Precision Nutrient Management in Intensive Irrigated Rice Systems – The Need for Another On-Farm Revolution

By A. Dobermann and K.G. Cassman

The potential for developing rice varieties for irrigated systems with increased nitrogen (N), phosphorus (P), and potassium (K) use efficiency will require many years of research and improvements in selection methods used in breeding programs. Thus, improvement in nutrient use efficiency in irrigated rice over the next 10 years must focus on better soil and crop management. At issue is whether the management strategies practiced by rice farmers are adequate to maintain the current yield levels over the long term and to support future yield increases needed to meet growing demand.

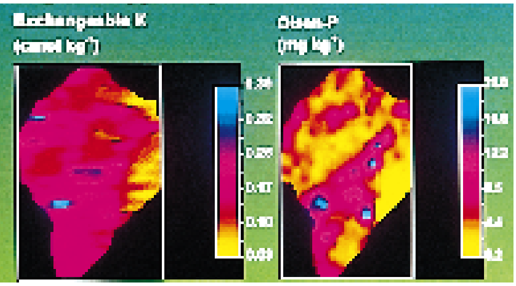

Figure 1. Nutrient depletion due to intensive rice cropping: K and P status in rice soils of Nueva Ecija, Philippines (19,196 ha).

Rice has been grown as a foodcrop for more than 6,000 years in Asia. Today, more than 90 percent of global rice supplies are produced and consumed in Asia, contributing 30 to 75 percent of dietary calories for populations in those countries.

Irrigated rice accounts for 75 percent of the overall rice production in Asia. Average yields must rise from 4.9 t/ha in 1990 to 8.0 t/ha by the year 2025 to meet increased demand from population growth.

Further intensification of lowland rice systems that produced 479 million tonnes in 1990 will be needed to meet Asia's estimated future requirements of 686 million tonnes for the year 2025. Much of this increase must come from existing irrigated land (that is already now harvested twice a year) since a net increase in irrigated area for lowland rice is not to be anticipated.

This increase in yield levels will lead to a marked increase in net nutrient removal from rice fields. Total net K removal, for example, already exceeds the total K fertilizer consumption in south and southeast Asia by a large margin, and it is likely that this gap will widen further.

The K requirements of rice vary from 17 to 30 kg K per tonne of grain. For yields above 8 t/ha, total K uptake exceeds 200 kg/ha .

In irrigated rice areas of Asia the amount of K annually cycling from the soil into rice plants is in the range of 7 to 10 million tonnes. About one million tonne of K is removed with harvested grain alone.

Researchers at the International Rice Research Institute (IRRI) have analyzed a number of long-term experiments on continuous, irrigated rice systems in Asia. They suggest that under continuously submerged conditions, the N supplying capacity of the soil is reduced, leading to a decreased yield contribution from nutrient inputs.

Researchers had observed a consistent yield decline trend during dry seasons at the IRRI Research Farm between 1968 and 1991 at N rates of 150 kg/ha.

There are now clear indications from long-term fertility experiments in irrigated rice systems of developing Asia that negative P and K balances may impede N efficiency. Some of this research was begun as early as 1964 and includes sites at which the initial soil fertility status was high.

Table 1 shows data from 11 sites in China, India, Indonesia, Philippines and Vietnam, most of which produced net negative K balances for all treatments and net negative P balances for treatments without P inputs when monitored in 1993 (Dobermann et al.,1995).

Indigenous nutrient supply varies widely among rice fields within small domains, as illustrated in Figure 1. However, blanket prescriptions for the rate and timing of fertilizer applications are presently issued by national research and extension authorities for large recommendation domains. In many cases, farmers do not follow those blanket recommendations, but they also do not adjust their fertilizer rates according to soil nutrient supply. Achieving and sustaining average yields of 7 to 8 t/ha will require improved nutrient management strategies that focus on increasing the use-efficiency of nutrients from both indigenous and external sources such as fertilizers.

Since current fertilizer management practices in intensive, irrigated rice systems are not tailored to differences in indigenous nutrient supply and crop demand, a new concept for integrated nutrient management is proposed. The objectives and tactics for management differ for each essential nutrient.

Table 1. Mean partial net P and K balances in different fertilizer treatments of long-term fertility experiments for irrigated rice in five Asian countries.

