ResearchGate

See discussions, stats, and author profiles for this publication at: https://www.researchgate.net/publication/286274448

Fertilizer use, markets, and management

Article · January 2010

CITATIONS
23

READS
380

4 authors, including:

Stephan M Haefele
Rothamsted Research

185 PUBLICATIONS **6,841** CITATIONS

SEE PROFILE

Upendra Singh
International Fertilizer Development Center (IFDC)

187 PUBLICATIONS **12,961** CITATIONS

SEE PROFILE

All content following this page was uploaded by Stephan M Haefele on 04 April 2022.

The user has requested enhancement of the downloaded file.

Fertilizer use, markets, and management

D.I. Gregory, S.M. Haefele, R.J. Buresh, and U. Singh

Fertilizer and rice production

The role of fertilizers in rice production

Total fertilizer nutrient consumption (N + P_2O_5 + K_2O) worldwide reached about 169 million tons in 2007 (IFA 2009a). Total consumption for most countries with significant rice areas increased continuously in the last 50 years, and this trend is also probably valid for fertilizer use on rice. For the whole of Asia, fertilizer consumption rose from 3.8 million t in 1961 to 92.3 million t in 2007 (FAOSTAT 2009). In the same time period, fertilizer consumption increased from 0.6 million t to 19.1 million t in South America and from 0.7 million t to only 3.9 million t in Africa. The only countries with a large rice area and a consistent negative trend of total fertilizer consumption were Japan (a decreasing trend since the early 1980s) and South Korea (a decreasing trend since the late 1990s). The only two countries in Africa with a significant rice area and considerable total fertilizer consumption were Egypt (1.6 million t in 2007) and Nigeria (0.2 million t in 2007).

Comprehensive statistics for crop-specific fertilizer consumption are available only for very recent years (IFA 2009a) although less comprehensive data are available for 2002 and 1999 (FAO 2002, 1999). They indicate that, in 2007, about half of all fertilizer used worldwide was applied on cereals, whereas the other half was used on oilseeds (about 10%), fruits and vegetables (17%), and other crops (together 23%). Most cereal fertilizer is applied on maize, wheat, and rice in almost equal shares (Table 1).

The development of fertilizer use on rice in selected countries during the current decade indicates that fertilizer consumption is still increasing in most developing economies (China, India, Vietnam, Indonesia, and Bangladesh), whereas it seems to be stagnating or even decreasing in “developed” economies (the U.S., Japan, Republic of Korea, and Europe). However, consumption has stagnated in Pakistan, the Philippines, and Myanmar (Table 2). Fertilizer use on rice in selected countries that represent 93% of total nutrient use on rice in 2007 is shown in Table 3. These countries accounted for only 82% of the total rice area in that year, signifying that fertilizer use on the remaining rice area is on average lower. Important rice-producing countries not included are Japan, Republic of Korea, Myanmar, Cambodia, Nigeria, and Nepal. By far the biggest fertilizer consumers for rice are China (9.2 million t) and India (6.7 million t), followed by Indonesia, Bangladesh, and Vietnam, with consumption around 1.5 million t for each; all other countries consume less than 0.5 million t for rice cultivation. However, the estimation of fertilizer rates per hectare shows that the highest users, with more than 200 kg N + P_2O_5 + K_2O/ha, are the U.S., China, Vietnam, Egypt, Malaysia, Turkey, and Chile. Average rates between 100 and

Table 1. Area, average yield, and fertilizer use for different cereals worldwide expressed in million tons (Mt) and share of total global fertilizer use in 2007.

Crop	Area (million ha)	Yield (t/ha)	Total fertilizer use ($N + P_2O_5 + K_2O$)		Total N use		Total P_2O_5 use		Total K_2O use	
			(% of total)	(Mt)	(% of total)	(Mt)	(% of total)	(Mt)	(% of total)	(Mt)
Maize	158	5.0	15.3	25.8	16.8	16.9	12.4	4.9	14.2	4.1
Wheat	214	2.8	15.1	25.5	17.3	17.4	16.2	6.4	6.0	1.7
Rice	156	4.2	14.4	24.3	15.6	15.7	12.3	4.8	13.3	3.8
Other cereals	–	–	4.8	8.1	5.1	5.1	5.1	2.0	3.3	0.9
Sum			49.7	83.8	54.8	55.1	46.0	18.1	36.7	10.6

Sources: IFA (2009a), FAOSTAT (2009).

Table 2. Fertilizer use on rice for selected countries.

Country	2001[a]	2002[a]	2006[b]	2007[b]
	(million tons N + P_2O_5 + K_2O)			
China	6.54	8.17	8.90	9.17
India	5.06	4.71	6.31	6.73
Bangladesh	1.31	1.40	1.49	1.47
Vietnam	1.31	1.38	1.47	1.51
Indonesia	0.92	1.11	1.28	1.40
Brazil	0.32	0.33	0.45	0.44
Thailand	0.21	0.21	0.41	0.35
Japan	0.42	0.54	0.36	–
Pakistan	0.29	0.30	0.34	0.32
U.S.	0.31	0.31	0.30	0.35
Republic of Korea	0.29	0.28	0.29	–
Philippines	0.27	0.25	0.25	0.26
Myanmar	0.16	0.12	–	–
Malaysia	0.06	0.06	0.18	0.19
Egypt	0.11	0.11	0.13	0.13
Europe 27	0.11	0.12	0.09	0.10
Argentina	0.02	0.02	0.02	0.02

[a] Source: Estimated based on total fertilizer use from FAOSTAT data (last updated 2009) and mean fertilizer fraction applied to rice from 2006 to 2007 according to IFA (2009a). [b] Source: IFA (2009a).

Table 3. Fertilizer use on rice including total rice area, average yields, and estimated mean rates for selected countries at the global level in 2007.

Country	2007 fertilizer use for rice (000 t)				2007 rice area (000 ha)	2007 average yield (t/ha)	Mean fertilizer use (kg/ha)		
	N	P_2O_5	K_2O	N + P_2O_5 + K_2O			N	P_2O_5	K_2O
China	5,632	1,800	1,736	9,168	29,230	6.35	193	62	59
India	4,390	1,432	903	6,725	44,000	3.21	100	33	21
Indonesia	1,168	112	119	1,399	12,166	4.69	96	9	10
Bangladesh	1,159	172	137	1,468	11,200	3.88	103	15	12
Vietnam	772	454	286	1,513	7,305	4.87	106	62	39
Pakistan	266	53	3	322	2,600	3.19	102	20	1
Thailand	262	69	15	346	10,360	2.69	25	7	1
U.S.	255	45	45	346	1,112	8.05	229	40	40
Philippines	212	36	12	260	4,250	3.76	50	8	3
Brazil	146	143	154	443	2,901	3.88	50	49	53
Egypt	113	21	0	133	668	9.97	169	31	0
Malaysia	90	47	53	190	660	3.38	136	71	80
Iran	75	24	7	106	630	5.56	119	38	11
Europe 27	46	17	31	95	606	5.77	76	28	51
Argentina	17	3	2	22	164	6.55	106	18	12
Russia	14	5	1	20	189	3.31	74	26	5
Turkey	12	5	1	17	85	8.06	141	59	12
Mexico	6	2	2	10	71	4.93	85	28	28
Chile	2	2	2	5	27	5.28	75	75	75
Sum	14,637	4,442	3,509	22,577	128,224		114	35	27

[a] Source: All data on fertilizer use by country in 2007 is based on IFA (2009a), rice area and yield data are based on FAOSTAT data, and both were used to estimate fertilizer use per hectare.

200 kg/ha are used in India, Indonesia, Bangladesh, Pakistan, and Brazil; very low rates (<100 kg/ha) are used in Thailand, where relatively lower-yielding high-quality varieties are common, and the Philippines. Unbalanced fertilizer use (i.e., a dominant use of N fertilizer) seems to occur especially in Indonesia and Pakistan and to a lesser extent also in Bangladesh, the U.S., and Egypt.

Comparing country averages of applied N rates and yields shows that yields increase with increasing N application but that the efficiency of N fertilizer use varies considerably between countries (Fig. 1). Figure 1 suggests very high partial factor productivity of N (grain yield per N applied) in countries with a small, well-developed rice area and temperate climate conditions in the rice-cropping season (e.g., Egypt, Turkey, Europe, Argentina), high to normal N-use efficiency (e.g., Vietnam and Indonesia), and relatively low N-use efficiency (e.g., India, Pakistan, China, and Malaysia), where rice is mostly grown under tropical climate conditions. The reasons for low N efficiency can be manifold, including, for example, excessive N application (possibly in China) or a high percentage of rainfed rice area with multiple yield-limiting stresses (e.g., India).

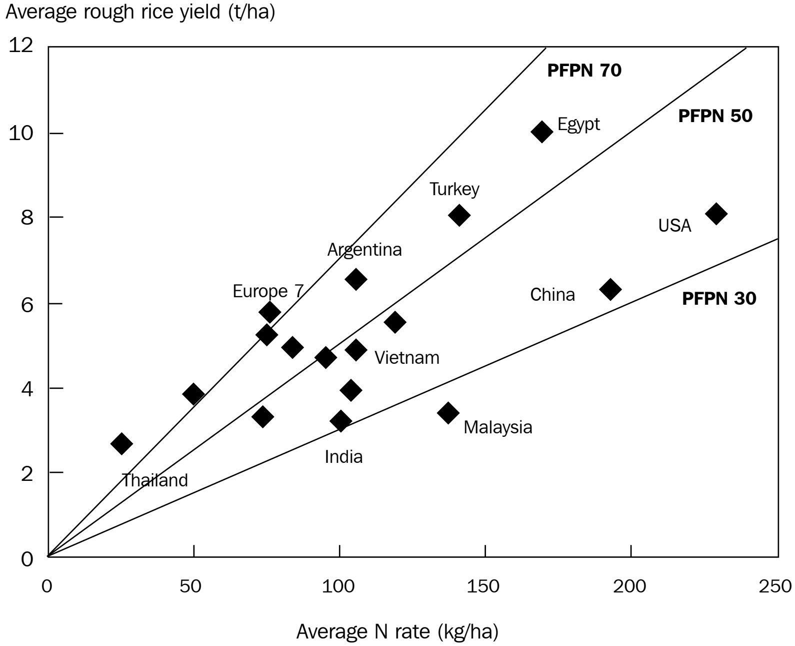

Fig. 1. Average N-use efficiency for selected countries. Data source is Table 3, and added are envelope lines of high, normal, and low partial factor productivity of N (PFPN of 70, 50, and 30 kg unmilled rough rice yield per kg N applied, respectively).

Fertilizer as a contributor to total factor productivity

Total factor productivity (TFP) is a measure of output in relation to the aggregate of all inputs—a composite measure of gains in reducing yield gaps between farmer yields and potential optimum economic yields. Total rice area increased by only 0.49% annually between 1987 and 2007 (FAOSTAT 2009). Yields increased 1.31% annually and changes in irrigation accounted for an estimated 0.3% of this total annual increase. Increased use of fertilizer has been a major factor in TFP contributing between one-third and one-half of yield growth in developing countries since the start of the Green Revolution (Bruinsma 2003).

