root system. Only 14% of the maize area receives split applications of N after planting (Padgitt et al., 2000).

During the past 35 years maize farmers have made considerable investments in soil conservation measures and in building soil fertility through P and K applications that exceeded crop removal (Figure 1). Only grain is removed and all crop residues are re-

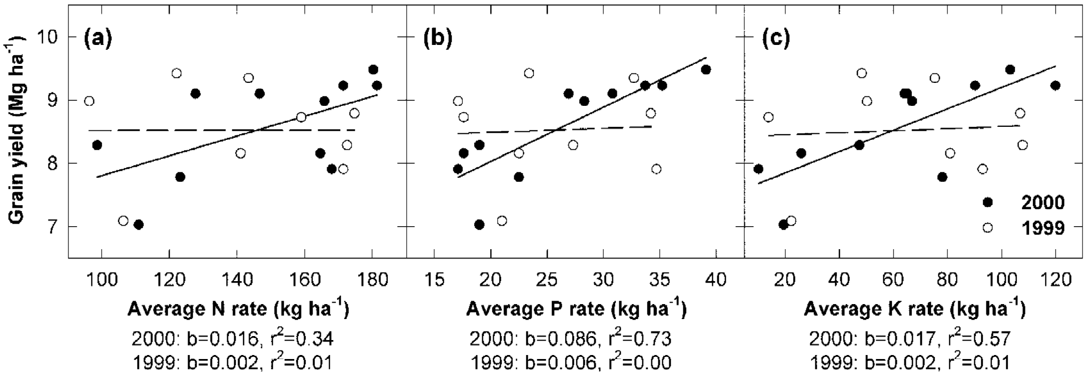

Figure 2. Correlation between maize yield and the average rates of fertilizer nutrients applied in the top 11 maize states of the USA in 1999 and 2000. Yield data: Mean annual maize yields, National Agricultural Statistics Service, USDA http://www.usda.gov/nass; Fertilizer data: Mean N, P, and K amounts applied to maize, USDA Annual Cropping Practices Surveys, http://www.ers.usda.gov.

cycled. At current average yield levels, maize grain removes 105 kg N, 20 kg P, and 26 kg K ha^{-1} per crop. Fertilizer rates used by maize farmers in the USA corn belt since 1965 exceeded this net nutrient removal, but the difference is declining in recent years (Figure 1). For example, the average P surplus decreased from 13 kg P ha^{-1} per crop in 1980–1984 to just 4 kg P ha^{-1} per crop in 1996–2000. Since the late 1970s, USA maize farmers have been taking advantage of residual soil P and K supplies built up by previous nutrient applications (Uri, 1998), but large differences exist within the region. Across the Corn Belt, about 50% of all soil samples analyzed each year test in the medium or higher soil test P categories (Bray-1 P equivalent larger than 25 mg kg^{-1}). This average proportion has remained virtually unchanged since 1975, but ranges from 13% in South Dakota to 83% in Michigan (PPI, 2001). More than 50% of all soils test above 160 mg K kg^{-1} (1 *N* NH_4-acetate equivalent, range from 23% in Michigan to 89% in Wisconsin). Average soil test K levels have declined since 1980 in the eastern part of the Corn Belt (Illinois, Indiana, and Ohio), whereas they increased in Iowa and Minnesota or remained unchanged in states with large native soil K reserves such as Nebraska or Kansas (PPI, 2001).

Nutrients supplied with farmyard manure affect the general trends shown in Figure 1. At present, 17% of the maize area and 6% of soybean area receive an application of livestock manure, but maize-based systems account for 89% of the total manured area in the USA (Padgitt et al., 2000). The top 11 maize states shown in Table 1 produce about 425 000 tons of recoverable manure-N (manure nutrients available for land application after deduction of losses due to storage and transportation) and 270 000 tons recoverable manure-P, which is equivalent to roughly 40% of the available manure nutrients for land application in the USA (Kellogg et al., 2000). Assuming a similar share during the past 20 years and an increase in the total manure amount of roughly 20% from 1982 to 1997 (Kellogg et al., 2000), the average annual manure nutrient input on land used for maize-based cropping systems increased from 6 kg P and 10 kg N ha^{-1} in 1982 to just 7 kg P and 11 kg N ha^{-1} in 1997. Because manure is mostly applied on arable land in close proximity to livestock operations, the actual rate of nutrients applied in manure is typically quite high on manured land. In states where manure production is high relative to the available land area and crop nutrient removal, the percentage of soil samples testing in high and very categories of soil test P has been increasing in recent years (PPI, 2001). In Michigan and Wisconsin, for example, 40–50% of all soil samples analyzed test higher than 50 mg P kg^{-1} (Bray-1 P equivalent, PPI, 2001). Comprehensive nutrient management planning has become one of the key environmental and economic challenges for the Corn Belt region because of the continuing trend towards large-scale industrial livestock production systems (Gollehon et al., 2001).

Nutrient management in intensive rice systems in Asia

Irrigated double- and triple-crop rice systems occupy about 41 million ha in south and southeast Asia and contribute about 58% of global rice supplies (Table 1). There are at least 50 million irrigated rice farms in Asia because farm size is typically small, ranging from 0.3 ha in densely populated areas such as the Red

Table 2. Nutrient management practices and nitrogen use efficiency in intensive rice and maize systems. Values shown refer to the main grain crop grown, i.e., maize for the USA and rice for Asia

	Irrigated and rainfed maize north-central USA[1]	Intensive irrigated rice south and southeast Asia
Fertilizer recommendations	State-specific, often soil test-based	Country-specific, blanket for large areas
Sample grain yield (Mg ha^{-1} crop^{-1})[1]	9.4 (7.5–10.4)	5.2 (4.0–5.9)
Fertilizer-N use (kg N ha^{-1} crop^{-1})[1]	146 (94–185)	111 (86–138)
Fertilizer-P use (kg P ha^{-1} crop^{-1})[1]	22 (10–34)	18 (11–25)
Fertilizer-K use (kg K ha^{-1} crop^{-1})[1]	49 (0–86)	17 (0–46)
Predominant N application technology	NH_3, UAN solution knife, dribble, broadcast	Urea Broadcast
Soil testing (% of area)[2]	46	Negligible
Plant tissue testing (% of area)[2]	2	Negligible
Nitrogen inhibitor used (% of area)[2]	14	Negligible
Number of N applications per crop[3]	1.8	2.6
N applied before crop emergence (%)[4]	77	33
Partial productivity of N (kg kg^{-1})[1,5]	60 (48–80)	45 (32–59)
Recovery efficiency of N (%)[6]	37 (30)	31 (18)

[1] Rice: medians and 25–75% quartile ranges of 207 rice–rice and rice–wheat farms in India, China, Thailand, Vietnam, Indonesia and the Philippines surveyed from 1995 to 1997 (Dobermann, 2000). Maize: medians and 25–75% quartile ranges of a sample of 4712 farms in Iowa, Illinois, Nebraska, Minnesota, Indiana, Ohio, South Dakota, Wisconsin, Missouri, and Michigan surveyed in 1994 (USDA, 1994 Cropping Practices Survey, unofficial data files, http://www.ers.usda.gov). Note that 1994 was a high-yielding year in most states.

[2] Rice: no exact numbers are available, but this practice is not common. Maize: average of 1859 farms surveyed in 1999 (USDA, 1999 Cropping Practices Survey, unofficial data files, http://www.ers.usda.gov).

[3] Rice: average of farms at seven sites in China, India, Indonesia, Philippines, Thailand, and Vietnam and range of means among sites, 1995–97 (Moya et al., 2002). Maize: average of 1922 farms surveyed in 2000 (USDA, 2001).

[4] Nitrogen applied before or at planting (% of total N amount). Rice: average of farms at seven sites in China, India, Indonesia, Philippines, Thailand, and Vietnam and range of means among sites, 1995–97 (Moya et al., 2002). Maize: average of 1859 farms surveyed in 1999 (USDA, 1999 Cropping Practices Survey, unofficial data files, http://www.ers.usda.gov).

[5] Partial factor productivity of fertilizer N = kg grain yield per kg N applied.