Phosphorus (10 sites, 1993)

Treatment	Olsen-P mg/kg	Grain yield kg/ha	Fertilizer P input	Recycled P in stubble	Total P uptake	Net P balance
			kg P/ha			
Control	3.9	3,341	0	0.6	7.6	-7.0
+N	3.3	4,654	0	0.6	8.5	-7.9
+NP	9.5	5,530	20	2.1	17.2	4.9
+NK	3.3	5,112	0	0.5	8.5	-8.0
+NPK	9.4	6,189	20	2.0	18.3	3.7

Potassium (9 sites, 1993)

Treatment	Extract K cmol/kg	Grain yield kg/ha	Fertilizer K input	Recycled K in stubble	Total K uptake	Net K balance
			kg K/ha			
Control	0.279	3,277	0	11	54	-43
+N	0.260	4,565	0	14	71	-57
+NP	0.251	5,426	0	12	75	-63
+NK	0.326	4,795	38	18	90	-34
+NPK	0.312	5,855	44	25	111	-42

China, India, Indonesia, Philippines, Vietnam

1. Dynamic soil- and plant-based management is needed for N. The ability to adjust the quantity of applied N in relation to variation in the indigenous N supply is as important as the timing, placement and source of applied N (Peng et al., 1996; Cassman et al., 1996). Therefore, N management is based on these factors.
    - Estimation of crop demand, potential indigenous nutrient supply, and recovery from applied inorganic and organic sources over time to predict the total amount of applied N that is needed.
    - Estimation of soil N release during early growth stages to identify the need for a basal N application.
    - Monitoring of plant N status to optimize timing of split applications in relation to crop demand and soil N supply.
2. Management of P and K requires a long-term strategy because neither P nor K is easily lost or added to the root zone by the biological and chemical processes affecting N (nitrification-denitrification, NH_3 volatilization, biological N fixation, leaching). Therefore, the issue of maximizing the recovery efficiency of fertilizer P and K is less important than predicting the need for applied nutrients and the amount to apply. However, management must emphasize the maintenance of available soil nutrients to insure that soil P and K supply does not limit crop growth and thus reduce N use efficiency. Changes in potential indigenous nutrient supply can be predicted as a function of the nutrient balance. Key components of P and K management include the following.
    - Estimation of crop demand, potential indigenous nutrient supply, and recovery from applied inorganic and organic sources over time to predict the amount of applied P and K required to sustain a targeted yield level.
    - Knowledge of the relationship between the P and K balance and changes in potential indigenous nutrient supply over time.
3. Diagnosis of potential deficiencies is the key management tool for nutrients such as magnesium (Mg), zinc (Zn) and sulfur (S). Once identified as a problem, deficiencies can be alleviated by regular or one-time measures as part of a general fertilizer/soil use recommendation. Similarly, diagnostic criteria are needed to identify other nutritional disorders such as salinity, iron (Fe) toxicity, or boron (B) toxicity to make adjustments in the N, P, and K management that account for these limitations or to alter soil management practices to reduce the severity of these toxicities.

Table 2. Current and projected requirements of N, K, P, and S in irrigated rice systems of Asia. Estimates for 1991 are based on a harvest area of 74 million ha and an average yield of 4.9 t/ha (IRRI 1993). Estimates for 2025 assume a constant harvest area of 74 million ha and average yields of 8 t/ha to meet the projected rice demand of 592 million tonnes from irrigated systems (Cassman and Pingali, 1995). All values are given on elemental basis.

	Average nutrient content at harvest		Uptake per tonne of grain yield[3]	Annual removal with grain		Total annual uptake with grain and straw	
	Grain	Straw	kg/tonne grain	1991	2025	1991	2025
	%			million tonnes/year			
Nitrogen[1]	1.05-1.40	0.50-0.80	15-22	3.8-5.1	6.2-8.3	5.4-8.0	8.9-13.0
Potassium[1]	0.25-.033	1.30-2.00	15-25	0.9-1.2	1.5-2.0	5.4-9.0	8.9-14.8
Phosphorus[1]	0.15-0.25	0.05-0.10	2-4	0.5-0.9	0.9-1.5	0.7-1.4	1.2-2.4
Sulfur[2]	0.06-0.15	0.05-0.10	1.5-2.5	0.2-0.5	0.4-0.9	0.6-0.9	0.9-1.5

[1] N,P and K concentrations in grain and straw measured as the interquartile range of 192 plots of long-term fertility experiments with rice at 11 sites in China, India, Indonesia, Vietnam, and the Philippines (K. Cassman and A. Dobermann, unpublished data).

[2] Sulfur concentrations in grain and straw based on literature data (Yoshida 1981; Mohapatra et al 1993).

[3] Average total nutrient uptake in above-ground biomass (grain + straw) per tonne of grain yield adjusted to 14 percent moisture content.

In a model developed for maize by Janssen et al., 1990, a Nutrient Decision Support System (NuDSS) for irrigated rice has been initiated which provides the user with more cost-effective fertilizer recommendations. The approach is based on equations describing:

(i) supply of N, P and K as a function of chemical soil test values,
(ii) actual NPK uptake as a function of supply and
(iii) grain yield as a function of NPK uptake (NPK interactions are acknowledged).

