IRRI DISCUSSION PAPER SERIES NO. 27

# Research on natural resources management: strategic research issues and IRRI's approached to addressing them

G.J. Kirk, A. Doberman, J.K. Ladha, D.C. Olk, R. Roetter, T.P. Toung, and L. Wade

IRRI
INTERNATIONAL RICE RESEARCH INSTITUTE
PO Box 933, Manila 1000, Philippines

The International Rice Research Institute (IRRI) was established in 1960 by the Ford and Rockefeller Foundations with the help and approval of the Government of the Philippines. Today IRRI is one of the 16 nonprofit international research centers supported by the Consultative Group on International Agricultural Research (CGIAR). The CGIAR is cosponsored by the Food and Agriculture Organization of the United Nations (FAO), the International Bank for Reconstruction and Development (World Bank), the United Nations Development Programme (UNDP), and the United Nations Environment Programme (UNEP). Its membership comprises donor countries, international and regional organizations, and private foundations.

As listed in its most recent Corporate Report, IRRI receives support, through the CGIAR, from a number of donors including UNDP, World Bank, European Union, Asian Development Bank, Rockefeller Foundation, and the international aid agencies of the following governments: Australia, Belgium, Canada, People's Republic of China, Denmark, France, Germany, India, Indonesia, Islamic Republic of Iran, Japan, Republic of Korea, The Netherlands, Norway, Philippines, Spain, Sweden, Switzerland, United Kingdom, and United States.

The responsibility for this publication rests with the International Rice Research Institute.

## IRRI Discussion Paper Series

The IRRI Discussion Paper Series was created as a flexible means for IRRI scientists to share information with specialized institutions and individuals. Each paper is produced from camera-ready copy supplied by the author and is processed through IRRI's Communication and Publications Services. The papers are read for typographical accuracy only and are not subjected to the normal IRRI editing or peer review processes.

The series is intended to be a fast means of presenting preliminary results of research still in progress, but which could be of immediate use to others. The series also contains special project reports, consortia and network reports, short proceedings or reports of meetings and workshops, recommendations from a particular workshop, and similar materials.

IRRI invites feedback from readers, which will be useful to the authors when they are refining their materials for formal publication in journals or as monographs.



P.O. Box 933, Manila 1099, Philippines
Phone: (63-2) 845-0563, 812-7686
Fax: (63-2) 891-1292, 845-0606
Email: Postmaster@IRRI.CGNET.COM
Home page: http://www.cgiar.org/irri
Riceweb: http://www.riceweb.org
Riceworld: http://www.riceworld.org
Telex: (ITT) 40890 RICE PM
(CWI) 14519 IRILB PS
(RCA) 22456 IRI PH
(CWI) 14861 IRI PS

**Suggested citation:**
Kirk GJD, Dobermann A, Ladha JK, Olk DC, Roetter R, Tuong TP, Wade L. 1998. Research on natural resources management: strategic research issues and IRRI's approaches to addressing them. Manila (Philippines): International Rice Research Institute.

**ISBN 971-22-0104-X**
**ISSN 0117-8180**

# Research on natural resources management: strategic research issues and IRRI's approaches to addressing them

G.J.D. Kirk, A. Dobermann, J.K. Ladha, D.C. Olk, R. Roetter, T.P. Tuong, and L. Wade

1998

IRRI
INTERNATIONAL RICE RESEARCH INSTITUTE
P.O. Box 933, Manila 1099, Philippines

# Research on Natural Resources Management:
## Strategic research issues and IRRI's approaches to addressing them

G.J.D. Kirk, A. Dobermann, J.K. Ladha, D.C. Olk, R. Roetter, T.P. Tuong, and L. Wade

During the process of the IRRI's Fifth External Program and Mangement Review, the review team requested that IRRI present the strategic research issues involving research on natural resources management and its approaches to addressing them in the four rice ecosystems--irrigated, rainfed lowland, flood-prone, upland--and in cross-ecosystems work. What follows was IRRI's response.