In the past decade, fertilizer use has continued to grow in developing countries by 3.6% per annum, and it is estimated that this is contributing around 0.6% per annum to TFP (Fischer et al 2009). Growth through intensification and increased fertilizer use is no longer important in industrial countries and in some Asian countries fertilizer use is already high. Environmental concerns regarding externalities may increasingly restrict fertilizer overuse. In sub-Saharan Africa, neither irrigation nor increased fertilizer use have been important productivity factors, with almost static yield levels and increased production arising from increased cultivation area. In the last decade, a declining trend in rice TFP is evident in South and Southeast Asia, but Latin America shows an increasing trend. Improved nutrient-use efficiency at the farm level will be a requirement for improved fertilizer contributions to total factor productivity.

The need of rice for added fertilizer nutrients

Supplies of nitrogen (N), phosphorus (P), and potassium (K) from the soil, crop residues, irrigation water, and biological N_2 fixation are often insufficient to sustain high rice yields, making the application of fertilizer N, P, and K essential for profitable rice production. Nitrogen is the most limiting nutrient and some rice soils that have a high capacity to fix applied phosphate require early, high applications of P (Linquist and Sengxua 2001). Deficiencies of secondary nutrients (S, Ca, and Mg) and micronutrients (Cl, Na, Fe, Mn, Cu, Mo, B, Co, and Si), except for Zn, are generally less frequent for rice and often limited to specific soils. The roles of major, secondary, and micronutrients in rice production are well known and defined (Dobermann and Fairhurst 2000).

Nitrogen fertilizers and future costs

Nitrogen fertilizer use on rice accounted for between 12% and 15% of the total global fertilizer N use of 100 million t/year in 2007. Approximately 67% of this N is produced and used as urea, the most concentrated solid N fertilizer. Urea use on rice accounts for an estimated 85% of rice fertilizer N—10.8 million t. Future projections of total global N fertilizer use vary from a modest increase from 100 million t/year in 2007 to 121 million t by 2050 (Wood et al 2004) to 155 million t by 2070 (Frink et al 1999), respectively, representing annual growth of 0.5% and 1.1%. These very subjective projections represent more than a halving of the growth in the past decade and much will depend on improvements achieved in N-use efficiency, which is likely to be driven by higher energy prices.

The global fertilizer industry is increasingly concentrated in regions with access to least-cost feedstock and raw materials, which account for 70% to 80% of direct production costs. Ammonia production is the basis for all N fertilizer production. Natural gas (NG) accounts for 67% of the hydrocarbon feedstock for ammonia production and coal accounts for 26% (Prud'homme 2009). A ton of ammonia requires 28–31 GJ of NG and a ton of urea 18–19 GJ of NG. The technological efficiency limits of hydrogen separation from hydrocarbon feedstock have been reached (IFA 2009b) but current research into the use of molybdenum, silicon-tantalum, and zirconium catalysts for reforming ammonia may result in lower pressure and temperature requirements for the Haber-Bosch ammonia production process, thus reducing plant construction costs and energy use at some time in the future. Meanwhile, NG prices are rising, and each US$1 increase per GJ adds $18 to $19 per ton of urea, and these cost pressures will likely continue for the foreseeable future. Climate change legislation restricting greenhouse gas emissions will also add to ammonia and nitric acid production costs. Capital investment recovery in new ammonia-urea production plants today adds more than $100 per ton to the cost of urea and the increasing quantities traded (i.e., more than 30% and rising) add to transportation costs for many markets. By 2060, it may not be unrealistic to anticipate delivered urea costs increasing from a base of $300/t to between $600 and $700/t in real terms, reversing the downward trend in real N prices experienced over the past 50 years. This will create a significant incentive to improve N-use efficiency for the production of rice and other crops.

Phosphate fertilizers, future availability, and cost

Phosphate fertilizers are derived from phosphate rock (PR). Three countries account for 65% of PR production: China (29%), the U.S. (19%), and Morocco (17%). Total world phosphate fertilizer production is around 38 million t P_2O_5 per year and 80% of this is based on phosphoric and sulfuric acid production. Increasingly, phosphate rock is processed at or close to mine sites and processed phosphate fertilizers are exported to world markets.

To date, 80% of PR used for fertilizer production has been high-quality, sedimentary rock, but the quality and reserves available are declining. Future expansion of PR production will be concentrated in North Africa and China. Recent estimates (Cordell et al 2009) using the Hubbert Curve, which predicts declining production of oil and other mineral resources when half of the reserves have been exploited, indicate peak production by 2034. However, uncertainty exists concerning the estimated level of global reserves. The cost of extracting, beneficiating, and processing igneous PR is higher than with sedimentary PR, and it can therefore be expected that the real costs of PR and phosphate fertilizer will increase over the next 50 years. Lower-quality rock can add 30% to 40% to the cost of producing phosphoric acid. Assuming that 30% of phosphoric acid will be produced from lower-quality PR by 2050, the average real cost of phosphoric acid would increase by about 10%. The market adjustment is going to be difficult and favor additional production mainly from existing large sedimentary PR processors with access to lower-quality rock. As with N fertilizers, these cost increases will provide incentive to lower fertilizer processing costs and improve field-use efficiency.

Potash fertilizers, future availability, and cost

There is no shortage of potash resources for fertilizer production but these resources and production are even more concentrated than either N or P, with 76% of production accounted for by Canada, Russia, Belarus, and Germany, and more than 80% of the 30 million t of annual potash use represent international trade. Any disruptions to mining, processing, or distribution have a significant short-term impact on international prices. After a 30-year period of relatively low potash prices around $100/t for muriate of potash (MOP), there was a large spike in 2007-08 to $1,100/t and then prices settled to around $350/t in 2009 as demand fell in response to the very high prices.

The cost of mine development has risen considerably. Canadian data indicate an investment cost of more than $2.5 billion for new mine development, excluding infrastructure, and 10-year development lead times. Although there are large increases in planned production expansions, including new mine developments, it can be expected that most capacity expansions will be at existing sites, where development costs can be 40% of new site costs. Pressures on production costs will remain into the future and the ability for the industry to rapidly respond to upward demand fluctuations will be limited.

The need for improved fertilizer efficiency

The anticipated long-term N and P fertilizer production cost increases and persistence of increased potash production prices raise serious questions concerning the continued economic use of fertilizers at current application rates, even without considering potential needs for increased rates to raise productivity. Increased production and distribution costs can be offset to some extent by improved market efficiency, especially in Africa, and by improved policy environments in some of the smaller Asian markets, but far more cost reduction can be achieved by improved nutrient-use efficiency from improved field management of existing products and new-product technology.

Under current rice-farming practices in Asia, about one-third of the fertilizer N applied to irrigated rice grown on submerged soils is taken up by the rice crop. About one-third of the fertilizer N remains in the soil at crop harvest and about one-third of the added N is lost as gas to the atmosphere, mostly through ammonia volatilization (Buresh et al 2008). The recovery efficiency of fertilizer N (RE_N) can be increased with improved fertilizer N management although it typically remains below 50% in farmers' fields (Witt and Dobermann 2004). The recovery efficiency can be lowered by abiotic and biotic stresses, and it decreases at very high applications of fertilizer N.

Fertilizer market efficiency

Policy distortions, subsidies, and improvements

Twelve of the major Asian fertilizer markets are closely regulated by government controls and market-distorting policies are caused by fertilizer subsidies and other instruments. This situation was exacerbated by the global 2007-08 fertilizer price spike and economic crisis. The Fertilizer Control Order of India, which has governed that country's fertilizer sector since the 1960s, treats fertilizer as a strategic commodity.

This created positive support for fertilizer production and market demand but at an unsustainable cost. In 2008, the Indian fertilizer subsidy cost was around $24 billion. Low subsidized prices for urea unmatched by similar levels for P and K created a situation of unbalanced fertilization, with excessive use of N and underuse of P and K. The N-P-K ratio in India in 2007 is estimated at 6.6-1.1-1 and on rice at 5.9-0.8-1. Recent changes to the subsidy policy that were aimed at improving the balance in nutrient use remain, with distorted low urea prices. Subsidized prices in China have contributed to overuse of fertilizer on rice (and other crops), with average application rates of 310 kg nutrients/ha and a ratio of 8.5-1.5-1.0. By comparison, the ratio in the unsubsidized Thai market is estimated at 6.0-1.4-1.0.

Reducing marketing transaction costs in Asia and sub-Saharan Africa

In spite of the market distortions created by government policies in many of the major rice-producing countries, there is an increasing trend toward more conducive policies that encourage competitive and efficient markets. Thailand provides an excellent example of an enabling policy environment and market efficiency. Open, intensely competitive markets, supportive business and financial services, and a strong agricultural extension service provide farmers with products, technology, and output markets in a least-cost manner. Imported urea supply costs are summarized in Figure 2 for 2006. Thai rice farmers were paying between 40% and 90% less for urea imported from the Arab Gulf than small farmers in coastal eastern African countries (Chemonics International and IFDC 2007).

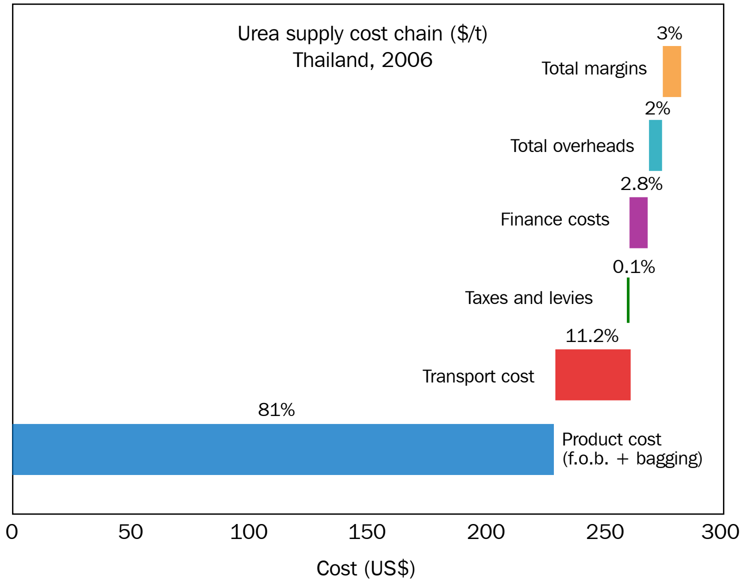

Fig. 2. Cost components of imported urea in Thailand, 2006. Source: Chemonics International and IFDC (2007).

Liberalization of domestic markets in China combined with continued state control over trade through variable tariffs and trade taxes has enabled Chinese farmers to be isolated from large international fertilizer price swings and has encouraged fertilizer use to the extent of overuse. Fertilizer production and markets in Bangladesh, Indonesia, and other Asian countries continue to be strongly influenced by central government controls and lack the economic allocation function of market pricing.

Poor infrastructure, weak institutions, and poor farm policies create obstacles to the adoption of new technology. These factors and thin fertilizer markets apply almost universally throughout sub-Saharan Africa and lack of farmer incentives to use and restricted access to timely supplies of fertilizer constrain fertilizer use, in addition to the high fertilizer-to-grain price ratios, which on average are double those in other regions (Morris et al 2007). In South and East Asia, many of these market constraints have been overcome, although the emphasis has been on services to irrigated agriculture while dryland crop production areas lag far behind.