[6] Recovery efficiency is the proportion of applied N fertilizer that is taken up by the crop and is determined by the difference in the total amount of N measured in aboveground biomass at maturity in replicated plots that receive N fertilizer and a control plot without applied N. Rice: mean and standard deviation of four consecutive rice crops at 179 sites in key irrigated rice domains of Asia, 1997–2000 (Dobermann et al., 2002). Maize: mean and standard deviation of 38 on-farm experiments conducted in Illinois, Michigan, Minnesota, Missouri, Nebraska, and Wisconsin during 1995–1999 (North Central Regional Research Project NC-218; Cassman et al., 2002).

River Delta of North Vietnam to more than 4 ha in areas of southern and northern India and central Thailand (Moya et al., 2002). Individual fields are even smaller (0.2–0.5 ha) so that only small machinery can be used. Labor input is high, ranging from 115 h ha^{-1} per crop in areas where rice is direct-seeded to more than 2000 h ha^{-1} per crop in transplanted rice fields (Table 1). Favorable climate and access to irrigation water allow farmers to grow two to three crops each year. Although soils that support these systems vary widely in quality, relatively high levels of fertilizer and pesticide use are typical in most intensive rice production systems. Rice–rice and rice–wheat (*Triticum aestivum* L.) are the two dominant cropping systems.

Rice yields in Asia increased at an average rate of 2.5% year^{-1} from 1967 to 1984, but yield growth rates dropped to 1.2% from 1984 to 1996 (Dawe and Dobermann, 1999). In some large rice production domains where farmers were early adopters of modern irrigated rice production technologies, yields appear to have stagnated since the mid-1980s (Cassman and Dobermann, 2001) although the current average irrigated rice yield of 5.3 Mg ha^{-1} per crop is only 60–65% of the climate-adjusted yield potential across Asia (Table 1). Rice accounts for 15–85% of the total fertilizer consumption in major rice-producing countries in Asia, but accurate numbers and their changes over time are difficult to obtain. Published estimates of fertilizer use on rice are either derived from estimated shares of rice in total fertilizer consumption (Hossain and Singh, 2000) or expert opinions about rates applied to different crops (IFA, 1999). It is generally concluded that the impressive gains in rice yields during the 1960s and 1970s were associated with increased use of fertilizers, particularly urea-N, whereas growth in fertilizer consumption has slowed in recent years (Hossain and Singh, 2000).

Regular surveys of rice farms in Central Luzon, Philippines conducted by the International Rice Research Institute since 1966 represent one of the few sources of on-farm data on fertilizer use trends on rice in Asia (Figure 3). After an initial steep rise due to the adoption of modern varieties and fertilizers, rice yields in Central Luzon during the past 20 years have fluctuated around 3.2 Mg ha^{-1} in the wet season and 4 Mg ha^{-1} in the dry season. Nevertheless, fertilizer use continued to increase during the same period, leading to a steady decline in PFP of applied nutrients since the mid-1970s (Figure 3). Similar yield trends are observed in other irrigated rice domains (Cassman and Dobermann, 2001) so that it is likely that a stagnation or even decline in PFP of fertilizer has become a common feature in rice systems of developing countries in Asia. There is no indication that this has led to a build-up of mineral N levels in the soil or an increase in the indigenous N supply, suggesting that the extra N remains in organic soil N forms that are less plant available (Cassman et al., 1998; Olk et al., 1996).

A network for strategic on-farm research in key irrigated rice domains of Asia was established in 1994 (Dobermann et al., 2002). Data from this study show that most irrigated rice farmers apply 86–138 kg N, 11–25 kg P, and 0–46 kg K ha^{-1} $crop^{-1}$ (Table 2), mostly broadcast by hand and with little use of special products such as slow-release fertilizers or N inhibitors. Typically, about one third of the N is applied before crop emergence and split application is common. Nevertheless, fertilizer-N efficiency has not increased substantially during the past two decades. Average RE_N in the late 1990s was only 0.31 kg kg^{-1} (Table 2), which compares to an average RE_N of 0.30 kg kg^{-1} (0.26 kg kg^{-1} in wet season and 0.33 kg kg^{-1} in dry season rice) measured in 236 experiments conducted with irrigated rice in Indonesia during the early 1970s (van Keulen, 1977). Only 20% of all farmers achieve RE_N >0.5 kg kg^{-1} which is comparable to N efficiency typically measured in well-managed experiments (Dobermann et al., 2002). Large variability in indigenous nutrient supplies among rice fields was found to be a general feature of intensive rice systems in Asia (Cassman et al., 1996; Olk et al., 1999; Wang et al., 2001). Fertilizer rates, particularly N, are typically not adjust to this spatial and temporal variability, resulting in a lack of congruence between nutrient supply and crop demand, sub-optimal yield and low N use efficiency (Cassman et al., 1998).

The Green Revolution in Asia significantly altered nutrient cycling in lowland rice systems so that concern was raised about negative nutrient input–output balances or other threats to sustainability such as a general decline in soil quality (Greenland, 1997). There is a paucity of data to address such issues because detailed on-farm studies of nutrient inputs and outputs rarely exist and the few studies conducted at research sites are unlikely to adequately represent the wide range of production environments where rice is grown. An attempt to estimate the average NPK input-output balance in an irrigated rice system under present conditions is presented in Table 3, but several assumptions must be validated in future research. Most uncertain is the N input from biological N fixation and nutrient inputs and losses from sources such as manure, rain, and irrigation. Information about net losses of nutrients from crop residues is also scarce. Compared to maize systems in the USA, larger amounts of rice crop residues are removed for use as fuel or fodder, or burned to facilitate more rapid planting of the subsequent rice crop.

Despite the low RE_N and large gaseous losses of fertilizer-N in many farms, N is sequestered in intensive rice systems with long periods of flooding. Field experiments with more detailed measurements support this conclusion and often suggest even larger positive N balances than the one shown in Table 3 (Ladha et al., 2000a; Witt et al., 2000). However, the accumulating N is likely stored in organic matter pools that are not easily plant available (Cassman et al., 1998). At comparable total soil N levels, the average indigenous supply of plant available N during a growing season is almost 3-fold larger in a typical USA maize field than in a lowland rice field of Asia (Cassman et al., 2002). Although N mineralization can be briefly