### Irrigated rice ecosystem

For crop and resource management in irrigated rice, it is useful to consider three yield gaps:

1. the gap between the yield potential of the current best germplasm and the absolute yield potential determined by climate and thermodynamics;
2. the gap between yield attainable at favored sites using the best established practices and yield attained at experiment stations;
3. the gap between present average farm yield and the highest yields at favored sites.

Studies in favorable areas in the Philippines suggest that the second gap has been closed; it will remain closed until germplasm with a higher yield potential is available. The third gap, however, remains substantial and there is considerable scope for raising average yields by improving the use and management of nutrients. Closing this gap will require much better tailoring of management to site-specific problems, as discussed below.

In tackling the first gap, we seek to develop plants with a genetic yield potential of at least 12.5 t $ha^{-1}$ of grain under tropical irrigated conditions. Such a yield will necessarily entail a much greater use of mineral fertilizers. Nitrogen in particular is important because of its close association with yield and because, if poorly managed, it is subject to high rates of loss. We calculate likely N fertilizer requirements for these yields as follows. Current maximum yields of 10 t $ha^{-1}$ under tropical irrigated conditions are achieved with a minimum of 18 kg of N in the crop per ton of grain, i.e., 225 kg $ha^{-1}$ in the crop for 12.5 t $ha^{-1}$ of grain. Based on N uptake from zero N plots, 50–80 kg $ha^{-1}$ of this might be obtained from soil reserves replenished by biological N fixation and crop residues, though fixation tends to decrease with increasing use of N fertilizers. Therefore, with the current average recovery of fertilizer N in crops achieved by the best farmers—50%—12.5 t $ha^{-1}$ of grain would require 290–350 kg $ha^{-1}$ of fertilizer. Clearly, therefore, efficiencies must be improved both to realize new yield potentials and to avoid large emissions of N into the environment. Greater efficiencies can be achieved by careful management, but this entails increased effort by farmers. We must also explore possibilities for modifying the plant to improve its efficiency.

In experiments over the past five years, we have measured soil nutrient levels and fertilizer efficiency in some 300 farmers' fields in continuous rice and rice-wheat systems in eight countries. Contrary to the accepted wisdom that irrigated rice systems are homogeneous, we have found large spatial and temporal differences in nutrient level and fertilizer efficiency, even in similar soil types. Differences between fields are in part due to historical differences in management. But the major cause of low and varying fertilizer use efficiency, particularly for N, is that the supply of nutrients from soil reserves and fertilizers is not well synchronized with the demands of the crop, and managing fertilizers to improve this synchrony is complicated. Thus, the average recovery of fertilizer N is only 30–40% and has not improved much over the past 30 years. Also, farmers are not able to adjust fertilizer rates to allow for short-range variation in soil conditions. Clearly, blanket fertilizer recommendations for large areas are inappropriate. We consider that farm-specific or even field-specific management will be required to close the third yield gap and attain yields of 7 t $ha^{-1}$ or more on a sustained basis. This will require tools for managing nutrients and for judging fertilizer requirements, as well as better extension services. We therefore anticipate improvements in extension services in many countries and greater adoption of "knowledge-intensive" technologies.

The possible decline in factor productivity as a consequence of intensification, observed in long-term trials at experiment stations under intensive rice-rice and rice-wheat cultivation, raises concern about the sustainability of extremely intensive rice production. The occurrence and extent of the productivity decline outside experiment stations and its causes are the subject of continuing research across Asia.

In the near future, the third gap will be exacerbated by water scarcity. Water supplies for irrigation are increasingly threatened by nonagricultural demands and by decaying infrastructure, and it will be necessary to use irrigation water much more efficiently. This may have implications for nutrient and weed management. Various technologies exist for improving water efficiency in rice. We need to be able to calculate what their adoption on individual farms would contribute to water efficiency on the broader scale of irrigation systems and water basins.