Fertilizer types and implications

Historically, straight fertilizers such as urea, triple superphosphate, and muriate of potash were used by the majority of smallholder rice farmers in Asia together with crop residues and other available organic matter, including green manure crops. More recently, there has been an increase in the use of compound and blended fertilizers containing N, P, and K together that provide added convenience and labor saving for application but add to the nutrient unit costs. When this additional cost is more than offset by more balanced application of nutrients, benefits accrue from additional yield per investment in fertilizers.

The increasing use of diammonium phosphate (DAP) as the phosphate source for both direct application and as an N and P source in blended fertilizer reduces the application of sulfur (S). Progress is being made in adding S to DAP and other high-analysis fertilizers and zinc coating of urea is providing a convenient means of addressing zinc deficiency.

Organic sources of nutrients (i.e., organic fertilizers) have been promoted for rice in Asia often as a response to rising prices of commercial manufactured fertilizer and misperceptions about environmental degradation in intensive rice production (Dobermann and Dawe 2008). The promotion of organic fertilizers has often failed to fully appreciate the bulkiness and low nutrient content of organic materials, the often negligible benefit of organic materials on the physical properties of submerged rice soils, and the typical mismatch between the ratios of nutrients in organic materials and the ratios of nutrients needed by rice.

The application of organic materials does not seem essential for sustaining organic matter and N-supplying capacity in submerged soils with continuous rice cultivation (Pampolino et al 2008). Organic amendments can play a more important role on poor soils with very low soil organic carbon contents and in water-limited, rainfed rice environments. Organic fertilizers and retained crop residues can supply appreciable K to rice, but they rarely supply enough N to meet the needs of a rice crop (Buresh et al 2010). Because organic materials have small or negligible environmental or sustainability benefits in lowland rice production, their use should be governed largely by profitability as a source of supplemental nutrients.

Current economics of fertilizer use on rice

The addition of fertilizer nutrients is a major cost in rice production, typically accounting for 15% to 30% of total production costs (Moya et al 2004, Pampolino et al 2007) depending upon government subsidies and labor costs. The economic return to fertilizer use depends on two factors: the ratio between fertilizer (input) and rice (output) price, and the yield increase per amount of fertilizer (or nutrient element) used. But both of these factors in turn depend on several other parameters, of which only the most important ones are considered here.

Figure 3 shows the ratio of the most widely used fertilizer materials in rice cultivation and the rice price at the international level, which is less affected by national policies and economic conditions (all data from the IRRI database; http://beta.irri.org/solutions). Since 1960, all fertilizer materials became more expensive relative to rice price, but most increases in the nutrient-rice price ratios for urea and DAP have occurred since the early 1990s. Therefore, the general trend on international markets indicated a reduced profit from fertilizer use.

However, this trend is not necessarily valid at the farm gate because national policies and markets can modify fertilizer as well as rice prices. This is indicated by Figure 4, which shows the development of the urea-N to unmilled rice (paddy) price ratio at the farm gate for some important rice-producing countries. In several countries, N fertilizer was quite expensive relative to the paddy rice price until the late 1980s, probably because of import taxes, supply limitations, and strong demand. By 2000, the farm-gate urea-N to paddy rice price ratio in the countries ranged between 1.7 and 3. However, in the last few years, fertilizer again became more expensive in several countries, including Vietnam and the Philippines (recent data were not available for Bangladesh, Indonesia, and Thailand). Thus, the clear trend of increasing relative fertilizer costs at the international level (Fig. 3) is blurred at the farm gate (Fig. 4), but the farm-gate urea-N to paddy rice price ratio has increased recently in at least some countries.

Production economics at the household level

Rice farmers in traditional systems relied on organic materials such as farmyard manure, crop residues, compost, and various green manure plants to increase plant available nutrients and maintain soil quality. Since the introduction of synthetic manufactured fertilizers, the use of organic materials declined continuously, mainly because synthetic manufactured fertilizers need less labor and are economically more attractive to farmers (Pandey 1999). However, this development differs between systems: farmers use much more fertilizer and very little organic material in favorable irrigated systems, whereas they use little synthetic manufactured fertilizer and considerable amounts of organic materials in unfavorable rice-based systems. These trends are clearly indicated by the survey data presented in Table 4. The data also show that the average returns to fertilizer use in rainfed lowlands are smaller as compared with irrigated lowlands, in

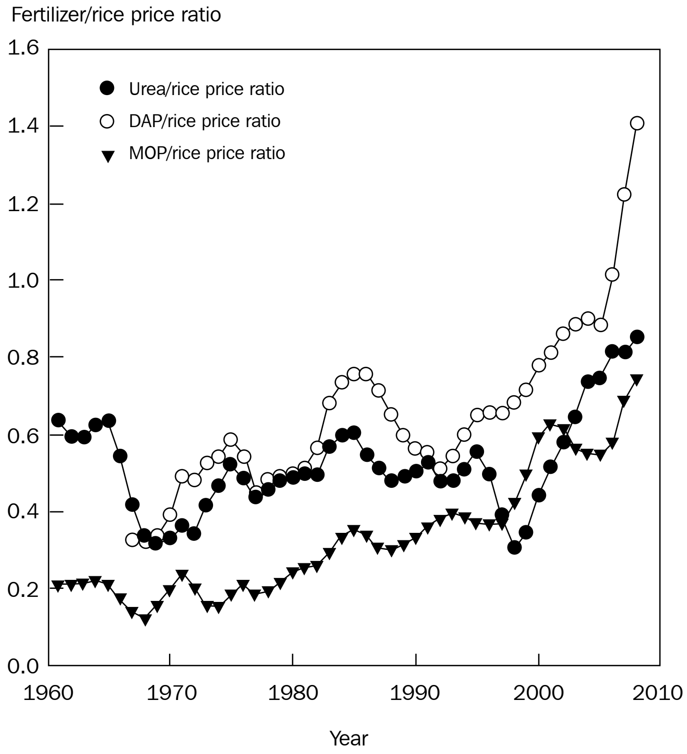

Fig. 3. The development of the fertilizer-rice price ratio based on international prices between 1960 and 2008. Shown is the 3-year moving average; the data used are the urea price valid for Europe, the DAP price valid for U.S. Gulf ports, the muriate of potash (MOP) price valid for Vancouver/Canada, and the international milled rice export price.

Table 4. Average fertilizer use and respective returns in rice by ecosystem in selected Asian countries.

Ecosystem	No. of plots	Yield increment[a] (t/ha)	Fertilizer increment[a] (kg/ha)	Average fertilizer use[b] (kg/ha)	Incremental net returns to fertilizer (US$/ha)	Relative incremental net profit (%)
Irrigated lowland[c]	493	2.93	139	123	460	98
Rainfed lowland[c]	1,215	1.09	54	47	258	73
Rainfed upland[c]	533	0.07	9	7	7	3

[a] Increments were calculated based on farmers using none or very small quantities of fertilizer for each ecosystem. [b] Overall average of fertilizer use (N+P+K). [c] Source: IRRI farm-level surveys of different ecosystems conducted between 2003 and 2008 in Indonesia, Nepal, Philippines, and Vietnam (irrigated lowlands), Cambodia, India, Indonesia, Laos, Nepal, Thailand, Vietnam (rainfed lowlands), and India, Laos, Nepal, and Vietnam (rainfed uplands).

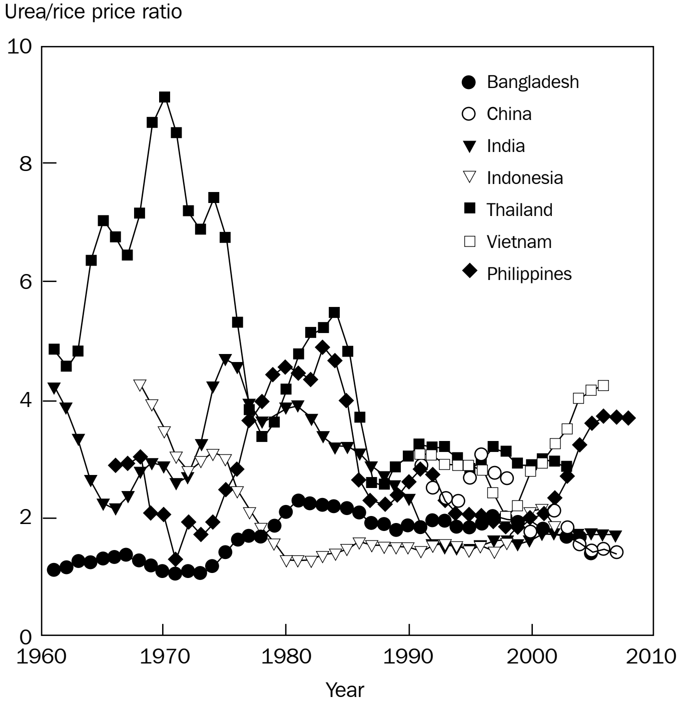

Fig. 4. The development of the urea-rice price ratio at the farm gate for selected important rice-producing countries between 1960 and 2008. Shown is the 3-year moving average; the data used are the domestic retail prices of N from urea and the farm-gate harvest price of unmilled rough rice.

both absolute and relative terms. The usual reason for lower returns to fertilizer use in rainfed systems is more frequent abiotic stresses (e.g., drought, flooding) and less fertile soils (e.g., low cation exchange capacity, salinity, and acidity). Furthermore, the survey showed that the relative contribution of fertilizer costs to total cash production costs was on average only 14–15% in rainfed environments, whereas it was about 33% in irrigated systems. Irrigated rice farmers made about twice as much profit per ha than rainfed farmers.

Unbalanced nutrient applications to match plant requirements are an important cause of low fertilizer-use efficiency. More visible responses to N applications and the higher costs of P and K are most often underlying causes. Both Asia and Africa have an excessive use of N in relation to both P and K, as illustrated in Figure 5. Good management such as using the best available varieties, proper weeding, optimal fertilizer rates, properly balanced ratios of added nutrients, and appropriate fertilizer timing can improve fertilizer-use efficiency.

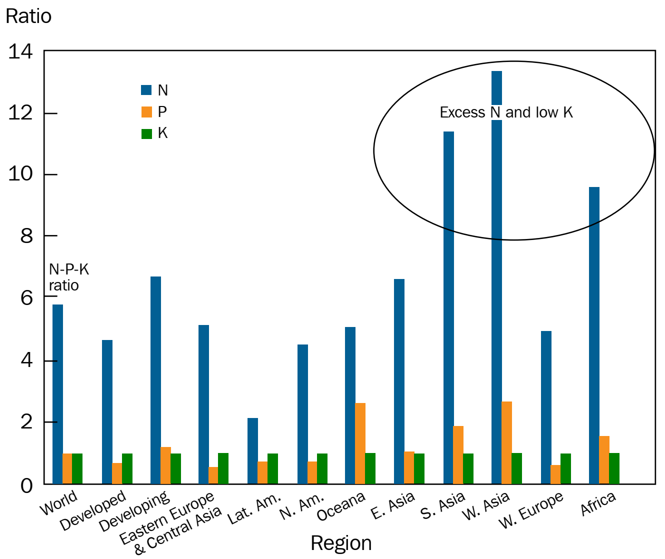

Fig. 5. Regional nutrient ratios for fertilizer use in different regions. Source: IFA (2009a).