Besides on-farm nutrient omission plots, ion-exchange resin capsules can be used on-site to predict potential P and K supply, to identify the need for basal N application, and to assess possible nutritional disorders such as Zn or S deficiency. The resin capsule offers the potential for multi-element on-site soil nutrient extraction in flooded rice soils at different growth stages without the need for collecting and processing soil samples.

In order to calculate the partial P and K balance within the NuDSS, fertilizer input rates, above-ground plant uptake, and the amount of nutrients recycled with incorporated straw are used as a minimum data set.

Estimates of nutrients in recycled straw can be obtained from estimates of the stubble and straw left in the field (Table 1). On a dry matter basis, one tonne of rice straw contains 5 to 8 kg N, 0.5 to 1 kg P, 13 to 20 kg K, and 0.5 to 1.0 kg S (Table 2). Straw is either removed from the field, burned, piled or spread in the field, incorporated into the soil, or used as mulch for the succeeding crop. Each of these practices has a different effect on nutrient recycling and the overall nutrient balance, and thus must be accounted for in fertilizer recommendations.

Nutrient omission plots can be established in farmers' fields to estimate grain yield and nutrient uptake supported by the indigenous soil nutrient supply. This plot received P and K fertilizer inputs but no N fertilizer, and therefore provides an estimate of soil N supply capacity. Similar omission plots can be established for P or K.

The Relationship Between Nutrient Uptake and Grain Yield

Physiological nutrient-use efficiency (PE) is defined as the grain yield increase per kg of nutrient accumulation in above-ground plant biomass. The relationship between grain yield and nutrient uptake is scattered within an "envelope" or range between two lines that define maximum accumulation (minimum PE) and maximum dilution (maximum PE) as shown in Figure 2. With a limited nutrient supply, there is maximum dilution of the nutrient in the plant, and uptake is not influenced by growth but only by supply (source limitation). Conversely, when the supply of a nutrient is large and growth is not limited by uptake, the internal nutrient concentration is high, and there is maximum accumulation (sink limitation). In this situation, growth is limited by other factors.

Using data from long-term fertility experiments, these relationships between grain yield and nutrient uptake were established for N, P, and K in modern rice varieties grown under irrigated conditions without limitations from pests, water, or other management factors (Figure 2). For N, this range was defined by two linear functions with a slope of 35 for maximum N accumulation (Y_{NA}) and 90 kg grain/kg N for maximum N dilution (Y_{ND}). The PE for P ranged from 220 to 900 kg grain per kg P. Depending on the availability of other nutrients, 16 to 33 kg P uptake/ha were needed to produce 8 tonnes grain ha. The slope of the relationship between grain yield and K uptake varied from 30 to 110 kg grain per kg K absorbed.

Improved nutrient management must focus on optimizing the PE of all major nutrients rather than maximizing the PE of a single nutrient. For example, very high PE of one nutrient (data points close to the line of maximum dilution) indicates that supply of this nutrient was a limiting factor. In such a situation, the full yield potential cannot be achieved. Therefore, integrated nutrient management should attempt to achieve PE values for N, P, and K that are approximately in the middle of the range enclosed by the lines of maximum dilution and of

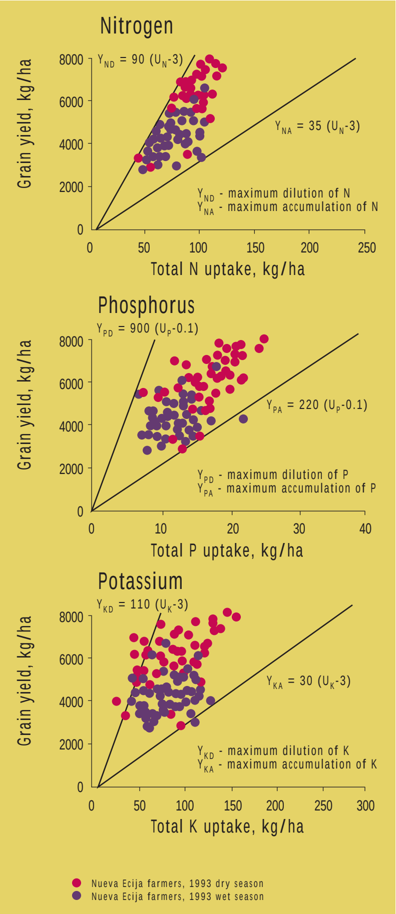

Figure 2. Envelopes describing the range of the relationship between total uptake of N,P and K with grain yield (14 percent moisture content) in modern rice varieties grown under irrigated conditions. The regression functions describing maximum accumulation (A) and maximum dilution (D) of each element in the plant were derived from long-term experiments conducted at 11 sites in five countries. For comparison, data collected from 60 farmers in Central Luzon, Philippines, are plotted as symbols.

maximum accumulation. Plotting actual crop uptake vs. grain yield data within such an envelope may also serve as a diagnostic tool for assessing the actual nutrition status in farmer fields. For example, PE of P in most farmer fields of a study in Nueva Ecija was in the middle of the envelope, and we may conclude that P supply was sufficient. On many farms, however, PE of N in the dry season was close to the maximum dilution line, suggesting limitations to crop uptake due to insufficient N management. The same holds true for K on some farms.