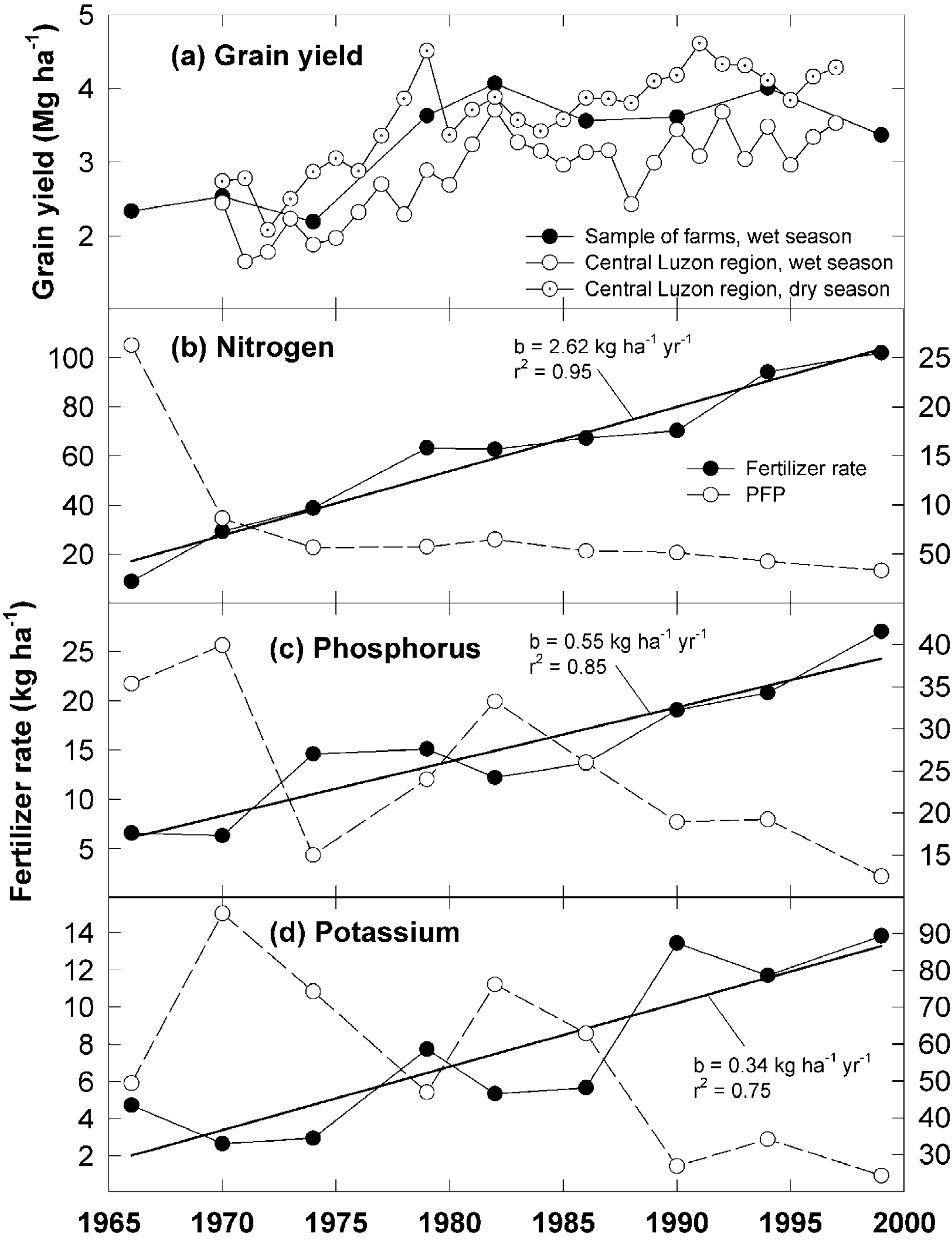

Figure 3. Trends in grain yield, fertilizer use, and partial factor productivity of fertilizer nutrients (PFP = kg grain yield per kg nutrient applied) in irrigated rice areas of Central Luzon, Philippines. Rice is grown in continuous annual double crop systems (dry season and wet season). Yield data (paddy): Mean of regular loop surveys of 58–146 farms and regional yields obtained from official statistics. Fertilizer data: Mean of loop surveys of 58–146 farms conducted by IRRI (data provided by D. Dawe and M. Hossain, Social Sciences Division, IRRI).

accelerated by measures such as soil drying or drainage, there is little indication that the indigenous N supply can be easily increased over time (Dobermann et al., 2000). At the average farm level, phosphorus applications generally appear to be in balance with rice yield increases and P removal, although P deficiency

Table 3. Estimated average input–output balance of N, P, and K in intensive rice systems of South and Southeast Asia with an average yield of 5.2 Mg ha^{-1} (Dobermann and Witt, 2000)

Inputs and outputs[1]	N (kg ha^{-1} $crop^{-1}$)	P (kg ha^{-1} $crop^{-1}$)	K (kg ha^{-1} $crop^{-1}$)
Inputs:			
Fertilizer	117	18	17
Farmyard manure	5	2	5
BNF[2]	50	0	0
Outputs:			
Gaseous losses[3]	87	0	0
Net removal with grain	58	12	13
Net removal with straw[4]	20	2	35
Input-output balance	+7	+6	−26

[1] Estimates are based on medians of fertilizer input, apparent recovery efficiency of applied nutrients, crop uptake, and crop residue amount measured for two consecutive rice crops in 207 farms in China, India, Indonesia, the Philippines, Thailand, and Vietnam (1995–1997, Reversing Trends of Declining Productivity in Intensive Irrigated Rice Systems, On-farm monitoring database, June 2000, IRRI.). At most sites, surface water with low nutrient content is used for irrigation so that the assumption was made that nutrient inputs from irrigation and rainwater are roughly equal to leaching losses (Dobermann et al., 1998). Average nutrient concentrations in irrigation water samples collected at all sites from 1999 to 2000 (N=125) were 2 mg N L^{-1}, 0.5 mg P L^{-1}, and 3 mg K L^{-1}. At an average water use of 500 mm per crop (1000 mm irrigation in a dry season and no supplemental irrigation in a wet season), this amounts to inputs of 10 kg N, 2.5 kg P, and 15 kg K ha^{-1} $crop^{-1}$, but leaching losses were not measured.

[2] An average input of N from biological N fixation (BNF) of 50 kg ha^{-1} was assumed (Koyama and App, 1979), but actual BNF inputs vary from about 28 to 51 kg ha^{-1} per crop (Cassman et al., 1998).

[3] Gaseous N losses were estimated from the fertilizer and manure N input and the measured recovery efficiency of applied fertilizer N, assuming that continuous fertilizer use does not result in a significant increase in residual mineral N in the soil.

[4] Net removal with straw includes nutrients lost due to removal or burning of crop residues and was estimated from plant nutrient accumulation in straw, amount of residue remaining, and the predominant crop residue management practice at each site.

still occurs in some areas. In contrast, potassium deficiency is likely to become an emerging constraint in many rice areas because there is a large negative K balance (Table 3), which is consistent with results from long-term experiments (Dobermann et al., 1998). Net removal of K from rice fields averages about 26 kg ha^{-1} per crop or 52 kg ha^{-1} on an annual basis in double-crop systems. At a similar level of annual grain production, the K input–output balance in maize systems of the USA appears to be about +30 kg ha^{-1} per year because K application rates are larger and fewer residues are removed.

Multifaceted future nutrient management needs

The comparison of USA maize and Asian rice systems suggests that the latter have lower nutrient use efficiency and average yields that are closer to the climate-adjusted yield potential than those of maize in North America. Available on-farm data indicate that the average RE_N is only 30% in rice and 37% in maize, whereas recovery efficiencies of 50–80% can be achieved in field experiments with good management in both environments (Cassman et al., 2002). As expected, nutrient efficiency (expressed as PFP) initially dropped in both systems during the early years of adoption of modern varieties/hybrids because fertilizer use increased rapidly from previously low levels. However, PFP has increased since the early 1980s in USA maize systems while the limited data available suggest that it has not increased in the major irrigated rice production domains of south and southeast Asia.

Differences in economic systems and government roles in farm programs as well as improved technologies supported by a strong research and extension system appear to be major reasons for the steady increase in nutrient efficiency in USA maize systems. Improved technologies include adoption of conservation tillage, hybrids with multiple tolerances to stresses, high seed quality, better weed control, soil testing and locally calibrated fertilizer recommendations, and timely planting and new fertilizer application techniques made possible by rapid improvements in mechanized equipment. In contrast, rapid initial advances in rice yields were mainly achieved through adoption of 'seed-and-fertilizer packages'. While USA farmers have conserved or even increased soil nutrient stocks, rice farmers in Asia appear to be depleting soil K reserves. While USA farmers use high-quality hybrid seed, rice farmers in Asia mostly rely on poorer-quality local seed sources because of less private sector involvement in seed production. The impact of technological progress on nutrient use efficiency is further illustrated by the trends observed in Japan. There, in contrast to most other Asian countries, PFP of macronutrients in irrigated rice has increased since the early 1980s, when fertilizer use began to decline because higher grain quality became important and environmental concerns stimulated the adoption of more sophisticated management technologies such as deep placement, splitting of N applications, models accounting for N mineralization, and the increased use of slow release fertilizers (Suzuki, 1997).

Despite these differences, similar challenges for plant nutrition exist in these two major cereals production systems because exploitable gaps in yield and nutrient use efficiency between current farm averages and attainable levels are similar. The need for more precise and diverse methods of nutrient management will be driven by a number of factors. First, germplasm improvement will widen the range of nutrient management solutions required for specific needs. Second, as yields of current varieties and hybrids approach the yield ceiling, the margin of error between nutrient excess and deficiency decreases markedly. This is because of the non-linear nature of the relationships between nutrient uptake and grain yield uptake requirements per unit yield increase as yields exceed about 70% of the yield potential (Witt et al., 1999). Therefore, a greater quantitative knowledge about crop response to nutrients and balanced plant nutrition is required to manage crops at high yield levels. Third, dynamic, site-specific nutrient management of small units such as single fields or areas within them will be required to overcome the current mismatch of fertilizer rates and crop nutrient demand at the farm level. Fourth, environmental concerns such as pollution of drinking water by nitrate, eutrophication of streams, lakes, and coastal marine environments, as well as net contributions of agricultural systems to global warming will force the development of improved management practices further enhancing nutrient use efficiency.