The following boxes give further details and our publications over the past 5 years. The corresponding projects in IRRI's Medium-Term Plan for 1998-2000 are indicated in brackets. See Appendix 1 for the list of projects by number.

**Box I1. Managing soil and fertilizer N**

Because fertilizer N applied to flooded soils may be rapidly lost by gaseous emission and by immobilization, mineral N levels go through boom-and-bust cycles following fertilization. Fertilizer N broadcast into floodwater can be absorbed very rapidly if timed carefully to match demand, but excessive uptake leads to increased risk of disease and lodging. This makes the balance with more slowly

**Publications**

Becker M, Ladha JK, Ottow JCG (1994) Nitrogen losses and lowland rice yield as affected by residue N release. Soil Sci. Soc. Am. J. 58:1660-1665.

Becker M, Ladha JK, Ottow JCG (1994) Parameters affecting residue N mineralization in flooded soils. Soil Sci. Soc. Am. J. 58:1666-1671.

Buresh RJ, Baanante CA (1993) Potential economic benefits of modifications to

released N from soil organic matter critical to overall efficiency. But fertilizer use and management by farmers apparently bear little relation to soil N reserves. Therefore, management tools are required for optimizing the use of soil and fertilizer N.

There is evidence that the decline in factor productivity observed at experiment stations under intensive rice cultivation is due to changes in N mineralization from soil reserves and/or greater immobilization of fertilizer N. Soil conditions are evidently shifting to a new steady state following intensification over the past 30 years. We do not yet know what the new steady state will be and do not understand the processes involved well enough to make predictions. In studying these processes, we have found an accumulation of phenolic compounds in soil organic matter under intensive rice cropping in different soils and under different climates, which we attribute to prolonged anaerobic soil conditions. Phenolic compounds can react strongly with nitrogenous compounds and we are examining the importance of such reactions in intensively cropped rice soils. In a preliminary study, soil N mineralization rates were correlated with the amounts and chemical nature of the younger of two humic acid fractions obtained from the soils. Rates of N uptake by crops in unfertilized plots were correlated with N mineralization rates measured in the same way.

To see if the decline in productivity could be reversed by increasing soil aeration, we have introduced a dry-season maize crop into one of the long-term double-cropped rice experiments at IRRI. After 3 years, the soil organic matter content has decreased significantly and there have been changes in soil N

urea that increase yield through reduction in nitrogen losses. Agron. J. 85:947-954.

Cassman KG, Gines GC, Dizon MA, Samson MI, Alcantara JM (1996) Nitrogen-use efficiency in tropical lowland rice systems: contributions from indigenous and applied nitrogen. Field Crops Res. 47:1-12.

Cassman KG, De Datta SK, Amarante ST, Liboon SP, Samson MI, Dizon MA (1996) Long-term comparison of agronomic efficiency and residual benefits of organic and inorganic nitrogen sources on irrigated lowland rice in the tropics. Expl. Agric. 32:427-444.

Cassman KG, Dobermann A, Sta. Cruz PC, Gines GC, Samson MI, Descalsota JP, Alcantara JM, Dizon MA, Olk DC (1996) Soil organic matter and the indigenous nitrogen supply of intensive irrigated rice systems in the tropics. Plant Soil 182:267-278.

Cassman KG, Kropff MJ, Gaunt J, Peng S (1993) Nitrogen use efficiency of irrigated rice: what are the key constraints? Plant Soil 155/156:359-362.

Cassman KG, Peng S, Olk DC, Ladha JK, Reichardt W, Dobermann A, Singh U (1998) Opportunities for increased nitrogen use efficiency from improved resource management in irrigated rice systems. Field Crops Res., in press.

Clement A, Ladha JK, Chalifour FP (1995) Crop residue effects of N mineralization, microbial biomass, and rice yield on submerged soil. Soil Sci. Soc. Am. J. 59:1595-1603.