The actual profit from fertilizer use depends on the costs of all fertilizers used (e.g., N, P, K, organic fertilizers), other inputs needed (labor for fertilizer and for the harvest/postharvest treatment of the additional grain yield), and investment costs (interest rates on credit). Complete partial budget analyses for fertilizer use in rice are rare but the general assumption is that farmers use fertilizer when the value/cost ratio is at least 1.5 to 2.

Improving nutrient-use efficiency through site-specific nutrient management (SSNM)

Much of the rice in the tropics and subtropics is produced on relatively small landholdings, which can vary across short distances in historical fertilizer use, yield attainable with farmers' management practices, retention of crop residues, and growth duration of rice cultivars. Blanket fertilizer recommendations for large areas or agroecological zones fail to account for these variations, which affect the need of rice for supplemental nutrients. Further improvements in productivity and profitability from fertilizer use consequently require approaches and algorithms for tailoring fertilizer use to the field-specific needs of rice.

Algorithms for determining fertilizer recommendations are often derived from factorial fertilizer trials conducted across multiple locations. SSNM for rice, as developed by IRRI with national organizations across Asia, is an alternative approach for dynamic management of nutrients to optimize supply and demand of a nutrient within a specific field in a particular cropping season (Dobermann et al 2002, 2004). It aims to increase the profitability of rice farming by achieving higher rice yield per unit of fertilizer invested.

The SSNM practices developed and evaluated in farmers' fields in 1997-99 increased yield and profit as compared with farmers' fertilizer practices (FFP) (Dawe et al 2004). The profitability of SSNM—as determined in on-farm trials from the difference in gross returns above fertilizer costs (GRF) for SSNM compared with FFP—averaged \$38 to \$82 per hectare at six of the eight irrigated rice areas studied across six Asian countries. Subsequent on-farm trials with irrigated rice in 2002-03 revealed a mean 7% increase in grain yield with SSNM compared with FFP across locations in India, the Philippines, and Vietnam (Pampolino et al 2007). Annual GRF for two rice crops as determined from focus group discussions at these locations averaged \$107 per hectare per year higher for farmer collaborators previously evaluating SSNM compared with farmers with no previous involvement with SSNM (Pampolino et al 2007).

Additional on-farm evaluations from 2001 to 2004 across four locations in three countries for both high- and low-yielding seasons consistently revealed higher yields for SSNM than for FFP (Fig. 6) (Buresh et al 2006). On-farm trials with wet-seeded rice in the Philippines in 2007 revealed yield gains averaged across two growing seasons of 0.6 t/ha or 13% with SSNM compared with FFP (Gabinete et al, unpublished data). The added net benefit from SSNM averaged \$109 to \$130 per hectare per season depending upon the seed rate for direct-seeded rice.

Principles of N management

During the past 20 years, emphasis on the parameter of N-use efficiency has evolved from recovery efficiency of fertilizer N (RE_N) to increased agronomic efficiency of fertilizer N (AE_N), which is the increase in grain yield per unit of fertilizer N applied. This emphasis on the output per unit of input without compromising on the need for high yield acknowledges the importance of ensuring increased profit for farmers (Buresh 2007). The greatest opportunities for rapid widespread improvements in AE_N in farmers' fields exist with optimizing fertilizer N rates to match the yield gain to applied fertilizer N and splitting the application of fertilizer N to match crop needs for supplemental N at critical crop growth stages.

With SSNM, the required fertilizer N is apportioned in several doses during the growing season to ensure that N supply matches crop need at critical growth stages. The leaf color chart (LCC) is an inexpensive and simple tool for monitoring the relative greenness of a rice leaf as an indicator of leaf N status (Alam et al 2005, Witt et al 2005). A standardized plastic LCC with four panels ranging in color from yellowish green to dark green has been developed and promoted across Asia (IRRI 2010b).

Principles of P and K management

The recovery efficiency of fertilizer P (RE_P) in farmers' fields typically averages about 15% to 30% for irrigated rice but the nonrecovered P is not mobile and adds

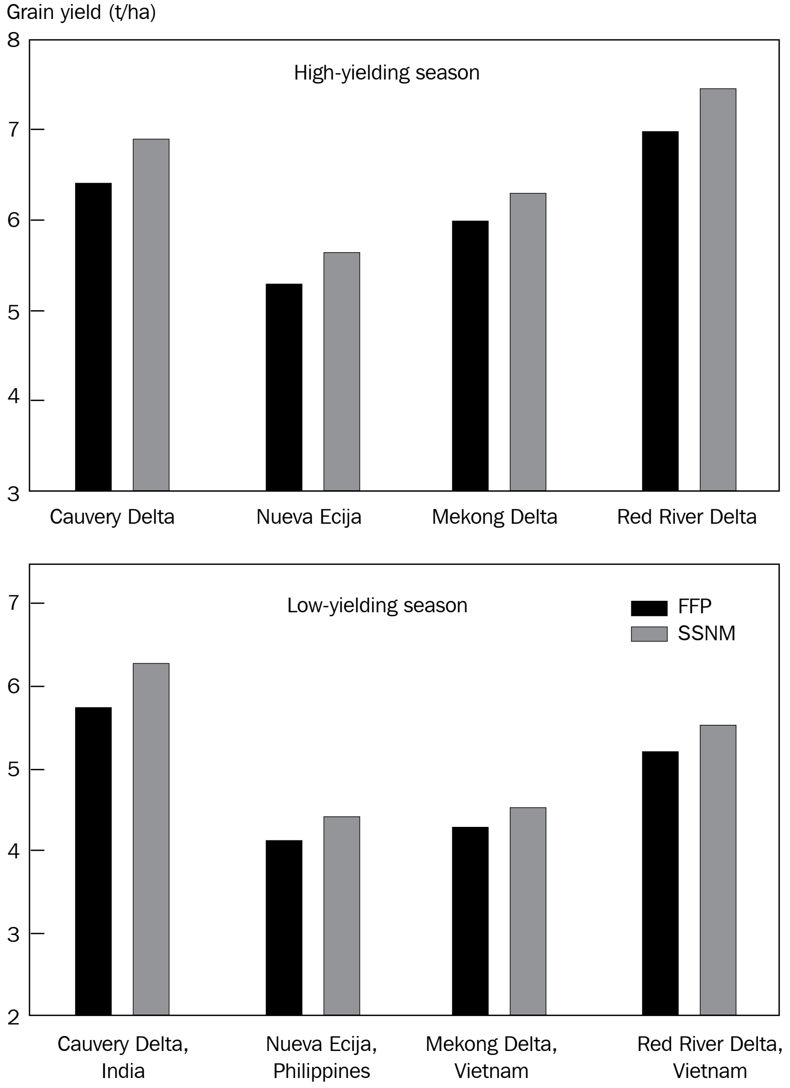

Fig. 6. Grain yield obtained from on-farm trials comparing site-specific nutrient management (SSNM) with farmers' fertilizer practice (FFP) at four locations in 2001-04. * = significant difference between the two treatments at *P*<0.05.

to the indigenous P in the soil. The recovery efficiency of fertilizer K (RE_K) varies greatly in farmers' fields. Although it can average 50% to 60%, it can also be relatively low when yield gain to applied nutrient is negligible. RE_P averaged 25% and RE_K averaged 44% in an on-farm evaluation of SSNM for irrigated rice across Asia (Witt and Dobermann 2004). RE_P of about 30% and RE_K of about 60% can be targeted in rice-growing environments with ample water and good crop management practices. Target efficiencies for rainfed environments could be lower.

Fertilizer P and K requirements for a specific field are determined with SSNM using estimated target yield, nutrient balances, and expected yield gains from added nutrient. When yield gain to P or K is negligible, fertilizer P or K requirements are derived solely from the estimated nutrient balance (i.e., nutrient inputs relative to nutrient removal by the crop). When yield gain to applied P or K is certain, fertilizer P or K requirements are determined from a combination of the nutrient balance and anticipated yield gain to nutrient application (Buresh et al 2010).

Nutrient needs for rice affected by water limitations

Most rice is grown on soils with continuous or prolonged periods of submergence leading to anaerobic soil conditions. This causes a tremendous change in soil biogeochemical characteristics, with mostly positive effects on plant availability of nutrients (Kirk 2004). After submergence, the soil pH-value tends to change toward neutral, affecting the availability of most nutrients positively. Subsequent adsorption and desorption reactions often lead to an increased availability of calcium, magnesium, and potassium. The changing soil redox reactions bring about the release of occluded and adsorbed soil P and ammonium becomes the major form of N present. The water layer also prevents any water limitation, and biological N_2 fixation in the floodwater and soil can contribute considerable N (Buresh et al 2008).

These benefits are of course not available or only partly available to rice systems without submerged soil conditions or with alternating wet and dry conditions (rainfed lowland rice and some irrigated areas). In the absence of submergence, the soil dries and becomes aerated. Soil aeration alters soil biogeochemical processes, often leading to a reduced supply of plant-available N and P, reduced Zn and Fe availability on high-pH soils, and increased P fixation. In addition, water-limited conditions reduce P availability more than other elements (Kirk et al 1998), making higher fertilizer-P rates necessary in drought-prone fields.

Limited or no water control in rainfed rice systems also has consequences for fertilizer management. It is a widespread practice in Asia and Africa to topdress a considerable fraction of the total urea into the water layer in the early vegetative phase and at panicle initiation. Optimal uptake and response to these applications require correct timing, which depends on crop phenology and sufficient field water resources at the application time. In rainfed systems, drought or flooding in the field might prevent optimal timing, the application might be conducted with too much or too little water in the field, or this might not be possible at all. Another difference is that traditional-type varieties are still widespread in many rainfed environments. For example, high-quality rice from traditional-type varieties is grown on millions of hectares in northeastern Thailand. These varieties have a much lower yield potential than modern semidwarf varieties and they need considerably lower fertilizer rates (Haefele et al 2006).

This short overview of some important characteristics and processes in rainfed systems shows the generally less favorable conditions for crop growth and nutrition in these environments. However, the basic principles of SSNM as well as the need for field-specific nutrient management are equally valid in rainfed lowlands and similar water-limited systems (Naklang et al 2006, Haefele et al 2006). Despite lower potential or attainable yields in rainfed than irrigated environments, the yield gain from applied nutrient—and hence need for fertilizer—is not necessarily lower for rainfed than for irrigated systems (Haefele and Bouman 2009, Haefele and Konboon 2009). But, fertilizer rates need to be adjusted to the average attainable yields, the production risk caused by abiotic stresses (e.g., drought, flooding, and salinity), and the local fertilizer-to-grain price ratios (Haefele et al 2010).