Potential role of germplasm improvement

In both USA maize and Asian rice systems, germplasm improvement during the past 30 years has resulted in greater yield stability as a result of substantial increases in tolerance to abiotic and biotic stresses (Duvick and Cassman, 1999; Peng et al., 1999; Tollenaar and Wu, 1999). Less certain is whether there has been a significant increase in yield potential. It is also uncertain whether major scientific breakthroughs in complex traits such as yield potential or traits that directly confer improvements in nutrient uptake efficiencies or physiological requirements can be achieved. Breeding genotypes that produce more grain per unit nutrient uptake in the plant appears questionable because it is difficult to further increase the harvest index and because relationships between crop growth rates and internal nutrient requirements appear to be tightly conserved (Burns et al., 1997). In rice, efforts are in progress to develop new plant types with a 25% larger yield potential (Peng et al., 1999), C_4-photosynthesis characteristics (Sheehy et al., 2000), or increased contributions from biological N fixation (Ladha and Reddy, 2000). Because such traits are under complex genetic control, it is not likely that these efforts will have measurable impact in the near future. There is little evidence of comparable efforts on maize in either public or private sector research. Instead, the private sector seed industry continues to focus on improving yield stability and stress tolerance through a multi-location selection process coupled with molecular approaches to incorporate specific traits for pest and herbicide resistance, and end-use quality.

Over the short-term, conventional and molecular breeding and biotechnology will probably contribute most by facilitating the development of crop genotypes with improved growth fitness and specific grain qualities. Growth fitness traits that affect nutrient management include (i) rapid early vegetative growth to reduce the period of inefficient resource use, (ii) root architecture for increased soil exploration and nutrient acquisition, and (iii) tolerance to abiotic and biotic stresses. Breeders can make contributions to improving nutrient efficiency by developing genotypes in which growth and spatial distribution of roots are more congruent with the release dynamics and the spatial distribution of nutrients in the soil. Genotypes with more rapid leaf area development that increases biomass accumulation during the crop establishment phase are likely to improve N use efficiency by increasing N uptake during the period of greatest soil N supply immediately after planting.

Although genotypic variation in nutrient uptake kinetics has been reported for rice (Teo et al., 1995) and maize (Baligar and Barber, 1979), field measurements and simulation models suggested that nutrient uptake capacities of root systems in current varieties and hybrids are unlikely to be a significant constraint to increasing nutrient use efficiency in intensive agricultural systems with adequate water supply, fertile soils and high fertilizer use (Burns, 1980; Kirk and Solivas, 1997; Peng and Cassman, 1998). However, major changes in cropping practices have occurred in both maize and rice systems, which re-emphasize the need for research on genotypic variation and genetic control of root architecture. In the USA, conservation tillage (no-till, ridge-till, or mulch-till) has increased to 47% of the total area planted to maize and soybeans (Padgitt et al., 2000). Long-term no-tillage may lead to surface accumulation of crop residue, P and K due to broadcast fertilizer application, uneven nutrient extraction by crop roots, and annual return of residues to the surface (Mackay et al., 1987; Vyn and Janovicek, 2001). Soil acidification may occur in zones with annual N injection (Bouman et al., 1995). In Asia, direct-seeding of rice has replaced transplanting as the dominant form of crop establishment in many areas. A move from transplanted rice to direct-seeding may be associated with lower N uptake from indigenous soil resources (Peng et al., 1996) or lower yields due to imperfect control of factors affecting nutrient use efficiency (Dobermann et al., 2002). Direct-seeding is often associated with shallow soil tillage and high plant density. This results in a shallower root system and a smaller soil volume from which nutrients are extracted by the plants, but it also changes the dynamics of nutrient uptake due to greater plant competition. Therefore, larger potential may exist for genetic manipulation of root architecture than attempting to exploit small differences in root nutrient influx parameters or internal nutrient utilization among cultivars or hybrids.

Genotypic differences in crop response to nutrient supply have often been described (Parks, 1985), but their physiological basis is poorly understood. Molecular tools may help obtain a better understanding of the genetic controls for tolerance to stresses, and thereby facilitate selection of germplasm better adapted to different soils or crop management practices. On marginal lands, farmers may be able to grow crops where drought and/or poor soil conditions have limited crop production in the past (Wood et al., 2000). On favorable land, traits such as increased nutrient recovery, lodging resistance or host-plant resistance to pests or certain pesticides help minimize yield losses and/or reduce production costs. Thus, future approaches for fertilizer management must also take into account effects on stress tolerance traits so that the targeted yield goals can be more consistently realized.

In 2001, 63% of the U.S. soybean area was planted with herbicide-tolerant transgenic varieties, 16% of the maize area was planted with Bt-maize and 7% with herbicide-tolerant maize (USDA, 2001, http://www.usda.gov/nass). To date, adoption of transgenic rice varieties has been minimal, but is likely to increase in the future (Conway and Toenniessen, 1999). The extent to which nutrient requirements and management of transgenic crops might differ from conventional varieties or hybrids has not received much attention (PPI, 1999). As long as genetic modifications do not alter plant traits or biochemical pathways that increase the genetic yield potential or harvest index, crop nutrient requirements are likely to be similar to those of non-transformed crops. This is probably true for the current generation of transgenic crops adopted by farmers. Field experiments conducted in Nebraska found only slight differences in yields of herbicide resistant soybeans as compared to their non-transformed sister lines (Elmore et al., 2001). Research on rape showed no significant differences in yield and oil content response to N among two transgenic hybrids and two non-transformed cultivars (Schuster and Rathke, 2001).

Future generations of transgenic crops, however, may have more pronounced differences in yield potential due to manipulations of more complex traits such as biochemical pathways involved in photosynthesis (Zeigler, 2001) or increased nutrient acquisition by more vigorous root systems. Improvements in grain quality through genetic engineering may also alter nutrient management requirements. Examples include low-phytate maize for human nutrition (Mendoza et al., 2001) or to reduce P content in manure (Waldroup et al., 2000), high-oil maize (Lambert and Hallauer, 1994), plants grown for functional foods or nutraceuticals (Dillard and German, 2000), vitamin A-enriched rice (Potrykus, 2001), or high phytase rice with an increased iron content (Lucca et al., 2001). Many obstacles must be overcome until these breakthroughs in biotechnology will have impact at the farm level, particularly in developing countries (Zeigler, 2001). Applied plant nutrition research should not lag behind such developments because the large-scale investments made into biotechnology will lead to rapid advances in the foreseeable future. Research is also necessary to study the ecological consequences of long-term use of transgenic crops on soil processes and nutrient cycling. For example, recent chemical analysis suggested that the lignin content of Bt-corn hybrids was 33–97% higher than that of their respective non-Bt isolines (Saxena and Stotzky, 2001). Reasons for this are not understood, but such differences are likely to affect pest resistance, non-target organisms, and the decomposition of crop residues.

Quantitative understanding of yield response to nutrients

Progress in fundamental soil and plant research has had insufficient impact on theoretical and practical concepts for nutrient management in intensive agriculture. Researchers in the USA and Asia have mostly developed fertilizer recommendations based on empirical yield-input relationships, whereas less attention has been paid to more quantitative plant nutrition concepts. In the USA, nutrient management issues are generally discussed within the framework of mobile (N) versus immobile (P, K) nutrients or nutrients that are environmentally sensitive (N, P) and those without known environmental risk (Havlin et al., 1999). Farmers rely on soil testing to determine field-specific application needs (Table 2), but the fertilizer recommendations for maize vary widely among states in the corn belt (Table 4). Algorithms for estimating N rates often include a yield goal and credits for crop rotation and other sources of N input, but the use of soil testing varies and in some states such as Iowa the recommendations do not explicitly account for most of these components (Table 4). Fertilizer-N algorithms that are based on soil tests tend to overpredict N rates in years with poor response to fertilizer due to unfavorable climate or inaccurate soil NO_3 testing (Bundy et al., 1999). Recommendations for managing 'immobile' nutrients such as P and K follow concepts 'sufficiency-deficiency correction', 'buildup and maintenance', or 'replenishment of crop removal' (Hergert et al., 1997). Critical soil test levels for P and K (derived from relative yield response curves) vary somewhat among states and soil types in the corn belt, but they have changed little since Bray's original research in Illinois conducted in the late 1930s and early 1940s (Bray, 1944, 1945, 1954). In most cases, economics of fertilizer use are not included in the fertilizer recommendation algorithms. In Asia, fertilizer recommendations for rice are mostly based upon empirical yield response functions that are extended on a district or regional scale. Soil testing and plant tissue analysis are rarely used (Table 2), mainly because infrastructure and commercial soil testing services are lacking (ESCAP/FAO/UNIDO, 1994). However, even if soil testing were available, many existing soil tests are of limited use for irrigated rice because they often fail to accurately predict the indigenous nutrient supply under field conditions. Routine soil tests often fail to extract soil nutrient fractions that are important for nutrient availability under flooded soil conditions. Moreover, in an irrigated rice field, the indigenous nutrient supply during a growing season is also much affected by the dynamics of flooding and drying cycles as well as nutrient inputs from sources other than the soil, such as irrigation and biological N_2 fixation in the soil–floodwater system (Cassman et al., 1996; Dobermann et al., 1996; Yadvinder-Singh et al., 2000).