Diekmann KH, De Datta SK, Ottow JCG (1993) Nitrogen uptake and recovery from urea and green manure in lowland rice measured by $^{15}N$ and non-isotope

relations: the short-term availability of fertilizer N to rice has increased, but mineralization of soil N has decreased. Also, the timing of crop residue incorporation affected subsequent rice growth, and this effect could be partially offset by N fertilizer additions. These effects appear to be due to processes other than short-term immobilization of N by microbes because the levels of available N in the soil are not altered, and the effects appear to be increasing over successive crops. Continuing research seeks to explain this.

We need a better understanding of how flooding-induced anoxia modulates soil organic matter transformations and N availability. Understanding dynamic systems such as this, in which a number of complex and interacting rate-processes are operating, calls for models. An adequate model of this system must account for the effects of oxygen and redox conditions, and it must be based on soil organic matter pools and properties that can be independently extracted and measured.

Further work is examining the effects of changes in soil inorganic constituents with intensification. There is evidence of an accumulation of ferrous iron in continuously flooded rice soils and an associated increase in the negative charge on soil particles. A consequence would be that the sorption of nutrient cations by the soil, particularly $NH_4$ and K, would increase, and hence their availability to plant roots would decrease. We are developing mathematical models of the consequences of this for $NH_4$ and K absorption by roots, including re-release of fixed cations by root-induced oxidation and acidification of the rhizosphere. **[IR2, IR3]**

techniques. Plant Soil 148:91-99.

Gaunt JL, Neue HU, Cassman KG, Olk DC, Arah JRM, Witt C, Ottow JCG, Grant IF (1994) Microbial biomass and activity in wetland rice soils. Biol. Fertil. Soils 19:333-342.

Kundu DK, Ladha JK, de Guzman LE (1996) Tillage depth influence on soil N distribution and availability in a rice lowland. Soil Sci. Soc. Am. J. 60:1153-1159.

Kundu DK, Ladha JK (1997) Effect of growing rice on N mineralization in flooded soil. Soil Sci. Soc. Am. J. 61:839-845.

Manguiat IJ, Mascarina GB, Ladha JK, Buresh RJ, Tallada J (1994) Prediction of nitrogen availability and rice yield in lowland soils: nitrogen mineralization parameters. Plant Soil 160:131-137.

Olk DC, Cassman KG, Mahieu N, Randall EW (1998) Conserved chemical properties of young humic acid fractions in tropical lowland soil under intensive irrigated rice cropping. Eur. J. Soil Sci., in press.

Olk DC, Cassman KG, Randall EW, Kinchlesh P, Sanger LJ, Anderson JM (1996) Changes in chemical properties of organic matter with intensified rice cropping in tropical lowland soil. Eur. J. Soil Sci. 47:293-303.

Rachhpal-Singh, Kirk GJD (1993) A model for predicting the fate of nitrogen fertilizer in lowland ricefields. I. Theory. J. Soil Sci. 44:271-283.

Rachhpal-Singh, Kirk GJD (1993) A model for predicting the fate of nitrogen fertilizer in lowland ricefields. II. Predicted dynamics of inorganic carbon, nitrogen and acidity in the soil and floodwater. J. Soil Sci. 44:285-297.

Reichardt W, Mascarina G, Padre B, Doll J (1997) Microbial communities of continuously cropped, irrigated ricefields. Appl. Environ. Microbiol. 63:233-238.

Schnier HF, De Datta SK, Fagi AM, Eaqub M, Ahmed F, Tejasarwana R, Mazid A (1993) Yield response of wetland rice to band placement of urea solution in various soils in the tropics. Fert. Res. 36:221-227.

Stalin P, Dobermann A, Cassman KG, Thiyagarajan TM, ten Berge HFM (1996) Nitrogen supplying capacity of lowland rice soils in southern India. Commun. Soil Sci. Plant Anal. 27:2851-2874.

Tran Thuc Son, Buresh RJ (1993) Incorporation of urea for transplanted rice as affected by floodwater and growing season. Fert. Res. 34:111-120.

Thiyagarajan TM, Stalin P, Dobermann A, Cassman KG, ten Berge HFM (1997) Soil N supply and plant N uptake by irrigated rice in Tamil Nadu. Field Crops Res. 51:55-64.