The nutrient management strategy proposed here is a generic approach which, within the context of extension, is applicable to different spatial scales. However, because variation in potential indigenous nutrient supply is large, **the scale of nutrient management recommendation domains must change from large regions to farms, single fields, or even single parcels within a larger field.**

A move from blanket recommendations for large regions to farm- or field-specific management will require a gradual transition. Over the shorter-term, other cost-effective methods to help farmers achieve increased nutrient use efficiency should be further explored. Customary rules on timing of N application or green leaf color charts could replace an expensive tool such as the chlorophyll meter. Readily available soil information such as maps, local knowledge, or simple agronomic soil classification systems may be used to improve fertilizer recommendations. In many countries of Asia, facilities for more sophisticated farmer support need to be built up. Included among these are: soil testing laboratories and a soil testing program, perhaps with the involvement of the private sector, fertilizer recommendation services, objective information about new fertilizer products, and use of mass media (radio, TV, newspapers) for extension of new technologies. Using a knowledge-intensive approach will also require a change in farmers' record keeping practices. Good estimates of yields and fertilizer use are required for single fields, and farmers need better means of measuring fertilizer doses more accurately.

Conclusion

Precision nutrient management should be applied on Asia's 74 million ha of irrigated rice in order to meet the requirements for another economically successful, but environmentally friendly, on-farm revolution. BCI

Dr. Dobermann is with the International Rice Research Institute (IRRI), P.O. Box 933, Manila 1099, Philippines. Dr. Cassman was formerly with IRRI, and now Head, Department of Agronomy, University of Nebraska-Lincoln, P.O. Box 830915, Lincoln, NE 68583-0915 USA.

Bibliography

Cassman, K.G., A. Dobermann, P.C. Sta.Cruz, G.C. Gines, M.I. Samson, J.P. Descalsota, J.M. Alcantara, M.A. Dizon, and D.C. Olk. 1996a. Soil organic matter and the indigenous nitrogen supply of intensive irrigated rice systems in the tropics. Plant Soil (in press).

Cassman, K.G., G.C. Gines, M. Dizon, M.I. Samson, and J.M. Alcantara. 1996b. Nitrogen-use efficiency in tropical lowland rice systems: Contributions from indigenous and applied nitrogen. Field Crops Res. 47:1-12.

Cassman, K.G., S.K. De Datta, S.T. Amarante, S.P. Liboon, M.I. Samson, and M.A. Dizon. 1996c. Long-term comparison of agronomic efficiency and residual benefits of organic and inorganic nitrogen sources on irrigated lowland rice in the tropics. Exp. Agriculture (in press).

Cassman, K.G., and P.L. Pingali. 1995. Intensification of irrigated rice systems: Learning from the past to meet future challenges. GeoJournal 35:299-305.

Dobermann, A., K.G. Cassman, C.P. Mamaril, and J.E. Sheehy. 1996a. Management of phosphorus, potassium and sulfur in intensive, irrigated lowland rice. Paper presented at the workshop Nutrient Use Efficiency of the Cropping System(s). 13-5 December 1995, International Rice Research Institute, P.O. Box 933, Manila 1099.

Dobermann, A., P.C. Sta.Cruz, and K.G. Cassmann. 1996b. Fertilizer inputs, nutrient balance, and soil nutrient-supplying power in intensive, irrigated rice systems. I. Potassium uptake and K balance. Nutrient Cycling in Agroecosystems 46:1-10.

IRRI. 1993. 1993-1995 IRRI rice almanac. International Rice Research Institute, P.O. Box 933, 1099 Manila, Philippines.

Janssen, B.H., F.C.T. Guiking, D. Van der Eijk, E.M.A. Smaling, J. Wolf, and H. Van Reuler. 1990. A system for Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS). Geoderma 46:299-318.

Mohapatra, A.R., A.K. Misra, and V. Sarkunan. 1993. Absorption pattern of secondary nutrients and micronutrients by high-yielding rice (Oryza sativa) varieties. Indian J. Agric. Sci. 63:586-588.

Peng, S., F.V. Garcia, R.C. Laza, A.L. Sanico, R.M. Visperas, and K.G. Cassman. 1996. Increased N-use efficiency using chlorophyll meter on high-yielding irrigated rice. Field Crops Res. (in press).

Yoshida, S. 1981. Fundamentals of rice crop science. International Rice Research Institute, P.O. Box 933, 1099 Manila, Philippines.