Recommendations such as those shown in Table 4 were the result of multi-site calibration and correlation research, but their principles were developed during a time when yields of maize or rice were half today's average yields. Errors associated with sampling and soil testing (sampling density and depth, laboratory variability), widely varying interpretation of soil test values and the relative insensitivity of current recommendations to different soil types and crop management practices have raised concern that the 'correlation and calibration' approach cannot keep pace with changes in intensified cropping systems (Hergert et al., 1997). The correlation/calibration yield-response approach would require frequent empirical verification and updating of recommendations in response to changes in cropping, but the requirement for multi-year and multi-location evaluation is both costly and slow.

In the future, fertilizer recommendation algorithms must be considerably more robust and accurate than current approaches. They must accommodate different crops, cropping systems, crop management technologies, soil conditions, and climate-driven yield potential. Single levels in a recommendation should then be based on standard conditions (e.g., maize planted in May on a no-till deep silt loam soil in Nebraska; rice direct-sown on a clay soil in the dry season in South Vietnam) that take into account the major factors gov-

Table 4. Examples of university fertilizer recommendations for maize in the USA

State	Nitrogen[1]	Phosphorus[2]	Potassium[3]	Source
Iowa (IA)	*All pre-emergence N:* Maize after maize: 150–200lb/acre Maize after soybean: 100–150 lb/acre *Pre-emergence + in-season application:* Pre-emergence: Maize after maize: 50–125 lb/acre Maize after soybean: 0–75 lb/acre Sidedress: $N = (CL - NO_3) \times 8$	Sufficiency concept. Tables based on five topsoil soil test categories (very low, low, optimum, high, very high) and two subsoil P levels (low, high). No P if STL >15 ppm (Olsen) or >20 ppm (Bray, Mehlich).	Sufficiency concept. Tables based on five topsoil soil test categories (very low, low, optimum, high, very high), two subsoil P levels (low, high), and two soil texture categories (fine, sandy). No K if STL > 130 ppm.	(Blackmer and Voss, 1997)
Nebraska (NE)	$N = -35 + (1.2 \times YG) - (8 \times NO_3) - (0.14) \times YG \times SOM) - N$ credits N credits: maize 0 soybeans 45 N from irrigation water manure	Sufficiency concept. Tabular values for two modes of application (broadcast, band) based on five topsoil soil test categories (very low, low, optimum, high, very high). No. P if STL > 10 ppm (Olsen) or > 15 ppm (Bray).	Sufficiency concept. Tabular values for two modes of application (broadcast, band) based on five topsoil soil test categories (vey low, low, optimum, high, very high). No K if STL > 125 ppm.	(Shapiro et al., 2001
Illinois (IL)	$N = 1.2 \times YG - N$ credits N credits: maize 0 soybeans 40 N from other chemicals) N from irrigation water	Buildup and maintenance concept for three geographical zones of different subsoil-P supply. Target STL 40–50 lb/acre. No P if STL >60–70 lb/acre. CR: 0.43 lb P_2O_5/bu yield.	Buildup and maintenance concept for two geographical zones of difference CEC. Target STl 260–300 lb/acre. No K if STL >360–400 lb/acre. CR: 0.28 lb K_2O_5/bu yield.	(Hoeft and Peck, 1999)
Minnesota (MN)	*Standard:* Tables based on previous crop (6), SOM (2 levels), YG (categories), NO_3 credit. *Western MN:* $N = 1.2 \times YG - NO_3$ – other N credits N credits: maize 0 soybeans 40	Yield goal-based: Bray-1: $P = (0.700 - 0.035\ STL) \times YG$ Olsen: $P = (0.700 - 0.044\ STL) \times YG$ Full amount if broadcast, reduced if row-applied. No P if STL >20 ppm (Olsen) or >25 ppm (Bray).	Yield goal-based: $K = (1.166 - 0.0073\ STL) \times YG$ Full amount if broadcast, reduced if row-applied. No K if STL > 175 ppm.	(Rehm et al., 2000)

[1] N = N rate (lb N/acre); YG = yield goal or yield potential (bu/acre); N credit = credits given for N supply from previous crop or irrigation; NO_3 = soil test nitrate-N level (ppm); CL = critical soil test nitrate-N level; SOM = soil organic matter content (%). Soil tests used: late spring nitrate in 0–30 cm depth (ppm, IA), soil organic matter in topsoil (%, NE), fall or spring soil nitrate-N (ppm) in 0–120 cm (NE) or in 0–60 cm (MN).

[2] P = P rate (lb P_2O_5/acre); YG = yield goal or yield potential (bu/acre); STL = soil test level; CL = critical soil test level. ML = maintenance soil test plateau. CR = crop nutrient removal per unit harvested yield. Soil tests used: Bray-1 (IA, IL, NE, MN), Olsen (IA, NE, MN), Mehlich-3 (IA).

[3] K = K rate (lb K_2O/acre); YG = yield goal or yield potential (bu/acre); STL = soil test level; CL = critical soil test level. ML = maintenance soil test plateau; CR = crop nutrient removal per unit harvested yield. Soil tests used: 1 *N* Ammonium acetate (IA, IL, NE, MN, IA), Mehlich-3 (IA)

erning crop response to the nutrient of interest. Such refinements can be made at different levels of complexity such that a general recommendation can be broken down into more meaningful and detailed specific recommendations. However, a key challenge is to improve the prediction of soil nutrient supply, fertilizer efficiency, plant nutrient accumulation, and its effect on yield in absolute terms (Sinclair and Park, 1993; Witt et al., 1999). Future improvements in estimating optimal fertilizer rates (F) will depend on how researchers will be able to solve the general equation:

$$\begin{aligned} Y_{\mathrm{a}} &= f(Y_{\mathrm{m}}, U_1, U_2, \ldots U_x) \\ F_1 &= (U_1 - I_1)/R_1 \\ &\ldots \\ F_x &= (U_x - I_x)/R_x, \end{aligned}$$

where Y_{m} is climatic and genetic yield potential, Y_{a} is attainable nutrient-limited yield, F_x is amount of applied fertilizer, U_x is amount of nutrient in the plant, I_x is supply of nutrient from indigenous sources, R_x is fraction of nutrient recovered in the plant, and 1 to x denote each of the essential plant nutrients.

Although several process-oriented crop simulation models have been developed for maize and rice, their use for solving this equation in practical nutrient management appears limited. Input data required by such models are often not available and most of them cannot account for nutrients other than N. Attempts have been made to model the complete soil-plant P (Greenwood et al., 2001) and K cycle (Greenwood and Karpinets, 1997) in a more applied but still process-oriented context. Another alternative is a robust, stepwise empirical model that encompasses a wide range of conditions as opposed to a narrowly defined local calibration or response curve. The QUEFTS model (Janssen et al., 1990; Smaling and Janssen, 1993) is such an empirical solution because it allows estimating the fertilizer requirement as a function of (i) climatic yield potential, (ii) the relationship between grain yield and plant accumulation of N, P, and K, (iii) the potential indigenous N, P, and K supplies, and (iv) recovery efficiencies of fertilizer N, P, and K. In this approach (i) can be estimated using a validated crop simulation model, (iii) must be measured using a soil test or a crop-based estimate, and (iv) is usually adjusted to local soil types and cropping conditions. Estimates for (ii) can be obtained from a generic relationship between grain yield and nutrient accumulation obtained from a large database from a wide range of production environments to account for nutrient interactions and differences in yield potential (Witt et al., 1999).