Timsina J, Singh U, Badaruddin M, Mesiner C (1998) Variety, nitrogen, and moisture effects in a rice-wheat sequence: experimentation and simulation. Agron. J., in press.

Watanabe I, Manguiat IJ, Mascarina G (1996) Nitrogen mineralization in tropical wetland rice soils. II. Application of exponential models. Soil Sci. Plant Nutr. 42:239-249.

Witt C, Cassman KG, Ottow JCG, Biker U (1998) Soil microbial biomass and nitrogen supply in an irrigated lowland rice soil as affected by crop rotation and residue management. Biol. Fertil. Soils, in press.

**Box I2. Increasing N efficiency of the plant**

We believe there is potential for improving both the efficiency of N absorption and the efficiency of its internal use by the plant. Although fertilizer N broadcast into ricefield floodwater is absorbed rapidly by roots at or near the soil surface if timed precisely to match plant demand, soil N and fertilizer N placed into the soil are absorbed less efficiently. Studies of maximum rates of influx into rice roots in hydroponic cultures maintained at realistic soil solution ammonium concentrations show that absorption will be rate-limiting following the initial boom in available N after fertilization.

Because N participates in all plant processes, it is difficult to separate efficiency from yield attributes in which N plays a part. Empirical selection is inadequate. We need to understand the mechanisms governing efficiency and to select for efficient biochemical or physiological pathways in phenotypes differing in other determinants of yield.

In recent collaboration, we have developed methods for studying at the cellular level the mechanisms controlling N absorption and assimilation. The work has shown that root transport systems for ammonium—thought to be the main form of N absorbed by rice in flooded soils—are suppressed for the most part and that there is often a substantial efflux of absorbed ammonium back out of root cells into the surrounding solution. With sufficient understanding of the molecular basis of these processes, it may be possible to increase the efficiency of absorption by manipulating the regulation of influx or decreasing efflux, and, as necessary, storing the additional N taken

**Publications**

Cassman KG (ed) (1994) Breaking the yield barrier. International Rice Research Institute, Manila.

Kirk GJD (ed.) (1994) Rice roots: nutrient and water use. International Rice Research Institute, Manila.

Kirk GJD, Solivas JL (1997) On the extent to which root properties and transport through the soil limit nitrogen uptake by lowland rice. Eur. J. Soil Sci. 48:613-621.

Kronzucker HJ, Kirk GJD, Siddiqi MY, Glass ADM (1998) Effects of hypoxia on $^{13}NH_4^+$ fluxes in rice roots: kinetics and compartmental analysis. Plant Physiol., in press.

Kronzucker HJ, Kirk GJD, Siddiqi MY, Glass ADM (1998) Nitrate fluxes and compartmentation in rice roots: a N-13 study. Plant Physiol., in press.

Ladha JK, Kirk GJD, Peng S, Reddy K, Singh U, Bennett J (1998) Opportunities for increased nitrogen use efficiency from improved rice germplasm in lowland rice ecosystems. Field Crops Res., in press.

Padre AT, Ladha JK, Singh U, Laureles E, Punzalan G, Akita S (1996) Grain yield performance of rice genotypes at suboptimal levels of soil N as affected by N uptake and utilization efficiency. Field Crops Res. 46:127-143.

Peng S, Cassman KG (1998) Nitrogen uptake of tropical rice. I. Quantification of maximum rate and recovery efficiency. Agron. J., in press.

Singh U, Ladha JK, Castillo EG, Punzalan G, Tirol-Padre A (1998) Genotypic variation in nitrogen use efficiency in medium and long duration rice. Field Crops Res., in press.

Shrestha RK, Ladha JK (1996) Estimation of rice genotypic variation in

up in cell vacuoles. It may also be possible to alter the form in which N is transported to the shoot so as to reduce the dependence of ammonium assimilation on the supply of carbon skeletons.