Secondary nutrients and micronutrients

Deficiencies of secondary nutrients (S, Ca, and Mg) and many micronutrients (Fe, Mn, Mo, B, Co) are often less frequent for rice and are often limited to specific soils. Acid soils, such as Acrisols, with very low base saturation at the exchange complex can have a positive response to the application of Ca and Mg carbonates (Goswami and Banerjee 1978). Response to Fe application can sometimes be observed on calcareous soil or in nonflooded rice systems, and response to Cu (copper) occurs, especially on organic soils (Dobermann and Fairhurst 2000). Deficiencies of Zn are mostly limited to alkaline soils but are becoming more common in many intensive systems, especially when most crop residues are removed and mainly high-analysis N and P fertilizers are used. Similar trends are reported for S and Si (silicon).

Increased use of concentrated fertilizers containing little or no S has led to S deficiency in rice crops, especially when crop residues are burned or removed. Management of S nutrition of rice depends on the production system. Under upland conditions, S nutrition of rice is little different from that of other crops. Under flooded conditions, several factors can induce S deficiency. These include shallow rooting; reduction of sulfate to sulfides, some of which are toxic (H_2S) and others low in solubility (FeS, ZnS); and slower mineralization of organically bound sulfur. Sulfur fertilizer is most effective when applied at sowing or transplanting (Blair and Lefroy 1998). Sulfate S application 2 weeks after transplanting has been shown to be effective (Dobermann and Fairhurst 2000) but delaying application until maximum tillering is not effective for treating S deficiency (Blair and Lefroy 1998). Recent work compared elemental S, S-coated DAP, MAP, TSP, and urea with gypsum in both surface and deep-placed applications on upland and flooded rice. Elemental S and S-coated urea were the most effective in providing the highest recovery of fertilizer S in the plants, followed by S-coated phosphate fertilizers (Yasmin et al 2007). Incorporation of elemental S in high-analysis phosphate fertilizers is possible and may be a means of ensuring adequate S fertilization in flooded-rice production systems.

The submergence created for rice cultivation influences electrochemical and biochemical reactions, and alters pH, pCO_2, and the concentration of certain ions. This environment increases the availability of Fe and Mn with a concomitant decrease in Zn and Cu. Sodic and upland soils and calcareous coarse-textured soils with low organic matter content suffer from Fe deficiency, besides Zn and Cu deficiencies.

Amending the soil with the required amount of Zn before transplanting is effective and easy to adopt, compared with repeated foliar sprays of 0.5% $ZnSO_4$ or the use of Zn-enriched seedlings through seed soaking in 2–4% $ZnSO_4$ solution, fertilizing the nursery with Zn, or seedling root dipping in 2% ZnO slurry. Hepta- as well as mono-hydrate $ZnSO_4$ are better than other sources of Zn (ZnO, $ZnCl_2$, and Zn frits). Zinc-blended diammonium phosphate (Zn-DAP), superphosphate, and nitrophosphates have also proved effective. Zinc-enriched organic manures (farmyard manure, greenleaf manure, and coir pith compost) have been found advantageous for the direct and residual crops. Zinc fertilization, when required, with an optimal dose of 25 kg $ZnSO_4$/ha once every two to eight crops yields high economic returns (Fairhurst et al 2007). Rice cultivars do not experience deficiency of B and Mo (Savithri et al 1998).

Uptake of improved nutrient management in rice farming

Improved management of conventional fertilizer

Putting SSNM into practice. The tailoring of fertilizer management to field-specific conditions is relatively knowledge-intensive because many factors, including crop yield, crop residue management, historical fertilizer use, use of organic materials, nutrient inputs in irrigation water, and growth duration of the variety, can all influence fertilizer management. This knowledge intensity has slowed the wide-scale promotion and uptake by farmers of best management practices based on SSNM principles. Adoption by farmers can also be constrained by confusion arising from contrasting recommendations for nutrient management received from different organizations and technical experts.

The widespread use of field-specific nutrient management by farmers requires transforming the knowledge-intensive principles of SSNM into locally adapted nutrient best management practices. Extension workers, crop advisors, and farmers require locally adapted guidelines that enable them to rapidly identify and implement nutrient best management practices for specific fields and rice-growing conditions.

The SSNM-based approach can be used to determine fertilizer N, P, and K requirements for a specific growing season and rice field based on estimates of the attainable target yield, nutrient balances, and probable yield gains from added nutrient. These estimates can be obtained for a specific growing season and rice field from responses to about 10 to 15 questions regarding historical rice yields, rice variety, crop rotation, fraction of crop residue retained, occurrence of sediment deposition from flood events, and landscape position. Computer-, Web-, and mobile phone–based tools can be used to acquire the responses to the questions, use the responses with

SSNM-based principles to determine fertilizer requirements, and then provide a personalized guideline with application times and amounts of fertilizer sources for a specific rice field. Such decision tools are now available with training materials and videos to facilitate the uptake by farmers of best management practices based on the SSNM concept (IRRI 2010a, b).

Decision tools for extension and farmers. Through an IRRI-coordinated partnership of public- and private-sector organizations in the Philippines, the results from more than a decade of research on SSNM for rice were used in 2008 to develop and verify decision support software titled *Nutrient Manager for Rice* for extension workers and farmers. A partnership of organizations in Indonesia likewise developed decision support software titled *Pemupukan Padi Sawah Spesifik Lokasi* (*Location-Specific Rice Fertilization*), which was tailored to rice production for the country. In the Philippines, *Nutrient Manager for Rice* was also released in 2009 as a Web version in English and five dialects of the Philippines (IRRI 2010a).

The experiences from the Philippines and Indonesia in transforming the scientific principles and research findings of SSNM into tools such as decision support software, videos, and quick guides for accelerating the uptake of nutrient best management for rice provide a model for replication in Asia and Africa. As of February 2010, additional decision tools for providing field-specific best nutrient management were under development and verification for rice in Bangladesh, China, India, Vietnam, and West Africa (IRRI 2010b).

Modified nitrogen fertilizer products

Many modifications to urea have been proposed to overcome losses of urea-N and the assessment of potential economic benefits has been reported (Buresh and Baanante 1993). Benefits vary considerably between product modifications depending on their cost, the cost of urea, and the value of rice. A brief summary of some product modifications is provided below.

a) Urea deep placement

Urea deep placement (UDP) is a method of fertilizer application that substantially increases N uptake efficiency in rice with a single application of N fertilizer. Large urea supergranules of 1.8 up to 2.7 g in weight were developed specifically for deep placement in rice production. The briquettes are applied by hand within 7 days after transplanting at the rate of one briquette for four hills. The placement of fertilizer near the root zone of the plant reduces N losses that occur from surface-applied (broadcast) methods and the efficiency of N fertilizer increases (Savant and Stangel 1990, 1998, Mohanty et al 1999). UDP also reduces nitrification-denitrification losses because of the placement of the fertilizer in the anaerobic layer. In addition to yield increases from 20% to 25% over conventional urea application (Fig. 7) and the above advantages, deep placement has the following benefits:

- One-time N application because ammonium-N exists in the proximity of the placement site, which maintains availability of the required N throughout the vegetative and grain formation stage of rice plants.

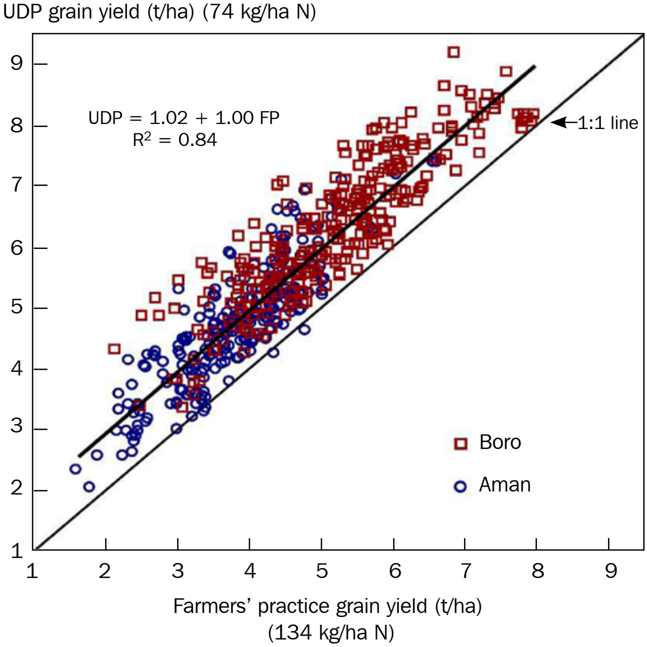

Fig. 7. Comparison of the effect of management with the farmers' fertilizer practice using conventional NPK and with urea deep placement (UDP) on rice yields In Bangladesh.

- Less weeding because of N placement in the rice root zone (Fig. 8). In general, this may even offset the additional labor required for deep placement.
- It helps promote biological N_2 fixation in the floodwater due to very low N concentration in the floodwater.
- N content in the straw is higher; straw is more nutritional for livestock.
- It helps decrease air pollution because of low gaseous loss of N.
- It helps decrease water contamination because of less runoff loss of N.

UDP is highly desirable for conditions that promote high ammonia volatilization and runoff losses—soils with more than 20% clay, low permeability and percolation rates, low ammonium sorption, and environments with poor crop establishment (prolonged transplanting shock) and heavy rainfall. UDP is unsuitable for sandy soils because of high leaching loss.

However, UDP technology has not been widely adopted by rice farmers for a multitude of reasons. Even in Bangladesh, where the technology has been widely promoted and developed, only 6% of the total rice crop used UDP in 2008. A lack of briquette supplies, the increase in direct seeding, and the relatively low cost of urea until recent years and reduced availability of rural labor may have all played a role in the slow adoption process.