Practitioners estimate crop nutrient uptake per unit biomass or yield (goal) using a single number (rule of thumb). Using such numbers, long-term research on maize in Nebraska concluded that crop removal-based fertilizer recommendations led to an uneconomically high use of P and K fertilizer with no significant yield gains over a sufficiency approach based on critical soil test levels (Olson et al., 1982). However, questions must be raised whether correct estimates of crop nutrient requirements per unit yield (or crop removal coefficient) are currently used because they (i) are typically derived from field experiments conducted at only few sites, which are most often located at research stations with high background levels of indigenous soil nutrient supply, (ii) assume linearity between crop yield and nutrient accumulation, and (iii) do not account for nutrient interactions and climatic yield potential as a driving force for optimal nutrient requirements (Witt et al., 1999). There is generally a close relationship between dry matter and nutrient accumulation across a wide range of sites and varieties, described by the same non-linear function for both maize and rice (Figure 4a). However, the relationship becomes scattered when grain yield is plotted against plant N accumulation. There are different plateaus for rice and maize that are related to differences in the genetic and climatic yield potential, but there is also large variation within each species, which is caused by a multitude of yield-limiting factors as well as excess of certain nutrients. In both crops, non-linear average relationships suggest decreasing internal efficiency of nutrients as yields approach the yield potential (Figure 4b). The same principles hold true for other nutrients such as P and K (data not shown). Using a single 'crop removal coefficient' may therefore lead to erroneous nutrient use and low efficiency.

In earlier work, C.T. de Wit and later H. van Keulen (van Keulen, 1977, 1986; van Keulen and Van Heemst, 1982) studied the relationship between yield and plant nutrient accumulation for several crops, including maize and rice. They showed a linear range followed by a parabolic plateau and concluded that an upper boundary exists at which a nutrient's concentration in grain (and straw) becomes diluted to the maximum possible extent when that nutrient is the sole factor limiting yield. In the QUEFTS model, Janssen et al. (1990) expanded this work by using two linear boundaries that described the range from maximum

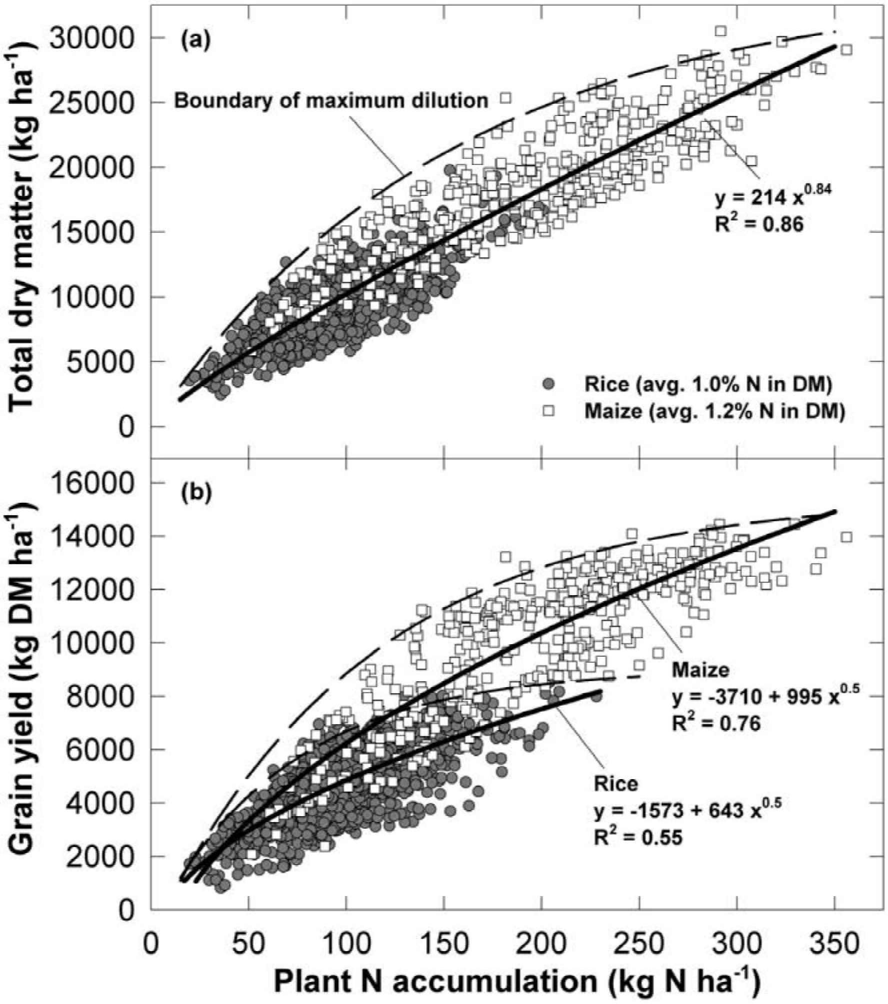

Figure 4. Relationships between total plant dry matter or grain yield and plant nitrogen accumulation in maize and rice. Irrigated rice: on-farm and research station experiments conducted in Asia during 1995–2000 (n = 1658). Maize: on-farm and research station experiments conducted in the north-central USA during 1995–2000 (n=470). Dashed lines indicate the apparent boundary of maximum dilution of nitrogen in the plant, whereas the solid lines show the average internal efficiency for each environment as obtained from non-linear regression.

accumulation to maximum dilution of N, P, and K in maize. Those ‘envelopes’ were then mathematically combined into linear parabolic plateau curves of optimal (balanced) nutrition of all three macronutrients. Witt et al. (1999) demonstrated how this method can be used to develop families of yield–optimal NPK accumulation curves for rice grown in environments with different climatic yield potential across Asia. Their model predicted a linear increase in grain yield of rice if nutrients are taken up in balanced amounts of 14.7 kg N, 2.6 kg P, and 14.5 kg K per 1000 kg of grain yield, until yields reached about 70–80% of the climate-adjusted yield potential. This compares to published estimates that range from 15 to 24 kg N, from 2 to 11 kg P, and from 16 to 50 kg K per 1000 kg yield (Witt et al., 1999). This comparison indicates that literature data appear to overestimate nutrient requirements if they are not based on experiments that represent the whole range of farming conditions.

Related research on defining generic nutrient dilution curves during crop growth describe the decline in critical plant N concentration with increasing crop biomass accumulation (Greenwood et al., 1990; Sheehy et al., 1998). Attempts are also being made to combine those concepts with the yield-nutrient accumulation relationships used in QUEFTS (Witt et al., 2001). All these approaches have a common foundation in that they seek to develop a quantitative understanding of crop nutrient requirements in a robust format that is suitable for practical nutrient management across a wide range of environments. However, except for recent research in irrigated rice (Dobermann et al., 2002), such an approach has not been evaluated by the soil testing and fertilizer management community in the USA and Asia.

Quantitative approaches are particularly suitable for favorable production environments, because in most years the yield response to nutrients is not severely confounded by other abiotic or biotic stresses. Their generic framework simultaneously accounts for interactions amongst macronutrient requirements and also allows the estimation of economic return from fertilizer application (Janssen, 1998). To improve the accuracy of this approach, however, future research must clarify a number of unanswered questions. First, available experimental data suggest that the upper boundary of maximum nutrient dilution in the plant at harvest is also non-linear (Figure 4b), not linear as assumed in models such as QUEFTS. Second, there is no clear theoretical justification for using a boundary line describing maximum accumulation of a nutrient in the plant because these are mostly situations of disturbed growth due to factors other than nutrients. Third, in modeling the nutrient interactions, the same weight is given to N, P, and K, whereas it is possible that nutrients such as K can be diluted relatively more in the plant than N before a significant reduction in growth occurs (Burns et al., 1997). However, Greenwood and Stone (2001) have recently shown K dilution curves for a range of vegetable crops, suggesting that, as for N, critical and maximum K concentrations during growth appear to be linearly related to relative growth rate. Critical P or K dilution curves analogous to those determined for N have not been published for cereal crops. Fourth, the nutrient requirements of a crop must be examined in relation to yield potential, with particular emphasis on requirements at yield levels that are 80% or more of the yield potential ceiling. A related issue is whether the linear range of the optimal relationship between grain yield and plant nutrient accumulation will simply extend further with additional increases in yield potential.