In addition, it may be possible to manipulate the absorption and assimilation of N forms other than ammonium. There is evidence of a yield advantage in absorption of nitrate by rice and it may be possible to enhance nitrate absorption from the aerobic floodwater-soil interface or its formation and absorption in the rhizosphere. It is also likely that some N is absorbed directly as amino acids: concentrations of amino acids in flooded soil solutions can be comparable to ammonium concentrations and studies of sterile nutrient solution cultures show that rice roots can absorb amino acids directly. This has interesting implications for efficient uptake of N mineralized from soil organic matter, which may be better in traditional cultivars than in modern cultivars bred for fertilizer-responsiveness, and for energy savings in N acquisition under high-yielding conditions.

**[IR1, IR2]**

$N_2$ fixation by $^{15}N$ dilution using $^{15}N$ stabilized soil. Soil Sci. Soc. Am. J. 60:1815-1821.

Wu P, Zhang G, Ladha JK, McCouch S, Huang N (1995) Molecular-marker-facilitated investigation on the ability to stimulate $N_2$ fixation in the rhizosphere by irrigated rice plants. Theor. Appl. Genet. 91:1177-1183.

Ying J, Peng S, Zhou N, Yang C, Visperas RM, Cassman KG (1998) Comparison of rice yield potential in temperate and tropical environments. III. Nitrogen accumulation and utilization efficiency. Field Crops Res., in press.

**Box 13. Increasing rice-related $N_2$ fixation**

Of the various biological N fixation systems in ricefields, free-living blue-green algae can fix useful amounts of N—10–140 kg ha$^{-1}$ year$^{-1}$—but the N is subject to high rates of loss by gaseous emission, and fixation is inhibited when N fertilizers are applied. Nitrogen fixed by plants incorporated into the soil—e.g., grain legumes grown before or after the rice, legume green manures, and *Azolla-Anabaena*—is used more efficiently and such systems have been shown to substantially reduce mineral N fertilizer

**Publications**

Becker M, Ladha JK, Ali M, (1995) Green manure technology potential, usage and limitations: a case study for lowland rice. Plant Soil 174:181-194.

Becker M, Ali M, Ladha JK, Ottow JCG (1995) Agronomic and economic evaluation of *Sesbania rostrata* green manure establishment in irrigated rice. Field Crops Res. 40:135-141.

Becker M, Ladha JK (1996) Adaptation of green manure legumes to adverse conditions in rice lowlands. Biol. Fertil. Soils 23:243-248.

Barraquio WL, Revilla L, Ladha JK

requirements at all yield levels. But in most situations, these systems are not economically viable. We are currently exploring the possibility of incorporating the machinery of N fixation in the rice plant itself.

Opportunities for this have been created by advances in the understanding of endosymbiotic associations with plants and of *Rhizobium*-legume interactions at the molecular level, and in techniques for introducing new genes into rice by transformation. In collaboration with various institutions, we have made exploratory studies on nodular and non-nodular associations. We have identified rice genotypes harboring various endophytic diazotrophs, and found in rice at least part of the genetic machinery for nodulation in legumes. We are screening rhizobial and non-rhizobial endophytes for abilities to colonize rice roots, fix N, and promote rice growth. We are continuing to study the presence and expression of legume nodulation genes in rice.

**[CE3]**

(1997) Isolation of endophytic diazotrophic bacteria from wetland rice. Plant Soil 194:15-24.

Kundu DK, Ladha JK (1995) Enhancing soil nitrogen use and biological nitrogen fixation in wetland rice. Expl. Agric. 31:261-277.

Kundu DK, Ladha JK (1995) Efficient management of soil and biologically fixed nitrogen in intensively-cultivated rice fields. Soil Biol. Biochem. 27:431-439.

Ladha JK, So R (1994) Numerical taxonomy of photosynthetic rhizobia nodulating *Aeschynomene* species. Int. J. Syst. Bacteriol. 44:62-73.