Khan et al (2009) compared the performance of UDP and the recommended use of conventional urea with the LCC in two seasons (aman and boro) for two years

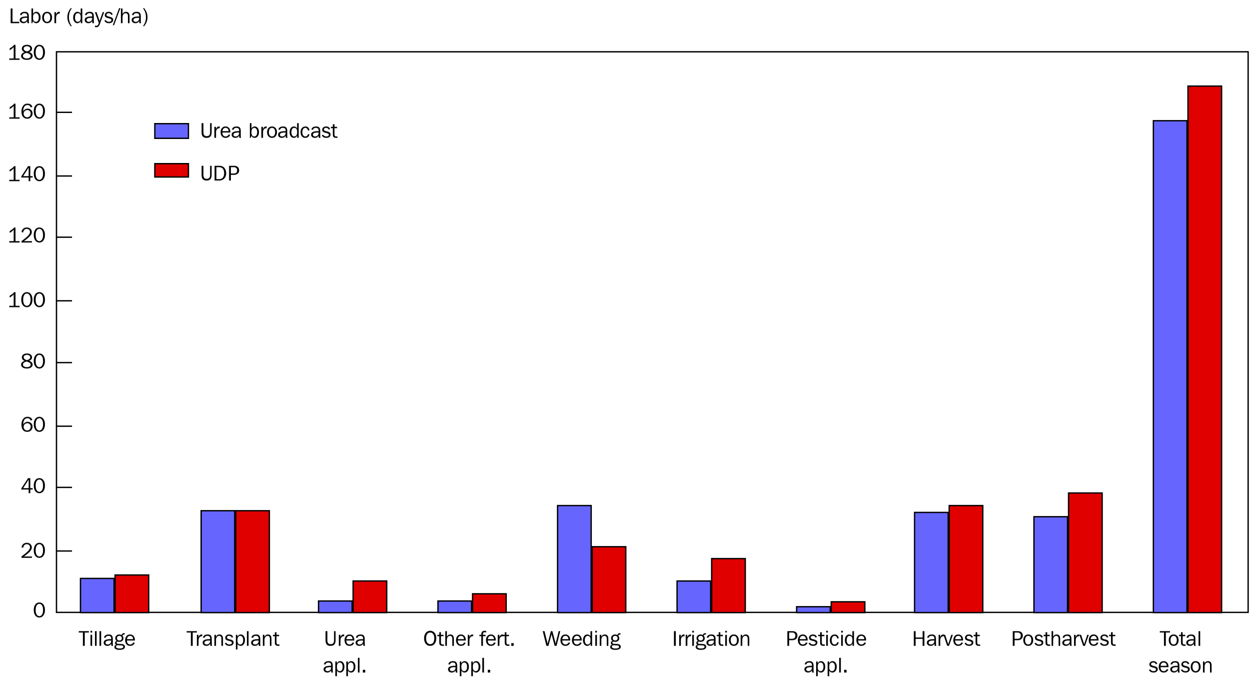

Fig. 8. Comparison of labor requirement for rice production with broadcast application of urea and urea deep placement (UDP). Source: Thompson and Sanabria (2010).

in a total of 456 farmers' fields in Bangladesh. All crop and fertilizer management, except for N management, was identical in the two treatments. Rice yields in both seasons were statistically identical for UDP and conventional urea managed with the LCC. Added net returns relative to the farmers' fertilizer practice were comparable for UDP ($39/ha) and conventional urea with the LCC ($56/ha) averaged across the two aman seasons, and higher for urea with the LCC ($106/ha) than UDP ($78/ha) averaged across two boro seasons (Table 5). Management of conventional urea with the LCC favored individual farmer benefits, and UDP favored national benefits, that is, less urea imports or production from scarce natural gas.

The recent developments such as the use of larger urea briquettes (1–3 g in size); inclusion of P, K, and micronutrients depending on site-specific requirements (Kapoor et al 2008); the manufacture and availability of briquettes at the village level; and the participatory development of mechanized applicators that reduce manual labor requirements by two-thirds have given renewed impetus to UDP technology.

b) Inhibitors and slow- and controlled-release products

Nitrogen fertilizers containing urease inhibitors may restrict ammonia volatilization loss by delaying the hydrolysis of urea to ammonium. The effectiveness of the most researched urease inhibitor for rice, N-(n-butyl) thiophosphoric triamide (NBTPT), varied widely among rice soils (Byrnes and Freeney 1996). The stabilized NBTPT inhibitor (Agrotain) has given a 10–20% increase in rice yield. Recent laboratory evaluation of Agrotain on a wide range of flooded soils showed that total ammonia

Table 5. Effect of N management with the leaf color chart (LCC) and urea deep placement (UDP), as compared with the farmers' conventional fertilizer practice (FP), on rice yield, fertilizer use, cost, and net returns during aman and boro seasons across two years in Bangladesh.

N management practice	Grain yield (t/ha)	Fertilizer use (kg/ha)[a] N	P	K	Yield increase (t/ha)[b]	Cost increase (US$/ha)[b]	Net returns ($/ha)[b]
Aman season							
FP	3.6 b	101 a	0 b	0 b			
LCC	4.4 a	88 ab	12.5 a	50 a	0.8*	76 ns	56 ns
UDP	4.3 a	51 b	12.5 a	50 a	0.7*	77 ns	39 ns
Boro season							
FP	6.3 b	153 a	19 a	34 b			
LCC	7.1 a	104 b	23 a	67 c	0.8+	49 ns	106*
UDP	7.0 a	77 c	23 a	67 c	0.7*	53 ns	78+

[a]Means within a column for a season having the same letters are not significantly different at the 0.05 level of probability. [b]*and + indicate significant at 0.05 and 0.10 level of probability from FP, respectively. ns = not significant at 0.10 level of probability from FP.

Source: Adapted from Khan et al (2009).

volatilization loss after 17 days was 1.8 to 7 times lower for urea + Agrotain than for urea alone (unpublished IFDC data).

For irrigated lowland and favorable rainfed rice, denitrification and leaching are not major N loss mechanisms. However, in rainfed rice with frequent drying and wetting cycles, and increased percolation (no puddling and lighter-textured soils), controlling the nitrification process and thus reducing leaching and denitrification losses could be an important component of N management. Highly water-soluble nitrification inhibitors such as dicyandiamide (DCD) were effective under upland conditions but had limited success under direct-seeded delayed flooded rice (Norman et al 1989). Other nitrification inhibitors such as DCD, AgrotainPlus, and 3, 4 dimethylpyrazole-phosphate (DMPP) might play a role in controlling nitrification-denitrification provided they are cost-effective.

Increased costs associated with coated fertilizers such as S-coated urea, Osmocote, Nutricote, Polyon, and Environmentally Safe Nitrogen (ESN) have limited their use to high-value crops. Rice yield increases of up to 20% and N recovery of 70–75% have been reported with controlled-release (Polyon and Nutricote) fertilizers (Singh et al 1995). On the other hand, preplant N application using controlled-release fertilizers (ESN and Duration Type) gave lower yields than conventional preflood urea application on direct-seeded rice (Golden et al 2009).

Modified phosphate fertilizer products

Controlled-release products. Most research and development on controlled-release fertilizers have been directed at N fertilizers. However, recent new products have concentrated on modifying the microenvironment interface of phosphate, soil, and plant roots.

Polymer coatings delay the release of water-soluble phosphate from the granule to reduce phosphate fixation; however, the temperature-sensitive release appears to be short-lived and the cost of polymer coating is high. Although no yield comparison results are available yet, this technology appears unlikely to be beneficial in flooded rice, and in warm environments, and might be better suited for high-value crops.

Another approach to improve phosphate efficiency is to surround the phosphate fertilizer granules with a high cation exchange capacity polymer, which forms a zone around the granules sequestering multivariant cations that normally form insoluble precipitates with water-soluble phosphate fertilizer. The effects are neither temperature nor pH dependent. However, the coatings add about 25% to the cost of the fertilizer and their use may be uneconomical for many rice production systems.

Phosphate-solubilizing microorganisms. Early work centered on the use of mycorrhiza fungi to increase the availability of phosphate to plant roots. Very few commercial applications were developed and benefits could be limited to nonflooded rice systems. Developments in genetic engineering may lead to future plant varieties that can directly use insoluble P from soils, but these possible developments may be a long way away.

Other technologies

The very recent but fast development of nanotechnology might also offer new opportunities in agriculture. Research into nano-encapsulation of plant nutrients by embedding plant nutrients in zeolites is being undertaken as an exploration of alternative means of providing slow-release plant nutrients. Zeolites are a group of naturally occurring minerals having a honey-comb-like layered crystal structure. The network of interconnected tunnels and spaces can be loaded with nano-particles of plant nutrients so that it acts as a reservoir for the nutrients that can be slowly released and matched to plant uptake. However, applicable technologies are not yet available.

Rice production and fertilizer use in Africa

Rice production in SSA is dominated by upland rice production systems, mainly by rainfed systems in the inland river valleys, both characterized by no or very limited water management control. Some highly productive irrigated systems do occur, but the average farmer's yield is around 25% of the yield potential. Lack of mechanization, the use of unimproved varieties, poor weed control, and lack of fertilizer use all contribute to the poor on-farm performance.

Average fertilizer nutrient use in Africa is only 8–10 kg/ha—about 5% of the world average. There are multiple reasons for this low use of fertilizer and underdeveloped agricultural input markets. Poor infrastructure, very high transportation costs, high transaction costs, limited access to output markets and finance for smallholder farmers, lack of knowledge, and inconsistent policies all contribute to the underdevelopment of input markets. A 2006 comparison between SSA and Asian fertilizer cost chains in Figure 9 illustrates how urea (and other fertilizer) costs in SSA are often 80% higher for African farmers than for those in Asia. The reasons for this include the small total market demand, the poor transport infrastructure and longer transportation distances, underdeveloped input market networks, the high cost and unavailability of credit, the comparative lack of farmer knowledge, the absence of enforceable fertilizer regulations, and inconsistent policy environments. All of these factors result in higher cost supply chains for African farmers.

Development of new NERICA® varieties and concerted holistic rice development programs led by the African Rice Center aim at doubling rice production in 10 years. Reaching that goal should be facilitated by the Comprehensive African Agricultural Development Programme (CAADAP), which calls for 10% of national budgets to be devoted to agriculture by 2015. With significant research and development efforts being made by national governments, international donor agencies, and international research centers, the constraints facing Africa's smallholder farmers, including rice producers, will hopefully be surmounted. Improved varieties and access to affordable fertilizer can then assist farmers in raising productivity in both upland and irrigated rice production.

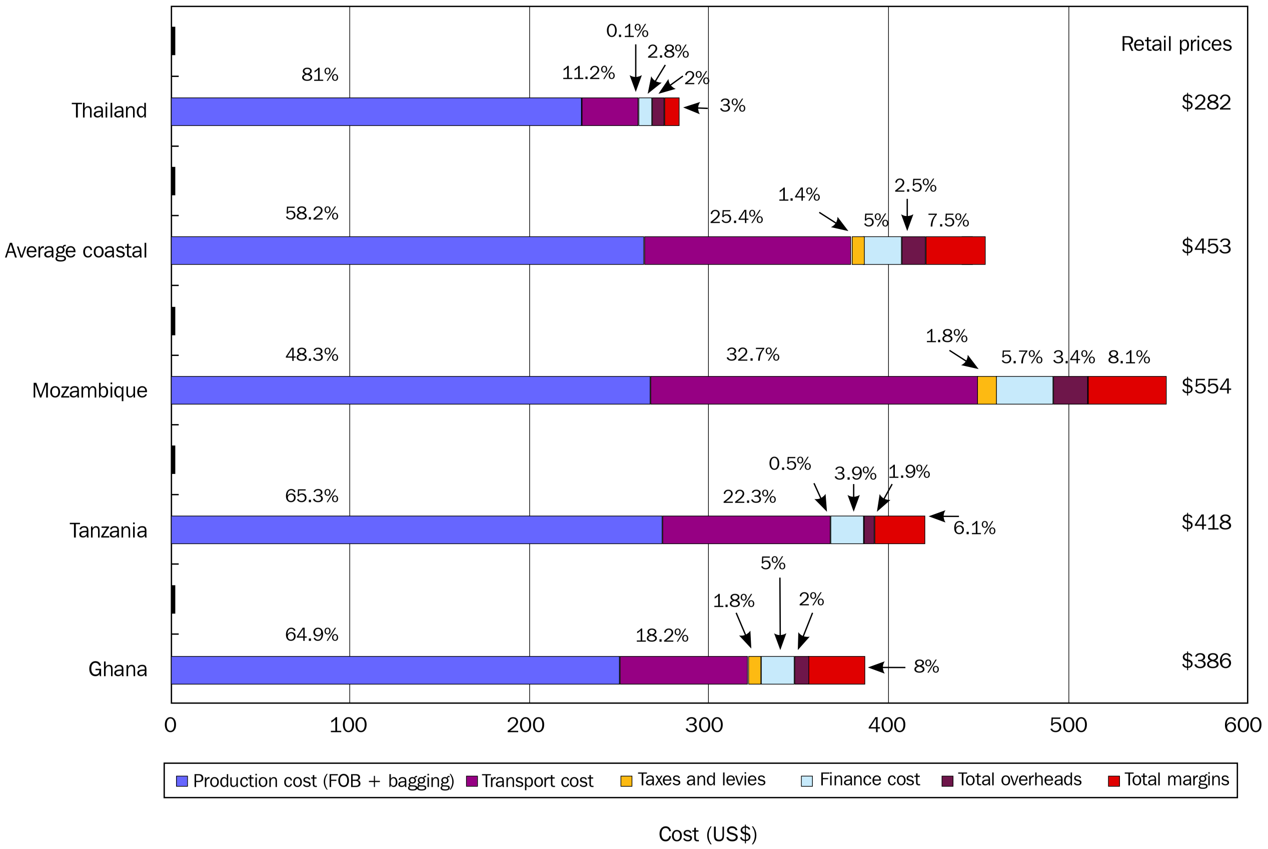

Fig. 9. Fertilizer supply chain costs comparing African coastal countries with Thailand In 2006. Source: Chemonics International and IFDC (2007).