Generic approaches for site-specific nutrient management

Precision farming or site-specific management in the USA has focused on managing spatial variability of nutrients within large fields by variable application of N, P, K, or lime using local fertilizer algorithms in combination with soil samples collected from grids or ‘soil management zones’ within a field (Pierce and Nowak, 1999). With the exception of liming, many of the case studies conducted so far have failed to demonstrate significant agronomic, economic, or environmental benefits over uniform applications (Ferguson et al., 2002; Lowenberg-DeBoer and Swinton, 1997; Pierce and Nowak, 1999; Wibawa et al., 1993). Reasons for this failure appear to result from: (i) insufficient characterization of spatial variation in indigenous nutrient supply (including sampling and laboratory error) and yield goals, (ii) use of empirical, single-nutrient fertilizer algorithms that are not suited for site-specific management (Ferguson et al., 2002), and (iii) insufficient post-emergence adjustment of N rates and timing of application to account for differences between the actual yield potential and the average climatic conditions that were assumed for making the fertilizer recommendation. Understanding is lacking of spatial cause–effect relationships that can be quantified, generalized and extrapolated. Reliance on grid soil sampling and inherently imprecise measurements such as soil test P and K for developing variable rate fertilizer application maps has largely proven unsuccessful. There is also a lack of multivariate response functions that can estimate the yield response to inputs, site characteristics, and varying plant density (Bullock et al., 1998). Currently, there are no standards for soil sampling designs, sampling intensity, or methods of interpolation used in creating nutrient management maps and rarely is there information provided about the quality of such maps (Pierce and Nowak, 1999). Quantitative propagation of errors is not well understood. Errors must be partitioned into those caused by unresolved spatial variation (due to sampling, soil testing, and interpolation), uncertainty about crop response models, and the application error associated with equipment performance. Recent studies suggest that it is unlikely that the classical soil sampling and soil testing approach can become a basis for precise nutrient management because the soil chemical analytical cost is large and because of the sampling, analytical, and interpolation error inherently associated with it (Viscarra Rossel and McBratney, 1998). Taking into account all uncertainties involved may lead to the conclusion that the optimum is reached with an uniform application of inputs (Viscarra Rossel et al., 2001), but no such studies have been conducted to compare different nutrients in environments with different yield potential and risk.

Site-specific nutrient management (SSNM) should be more broadly defined as the dynamic, location-specific management of nutrients in a particular cropping season to optimize the congruence of supply and demand of nutrients according to their differences in cycling through soil–plant systems (Dobermann et al., 2002). This definition accounts for (i) regional and seasonal differences in yield potential and crop nutrient demand, (ii) between- as well as within-field spatial variability in indigenous nutrient supply, (iii) within-season dynamics of soil N supply and crop N demand, and (iv) location-specific cropping systems and crop management practices. A generic SSNM concept must then consider the determinants and governing forces of (i) pre-emergence and long-term management of macro- and micronutrients and (ii) post-emergence (in-season) adjustment of N to account for the seasonal variability in growth and yield potential (Figure 5). Such a concept also takes into account the principal differences in managing nitrogen, less mobile nutrients such as P and K, and micronutrients (Dobermann and White, 1999). From 1997 to 2000, a field-specific variant of the SSNM strategy shown in Figure 5 was developed and evaluated in on-farm experiments at 179 sites in eight irrigated rice domains of Asia (Dobermann et al., 2002; Wang et al., 2001). Because significant field-to-field variability existed and within-field variability operated over short distances that were difficult to cope with (Dobermann et al., 1995, 1997), managing the variability among fields was identified as highest priority. Fertilizer application rates for N, P, and K were estimated for individual fields by accounting for the indigenous nutrient supply, yield goal, and nutrient demand as a function of the interactions between uptake requirements for N, P, and K (Witt et al., 1999). Crop-based estimates of the indigenous nutrient supply in nutrient omission plots were used because soil testing methods did not sufficiently predict this parameter. Different N management schemes were developed for each domain to account for regional variation in the primary factors driving N use efficiency (Figure 5). Average grain yield increased by 0.5 Mg ha^{-1} (11%) and N fertilizer rate decreased by 5 kg N ha^{-1} with field-specific management compared to the baseline farmers' fertilizer practice. Farmers' practices typically relied on a large N fertilizer application early in the season, when the capacity for crop uptake was small, and one or two additional N topdressings. In contrast, field-specific management utilized two to four topdressings that were applied to achieve greater synchrony with crop demand, and individual doses of pre-plant or topdressed N were smaller than those applied by farmers' practices. As a result, mean RE_N increased from 30% with farmers' practices to 40% with field-specific management. On average, profit increased by US$46 ha^{-1} per crop through the use of field-specific management. These results highlight the potential for SSNM in small-scale farming systems in developing countries, provided the technologies chosen match the systems' biophysical and socioeconomic characteristics.

Key avenues for developing a similar improved SSNM strategy for mechanized maize farming include (i) thematic mapping of soil properties using a combination of spatially dense auxiliary information (on-the-go soil sensors, remote sensing, yield maps) and destructive soil sampling, and (ii) decision aids for in-season N management in a large field. Reproducible procedures for delineation of functional soil zones for site-specific management (van Alphen and Stoorvogel, 2000) must be developed so that such 'zones' can be managed with greater precision and by using more precise nutrient models and recommendations. Many in-season N management concepts based on post-emergence soil or plant indicators were proposed for maize in the past, but most of them have not found practical acceptance due to their high cost or difficulties in implementing them in routine farming (Schroeder et al., 2000). Methods can be broadly divided into three approaches: (i) corrective N management, (ii) predictive N management, and (iii) predictive–corrective N management. In each of these, post-emergence N applications can be homogeneously applied to the whole field or, in the most advanced sense, varied over very short distances if a sensor is attached to a fertilizer spreader with variable-rate capabilities.

Corrective methods employ diagnostic tools such as a chlorophyll meter (Varvel et al., 1997), remote sensing (Blackmer et al., 1996), or on-the-go sensors (Lammel et al., 2001) to determine the need for an N topdressing. Although technology development is proceeding rapidly, the ability to interpret remotely sensed information about canopy N status to estimate the amount of fertilizer-N needed has proven to be a difficult challenge. At present, this approach relies on empirical comparison with an over- or under-fertilized reference strip to assess whether an additional yield response to N is likely to occur. However, if the

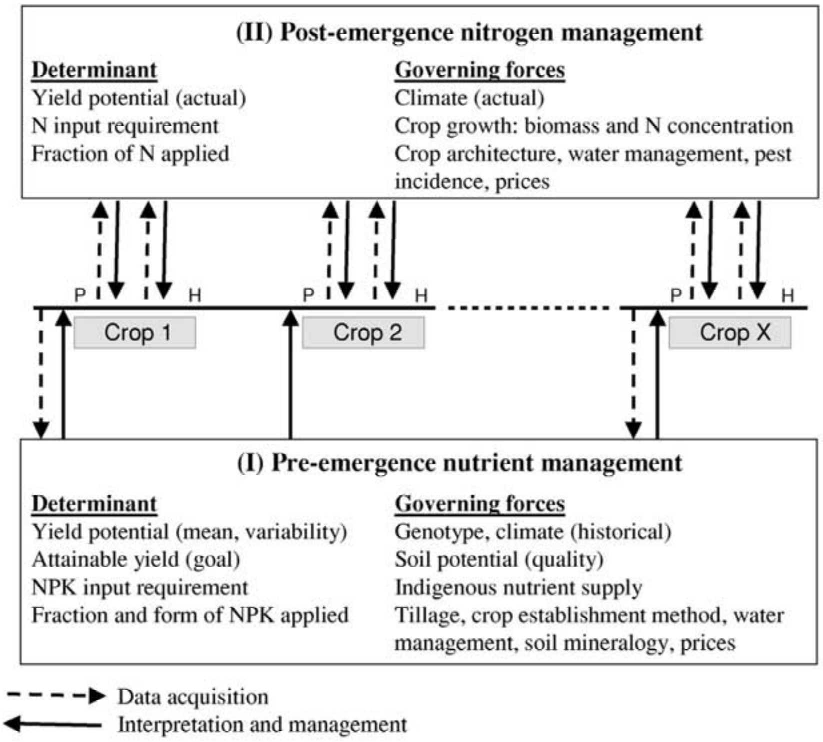

Figure 5. Determinants and their controlling factors in a general, dynamic, site-specific nutrient management scheme for non-legume field crops (P – planting; H – harvest).

diagnostic tools used would allow establishing quantitative relationships between reflectance and biomass (Bouman et al., 1992) and between reflectance and nitrogen status (Blackmer et al., 1996), future improvements in data interpretation can be made by applying concepts such as critical N dilution curves for a certain yield target (Greenwood et al., 1990; Witt et al., 2001). Moreover, corrective approaches require careful N management at all key growth stages to avoid N deficiency occurring at critical growth stages. If N deficiency occurs during early vegetative growth of maize, correcting it with late-season N applications is unlikely to fully compensate for the yield loss associated with yield components formed during early growth (Binder et al., 2000).

In contrast, predictive N management can be accomplished in real-time by using soil/crop models in combination with actual weather data (van Alphen and Stoorvogel, 2000). In predictive–corrective N management, this approach may be combined with other methods of crop diagnosis. For example, remote sensing data can be used as a forcing function in a crop growth model to improve the prediction by taking into account actual growth data (Bouman, 1995). With increasing availability of weather and remotely sensed data over the internet, these dynamic N management approaches are likely to become more attractive and cost-effective to maize farmers in the USA. The challenge will be to develop simplified crop models to estimate yield and the additional N needed to achieve it in response to actual crop conditions.

Managing the local and global environment

Increasing the amount of fertilizer used without an associated increase in nutrient efficiency may have adverse consequences for the environment and human health that are not reflected in the costs and returns of agricultural production (Uri, 1998). The main fertilizer compounds or transformation products contaminating water and air resources are N_2O, NH_3, NO_3, soluble phosphates, and traces of heavy metals. Preliminary estimates for the UK (Pretty et al., 2000) and Germany (van der Ploeg et al., 2002) suggest that the external costs of agriculture may be as large as the total worth of all farm goods produced, with abundant N use contributing to about one third of these costs.

Consequently, regulation of fertilizer use through laws or taxes has become part of intensive agriculture in developed countries, including maize farming in the USA (Uri, 1998). Unfortunately, little field research has been conducted to address the whole spectrum of agronomic and environmental consequences of crop intensification. Significant differences exist between maize systems in the USA and rice systems in Asia. In both, available estimates of external costs are sketchy at best because of difficulties in obtaining accurate numbers of the nutrient cycling processes involved. Moreover, fertilizer use affects crop growth and this enhancement of biomass production may be associated with positive as well as negative effects on the environment.

Nitrate contamination of water supplies is not a major issue when rice is grown in anaerobic flooded systems such as double-cropped rice (Bouman et al., 2001). However, intensive maize-based cropping systems in the corn belt may contribute significantly to nitrate contamination of groundwater (Spalding and Exner, 1993) or of whole regional watersheds such as the Mississippi River Basin feeding into the Gulf of Mexico (CAST, 1999). The Mississippi River exports about 1.8 million tons of N each year and it is estimated that agriculture's annual share is about 2-3 kg N ha^{-1} agricultural land — an equivalent to a total fertilizer value of \$410 million $year^{-1}$ (CAST, 1999). Several states have therefore implemented regulation governing fertilizer use by farmers in these areas. In Nebraska, best management practices required by law depend on the nitrate concentration in groundwater. In highly contaminated areas (Phase III areas with >20 ppm nitrate), irrigation water must be tested for nitrate, irrigation applications must be metered, soils must be analyzed for nitrate to 1 m depth annually on every field, fall and winter applications of fertilizers are prohibited, and spring applications must be split or must use an approved N inhibitor. Subsequent studies have shown that widespread adoption of these management practices has led to decreasing nitrate concentrations in the groundwater, but also to benefits for farmers because it enabled them to reduce fertilizer use without affecting crop yield (Bosch et al., 1995; Fuglie and Bosch, 1995).

Besides such local and regional environmental effects, maize systems have a significantly underutilized carbon (C) sequestration potential (Collins et al., 1999), which is related to the amount of biomass (crop residues) produced and thereby dependent on crop rotation, fertilizer use and nutrient efficiency (Halvorson et al., 1999). However, potentially positive effects of sequestering C in such agricultural systems may be offset by emissions of other greenhouse gases such as N_2O or high energy use (Robertson et al., 2000) if yields and nutrient use efficiency are below attainable levels. Similarly, although irrigated rice monoculture systems in Asia are known to sequester carbon (Bronson et al., 1997a) and emit little N_2O (Bronson et al., 1997b), recent estimates suggest that they contribute about 2–5% to the global methane (CH_4) budget (Matthews et al., 2000). Methane emission can be managed through a variety of means, including organic and inorganic amendments as well as crop management practices that also affect nutrient dynamics (Wassmann et al., 2000).

In general, the effects of improved nutrient management on environmental quality and other externalities are likely to be positive if they combine yield increases with increases in fertilizer use efficiency. Yield level, amount and decomposition of crop residues, soil organic matter, and soil N and P dynamics are important determinants of greenhouse gas emissions that can be manipulated through plant nutrition. Every increase in grain production that comes from higher yields per unit area contributes to sequestration of C and reduces the pressure to expand cultivated area to natural ecosystems or marginal land. Increased RE_N potentially results in less N runoff and leaching and reduced gaseous N losses into the environment. Increased PFP_N reduces the amount of fertilizer needed to produce a unit of grain, which will reduce CO_2 emissions resulting from the use of fossil energy to produce fertilizer-N.

In summary, assessing the local, regional, and global consequences of nutrient application in agriculture on the environment and human health must become an integral component of future agronomic research. Intensive agricultural systems can probably be designed in which an optimal balance of productivity, soil C sequestration, nitrate leaching, and emission of greenhouse gases is achieved through increased yield, more efficient use of fertilizers, conservation tillage, and irrigation. Educational programs in combination with non-regulatory incentives (Uri, 1998) that motivate farmers to increase nutrient use efficiency are preferable over regulatory levies because the latter expose farmers in one country to a competitive disadvantage (van der Ploeg et al., 2002). Multilateral agreements such as the Kyoto Protocol may further help reducing the external costs of agriculture in the future, but implementation of such international agreements is laden with obstacles.

Conclusions

The principal challenges to improving yields, input use efficiency, profitability, and environmental impact are similar in large-scale maize and small-scale rice systems. At present, average yield levels of maize and rice are only 40–65% of the attainable yield potential and the average recovery of fertilizer N is less than 40%. The commonly used approaches to soil fertility and fertilizer research and management may be insufficient for achieving greater input efficiency because they are too general and too empirical. Factors that will drive the need for more precise, dynamic, and diverse nutrient management approaches are (i) increasing yield levels that approach current yield potential ceilings in the best farms, (ii) future germplasm improvement in yield potential, grain quality, stress tolerance, and adaptation to more intensive management practices, (iii) spatial and temporal variability of soil nutrient supply and crop nutrient demand, and (iv) threats of regulation due to local and global environmental concerns.

Robust strategies for site-specific nutrient management must therefore be based on a quantitative understanding of seminal relationships between yield and nutrient uptake and the congruence between nutrient supply and crop demand. While the underpinning scientific principles guiding such an approach are generic, implementation will require consideration of appropriate technologies designed for different spatial scales. More resources should be devoted to strategic field- and on-farm research that follows systems approaches. Priorities include (i) farm level data on nutrient use and nutrient use efficiency, including trends over time and causes of variability, (ii) use of models and geospatial techniques to obtain a quantitative understanding of crop response to spatial and temporal environmental variation, (iii) better approaches for real-time N management, (iv) greater knowledge of nutrient management requirements for transgenic crops with specific end-use traits, and (v) interdisciplinary field research that addresses the entire spectrum of agricultural, ecological, and environmental functions of intensive cropping systems, which are the foundation of the human food supply.

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