A vision for the role of fertilizer in future rice production

Rice production now accounts for 10% of global fertilizer use and the main fertilizers used are determined more by the economics of manufacturing and logistics than by agronomic efficiency. Major fertilizer markets for rice in Asia are distorted by government pricing policies that encourage unbalanced and wasteful nutrient use. In sub-Saharan Africa, fertilizer use for rice production is severely constrained by underdeveloped marketing and infrastructure, and unfavorable fertilizer-rice price ratios. Generalized fertilizer recommendations and farmers' fertilizer management practices constrain the efficiency of nutrient applications and currently the manufacture, distribution, and use of fertilizer have many deficiencies and externalities detrimental to the environment. However, external fertilizer inputs will continue to be necessary to meet rice production needs for a global population of more than 9 billion people.

Broad changes foreseen for rice production and fertilizer use over the next 50 years include supply-side, climate, socioeconomic, and output market changes in farm production patterns that have implications for researchers, extension agents, fertilizer production and marketing, and policymakers. In sub-Saharan Africa, underdeveloped transportation infrastructure and fertilizer market systems add to the challenges on that continent to meet the growing demand for rice from local rice production systems.

Supply-side drivers

Manufacturing processes have reached scale and technical limits unless a new production process paradigm is achieved. Raw material resources for N fertilizers have increasing competition from growing energy demands and finite phosphate sources may become limiting within 50 years. Production costs will increase substantially, placing constraints on the economic use of fertilizer at the farm level. Some farm-gate cost reductions can be achieved through more efficient marketing systems but the brunt of improved efficiency must be borne by improved nutrient-use efficiency. Doubling nutrient-use efficiency should be an attainable target to be achieved through a combination of improved new or modified fertilizer products and more balanced site-specific nutrient applications augmented by new rice varieties that can use nutrients more efficiently and withstand stress better, and improved farmer knowledge of rice nutrition.

Current policies in China and India favor wasteful use of N by farmers and imbalance in nutrient use due to price distortions. Although difficult to alter, these policies are not sustainable and policy improvements can be expected over time that will have the effect of improving overall nutrient-use efficiency from more balanced nutrient applications.

In sub-Saharan Africa, drastic improvements are required to improve farmer knowledge and crop marketing that will incentivize an increased use of fertilizer and increase productivity not only for rice but for total food security. Similar improvements in the input marketing chain and financial services to agriculture and agribusiness are required together with longer-term investments in transportation to lower marketing costs.

Climate-change drivers

Rice production and nutrient management under changing climatic conditions with extremes of water and temperature conditions will lead to (i) rice production using less water with more aerobic soil conditions and drying-wetting cycles during crop growth, and (ii) more intensive crop production where water supplies are sufficient. There will be more likelihood of secondary and micronutrient deficiencies under scenario (i) and increased nutrient extraction under more intensive production systems. The need for fertilizer products with multiple primary nutrients, secondary nutrients, and micronutrients will increase to meet these new demands together with secondary and micronutrient additions to primary nutrient products such as urea and DAP.

The need will increase for locally adapted field-specific management practices using available fertilizer sources and tailored products providing the most economic returns at acceptable risk. There will be an even greater need for field-specific nutrient management and increased needs for climate and market information and hence a greater role for information technology tools and professional crop advisors. This increased level of science- and economic-based inputs for fertilizer management decisions will create an increased demand for simple, innovative decision tools that can be used by farmers. This represents a major challenge to extension services.

Nitrous oxide emissions in rice systems will likely increase under increased soil drying-wetting cycles, shortages of water, and diversification of cropping systems because of more aerobic soil conditions. Reducing NO_x emissions from urea will become more important and will partially drive the need for product enhancements. Combined with higher energy costs, climate change will be a major driver in the research effort for fertilizers with enhanced efficiency.

Socioeconomic drivers

Production of rice with less labor on small-scale landholdings will induce more mechanization and possible changes in crop establishment from transplanting to direct seeding on either saturated soil (i.e., wet seeding) or unsaturated soil (i.e., dry seeding). This trend could be intensified by increased areas of rice production from landholdings professionally managed for absentee land owners.

Manual application of fertilizer represents a relatively small proportion of the total labor required in rice production, and the optimal timing and distribution of fertilizer are comparable for transplanted and direct-seeded rice. Provided labor is available to broadcast fertilizer N during the growing season, the single most important fertilizer management intervention to increase the yield gain and efficiency from fertilizer N is better timing the application of fertilizer N to match crop needs for supplemental N.

The uptake of drills enabling mechanized sowing and placement of fertilizer could stimulate the application of greater proportions of fertilizer N at the time of sowing. Mechanized application of fertilizer could be especially attractive in reduced-till production systems where mulches or the absence of soil submergence could limit the movement of broadcast fertilizer N into the soil. The absence of farm labor during the crop growing season due to migration or off-farm employment could also lead to a trend toward the application of a greater fraction of fertilizer N at or near crop establishment and reduced splitting of fertilizer N applications—a trend already apparent in parts of China as small farmers increase off-farm employment activities. These trends will drive the need for N management and sources of N, such as timed-release N fertilizers, that can meet crop needs for the entire growing season.

Output market drivers

The population-driven increased demand for food production, especially grains, together with improved nutritional standards and aspirations will act as drivers for intensifying rice production and improving quality. This will probably see more cereals in cropping systems, shorter fallows, and less tillage. These factors will have implications for nutrient transformations in the soil, especially with the increased expansion of water-saving production systems. Under these emerging conditions, farmer management of fertilizer nutrients will be assisted by the next generation of fertilizers that will need to be not only more efficient but also easier to use efficiently. These may include products with improved ammonification and nitrification inhibitors, modified nutrient release mechanisms, slower nutrient release characteristics, bio-coatings, host-specific and climate-driven release mechanisms, as well as biofortified fertilizers containing nutritional supplements of iodine, zinc, and iron.

Development priorities

With rice accounting for approximately 10% of all fertilizer use today and an expected 50% increase in demand for rice over the next 50 years, some important priorities are apparent for research and development and extension on rice nutrition practices. Foremost among these are to get more out of the use with existing products. This will require intensification of extension to rice farmers on integrated soil fertility management, balanced fertilization practices, site-specific nutrient management, and simple, practical farmer-level tools to ensure improved management.

Current computer-, Internet-, and mobile phone–based decision tools that provide extension workers, crop advisors, and farmers with field-specific guidelines on nutrient management are only beginning to scratch the surface of what could be possible in the future with emerging information technology. Mobile phones are already capable of wireless banking, and connecting farmers to banks could open the doors for micro-financing, loans, and purchasing power that they have never had before. Emerging mobile phone applications for providing field-specific fertilizer guidelines (IRRI 2010a, b) could potentially link rice farmers through their phone to suppliers of fertilizer and financing options to purchase the fertilizer. Policies must be enacted to remove price distortions that encourage the overuse of N and discourage economical use of balanced, required nutrients at specific sites.

Fertilizer products with enhanced efficiency are required to reduce farm-level costs and reduce greenhouse gas emissions from rice fields. This will be a major area of future research. At present, polymer coatings are too expensive to be used economically under most circumstances for grain crops and alternative means to match nutrient release to crop nutrient uptake patterns are needed. Research programs that coordinate plant breeding with nutrient-use efficiency, stress tolerance, and herbicide and pest control traits will be important developments.

Improved marketing capacity, especially in sub-Saharan Africa, is required to ensure that the retailers of fertilizers and other inputs are better informed and more knowledgeable of product characteristics, best management practices, and farmer benefits. Government policies will generally need to be more supportive of the private sector in producing, procuring, distributing, and selling plant nutrients. This support will be best shown through policies that are conducive to private-sector business development, investment in transportation and communication infrastructure, the supply of market information, and regulation of the fertilizer sector.

References

Alam MM, Ladha JK, Rahman Khan S, Foyjunnessa, Harun-ur-Rashid, Khan AH, Buresh RJ. 2005. Leaf color chart for managing nitrogen fertilizer in lowland rice in Bangladesh. Agron. J. 97:949-959.

Blair G, Lefroy R. 1998. Sulfur and carbon research in rice production systems: nutrient use efficiency in rice cropping systems. Special issue of Field Crops Res. 56(1-2):1-236, March 1998.

Bruinsma J. 2003. World agriculture towards 2015/2030: an FAO perspective. Rome: Food and Agriculture Organization.

Buresh RJ. 2007. Fertile progress. Rice Today 6(3):32-33.

Buresh RJ, Baanante CA. 1993. Potential economic benefits of modifications to urea that increase yield through reduction in nitrogen losses. Agron. J. 85:947-954.

Buresh RJ, Pampolino MF, Tan PS, Rajendran R, Gines HC, Son TT, Ramanathan S. 2006. Reaching towards optimal productivity. e-ifc No. 10. International Potash Institute. www.ipipotash.org/eifc/2006/10/5.

Buresh RJ, Reddy KR, van Kessel C. 2008. Nitrogen transformations in submerged soils. In: Schepers JS, Raun WR, editors. Nitrogen in agricultural systems. Agronomy Monograph 49. Madison, Wis. (USA): ASA, CSSA, and SSSA. p 401-436.

Buresh RJ, Pampolino MF, Witt C. 2010. Field-specific potassium and phosphorus balances and fertilizer requirements for irrigated rice-based cropping systems. Plant Soil. DOI 10.1007/s11104-010-0441-z.

Byrnes BH, Freeney JR. 1996. Recent developments on the use of urease inhibitors in the tropics. Fert. Res. 42:251-259.

Chemonics International Inc. and IFDC. 2007. Fertilizer supply and costs in Africa. 103 p.

Cordell DJ, Drangert J, White SR. 2009. The story of phosphorus: global food security and food for thought. Global Environ. Change 19:292-305.

Dawe D, Dobermann A, Witt C, Abdulrachman S, Gines HC, Nagarajan R, Satawathananont S, Son TT, Tan PS, Wang GH. 2004. Nutrient management in the rice soils of Asia and the potential of site-specific nutrient management. In: Dobermann A, Witt C, Dawe D, editors. Increasing productivity of intensive rice systems through site-specific nutrient management. Enfield, N.H. (USA): Science Publishers, Inc., and Los Baños (Philippines): International Rice Research Institute. p 337-358.

Dobermann A, Dawe D. 2008. Can organic agriculture feed Asia? Rice Today 7(4):42.

Dobermann A, Fairhurst T. 2000. Rice: nutrient disorders and nutrient management. Singapore: Potash and Phosphate Institute (PPI) and Potash and Phosphate Institute of Canada (PPIC) and Los Baños (Philippines): International Rice Research Institute.

Dobermann A, Witt C, Dawe D, editors. 2004. Increasing the productivity of intensive rice systems through site-specific nutrient management. Enfield, N.H. (USA) and Los Baños (Philippines): Science Publishers, Inc., and International Rice Research Institute.

Dobermann A, Witt C, Dawe D, Abdulrachman S, Gines HC, Nagarajan R, Satawathananont S, Son TT, Tan PS, Wang GH, Chien NV, Thoa VTK, Phung CV, Stalin P, Muthukrishnan P, Ravi V, Babu M, Chatuporn S, Sookthongsa J, Sun Q, Fu R, Simbahan GC, Adviento MAA. 2002. Site-specific nutrient management for intensive rice cropping systems in Asia. Field Crops Res. 74:37-66.

Fairhurst T, Witt C, Buresh R, Dobermann A, editors. 2007. Rice: a practical guide to nutrient management. Second edition. Los Baños (Philippines): International Rice Research Institute and Singapore: International Plant Nutrition Institute and International Potash Institute. p 1-45.

FAOSTAT. 2009. Statistical databases and data-sets. Food and Agriculture Organization of the United Nations. http://faostat.fao.org/default.aspx.

FAO. 1999. Fertilizer use by crop. Fourth edition. Food and Agriculture Organization of the United Nations, Rome.

FAO. 2002. Fertilizer use by crop. Fifth edition. Food and Agriculture Organization of the United Nations, Rome.

Fischer RA, Byerlee D, Edmeades GO. 2009. Can technology deliver on the yield challenge to 2050? FAO Expert Meeting on How to Feed the World in 2050, Rome.

Frink CR, Waggoner PE, Ausubel JH. 1999. Nitrogen fertilizer: retrospect and prospect. Proc. Nat. Acad. Sci. USA 96:1175-1180.

Golden BR, Slaton NA, Norman RJ, Wilson Jr CE, DeLong RE. 2009. Evaluation of polymer-coated urea for direct-seeded, delayed-flood rice production. Soil Sci. Soc. Am. J. 73:375-383.

Goswami NN, Banerjee NK. 1978. Phosphorus, potassium, and other macroelements. In: Soils and rice. Los Baños (Philippines): International Rice Research Institute.

Haefele SM, Bouman BAM. 2009. Drought-prone rainfed lowland rice in Asia: limitations and management options. In: Serraj R, Bennett J, Hardy B, editors. Drought frontiers in rice: crop improvement for increased rainfed production. Singapore: World Scientific Publishing and Los Baños (Philippines): International Rice Research Institute. p 211-232.

Haefele SM, Naklang K, Harnpichitvitaya D, Jearakongman S, Skulkhu E, Romyen P, Phasopa S, Tabtim S, Suriya-arunroj D, Khunthasuvon S, Kraisorakul D, Youngsuk P, Amarante ST, Wade LJ. 2006. Factors affecting rice yield and fertilizer response in rainfed lowlands of northeast Thailand. Field Crops Res. 98:39-51.

Haefele SM, Sipaseuth N, Phengsouvanna V, Dounphady K, Vongsouthi S. 2010. Nutrient management for rainfed lowland rice in Laos PDR. Field Crops Res. (Submitted.)

Haefele SM, Konboon Y. 2009. Nutrient management for rainfed lowland rice in northeast Thailand. Field Crops Res. 114:374-385.

IFA (International Fertilizer Industry Association). 2009a. Assessment of fertilizer use by crop at the global level: 2006/07–2007/08. International Fertilizer Industry Association. 11 p.

IFA (International Fertilizer Industry Association). 2009b. Energy efficiency and CO_2 emissions in ammonia production, 2008-2009 summary report. International Fertilizer Industry Association.

IRRI (International Rice Research Institute). 2010a. Nutrient management decision tools. www.irri.org/nmrice. Accessed 2 August 2010.

IRRI (International Rice Research Institute). 2010b. Site-specific nutrient management. www.irri.org/ssnm. Accessed 2 August 2010.

Kapoor V, Patil SK, Singh U, Magre H, Shrivastava LL, Mishra VN, Das RO, Samadhiya VK, Sanabria J, Diamond R. 2008. Rice growth, grain yield, and floodwater nutrient dynamics as affected by nutrient placement method and rate. Agron. J. 100:526-536.

Khan MAH, Alam MM, Hossain MI, Rashid MH, Mollah MIU, Quddus MA, Miah MIB, Sikder MAA, Ladha JK. 2009. Validation and delivery of improved technologies in the rice-wheat ecosystem in Bangladesh. In: Ladha JK, Yadvinder-Singh, Erenstein O, Hardy B, editors. Integrated crop and resource management in the rice-wheat system of South Asia. Los Baños (Philippines): International Rice Research Institute. p 197-220.

Kirk GJD, George T, Courtois B, Senadhira D, 1998. Opportunities to improve phosphorus efficiency and soil fertility in rainfed lowland and upland rice ecosystems. Field Crops Res. 56:73-92.

Kirk GJD. 2004. The biogeochemistry of submerged soils. England: John Wiley and Sons Ltd. 291 p.

Ladha JK, Pathak H, Krupnik TJ, Six J, van Kessel C. 2005. Efficiency of fertilizer nitrogen in cereal production: retrospects and prospects. Adv. Agron. 87:85-156.

Linquist B, Sengxua P. 2001. Nutrient management in rainfed lowland rice in the Lao PDR. Los Baños (Philippines): International Rice Research Institute. 60 p.

Mohanty SK, Singh U, Balasubramanian V, Jha KP. 1999. Nitrogen deep-placement technologies for productivity, profitability, and environmental quality of rainfed lowland rice systems. Nutr. Cycl. Agroecosyst. 53:43-57.

Morris M, Kelly VA, Kopiki RJ, Byerlee D. 2007. Fertilizer use in African agriculture: lessons learned and good practice guide. Washington, D.C. (USA): The World Bank.

Moya PF, Dawe D, Pabale D, Tiongco M, Chien NV, Devarajan S, Djatiharti A, Lai NX, Niyomvit L, Ping HX, Redondo G, Wardana P. 2004. The economics of intensively irrigated rice in Asia In: Dobermann A, Witt C, Dawe D, editors. Increasing productivity of intensive rice systems through site-specific nutrient management. Enfield, N.H. (USA): Science Publishers, Inc. and Los Baños (Philippines): International Rice Research Institute. p 29-58.

Naklang K, Harnpichitvitaya D, Amarante ST, Wade LJ, Haefele SM. 2006. Internal efficiency, nutrient uptake, and the relation to field water resources in rainfed lowland rice of northeast Thailand. Plant Soil 286:193-208.

Norman RJ, Wells BR, Moldenhauer KAK. 1989. Effect of application method and dicyandiamide on urea-nitrogen-15 recovery in rice. Soil Sci. Soc. Am. J. 53:1269-1274.

Pampolino MF, Laureles EV, Gines HC, Buresh RJ. 2008. Soil carbon and nitrogen changes in long-term continuous lowland rice cropping. Soil Sci. Soc Am. J. 72:798-807.

Pampolino MF, Manguiat IJ, Ramanathan S, Gines HC, Tan PS, Chi TTN, Rajendran R, Buresh RJ. 2007. Environmental impact and economic benefits of site-specific nutrient management (SSNM) in irrigated rice systems. Agric. Syst. 93:1-24.

Pandey S. 1999. Adoption of nutrient management technologies for rice production: economic and institutional constraints and opportunities. Nutr. Cycl. Agroecosyst. 53:103-111.

Prud'homme M. 2009. Global fertilizers and raw materials supply and supply/demand balances 2009-2013. 77th IFA Annual Conference, Shanghai, May 2009.

Savant NK, Stangel PJ. 1990. Deep placement of urea supergranules in transplanted rice: principles and practices. Fert. Res. 25:1-83.

Savant NK, Stangel PJ. 1998. Urea briquettes containing diammonium phosphate: a potential new NP fertilizer for transplanted rice. Nutr. Cycl. Agroecosyst. 51:85-94.

Savithri P, et al. 1998. Soil and crop management technologies for enhancing rice production under micronutrient constraints. Nutr. Cycl. Agroecosyst. 53:1.

Singh U, Cassman KG, Ladha JK, Bronson KF. 1995. Innovative nitrogen management strategies for lowland rice systems. In: Fragile lives in fragile ecosystems. Proceedings of the International Rice Research Conference, International Rice Research Institute, Philippines. p 229-254.

Thompson TP, Sanabria J. 2010. The division of labor and agricultural innovation in Bangladesh: dimensions of gender. IFDC—An International Center for Soil Fertility and Agricultural Development. Paper Series (in press).

Witt C, Dobermann A. 2004. Toward a decision support system for site-specific nutrient management. In: Dobermann A, Witt C, Dawe D, editors. Increasing productivity of intensive rice systems through site-specific nutrient management. Enfield, N.H. (USA): Science Publishers, Inc. and Los Baños (Philippines): International Rice Research Institute. p 359-395.

Witt C, Pasuquin JMCA, Mutters R, Buresh RJ. 2005. New leaf color chart for effective nitrogen management in rice. Better Crops 89(1):36-39.

Wood S, Henao J, Rosegrant MW. 2004. The role of nitrogen in sustaining food production and estimating future nitrogen needs to meet food demand. In: Moiser AR, Syers K, Freney JR, editors. Agriculture and the nitrogen cycle: assessing the impact of fertilizer use on food production and the environment. Washington, D.C. (USA): Island Press. p 245-265.

Yasmin N, Blair GJ, Till R. 2007. Effect of elemental sulfur, gypsum, and elemental sulfur coated fertilizers, on availability of sulfur to rice. J. Plant Nutr. 30:79-91.

Notes

Authors' addresses: D.I. Gregory, agribusiness specialist, IFDC, PO Box 2040, Muscle Shoals, Alabama 35662, USA; email: lgregory@ifdc.org; S.M. Haefele, International Rice Research Institute (IRRI), DAPO Box 7777, Metro Manila, Philippines; email: s.haefele@cgiar.org; R.J. Buresh, IRRI, Philippines; email: r.buresh@cgiar.org; U. Singh, principal scientist/specialist/soil fertility, IFDC, USA; email: usingh@ifdc.org.

View publication stats