Reddy PM, Ladha JK, So R, Hernandez R, Dazzo FB, Angeles OR, Ramos C, de Bruijn FJ (1997) Rhizobial communication with rice roots: induction of phenotypic changes, mode of invasion and extent of colonization. Plant Soil 194:81-98.

Roger PA (1996) Biology and management of the floodwater ecosystem in ricefields. IRRI/ORSTOM, Manila.

Shrestha RK, Ladha JK (1996) Genotypic variation in promotion of rice dinitrogen fixation as determined by nitrogen-15 dilution. Soil Sci. Soc. Am. J. 60:1815-1821.

So RB, Ladha JK, Young JPW (1994) Photosynthetic symbionts of *Aeschynomene* spp. form a cluster with Bradyrhizobia on the basis of fatty acid and rRNA analyses. Int. J. Syst. Bacteriol. 44:392-403.

Stoltzfus, S, So R, Malarvizhi M, Ladha JK, de Bruijn FJ (1997) Isolation of endophytic bacteria from rice and assessment of their potential for supplying rice with biologically-fixed nitrogen. Plant Soil 194:25-36.

Torres RO, Pareek RP, Ladha JK, Garrity, DP. (1995) Stem-nodulating legumes as relay-cropped or intercropped green manures for lowland rice. Field Crops Res. 42:39-47.

Ventura W, Watanabe I (1993) Green manure production of *Azolla microphylla* and *Sesbania rostrata* and their long-term effects on rice yields and soil fertility. Biol. Fertil. Soils 15:241-248.

Ventura W, Ladha JK (1997) *Sesbania* phosphorus requirements when used as a biofertilizer for long-term rice cultivation. Soil Sci. Soc. Am. J. 61:1240-1244.

Wong FYK, Stackebrandt E, Ladha JK, Fleischman DE, Date RA, Fuerst JA (1994) Phylogenetic analysis of *Bradyrhizobium japonicum* and photosynthetic stem-nodulating bacteria from *Aeschynomene* species grown in separated geographical regions. Appl. Environ. Microbiol. 60:940-946.

**Box I4. Deficiencies of nutrients other than N**

Annual removals of P, K, S, and Si in harvested grain and straw have greatly increased over the past 30 years, but inputs of fertilizers, particularly K, have not increased in proportion. In part, this is because K is expensive and most Asian countries lack commercially exploitable deposits and depend on imports. Also, there is evidence of a decline in the efficiency of K fertilizer recovery in long-term trials, independent of changes in the efficiency of N and other nutrients. Deficiencies of K are now one of the major causes of the gap between average and attainable farm yields. But our understanding of the chemistry of K in flooded soils and of the factors influencing

**Publications**

Cassman KG, Peng S, Dobermann A (1997) Nutritional physiology of the rice plant and productivity decline of irrigated lowland rice systems in the tropics. Soil Sci. Plant Nutr. 43:1111-1116.

Dobermann A (1994) Factors causing field variation of direct-seeded flooded rice. Geoderma 62:125-150.

Dobermann A, Cassman KG, Mamaril CP, Sheehy JE (1998) Management of phosphorus, potassium and sulfur in intensive irrigated lowland rice. Field Crops Res., in press.

Dobermann A, Sta. Cruz PC, Cassman KG (1996) Fertilizer inputs, nutrient balance, and soil nutrient-supplying power in intensive, irrigated rice

its plant-availability is weak. We need a better understanding if we are to improve efficiency.

Areas for research include the factors governing release from slowly exchanging sites in clays in flooded soils; interactions between soil physical properties following puddling and rates of K transport to root surfaces—there is evidence of changes in soil bulk density with double- and triple-rice cropping; effects of root-induced changes in the soil on K availability, particularly root-induced acidification as a result of iron oxidation and ammonium nutrition; effects of changes in cation ratios with cropping, e.g., K/(Ca+Fe).

Straw management is critical to ricefield K budgets. As mechanical power becomes more widely available, it will be possible to manage straw better. In most Asian countries, straw is burned or removed for forage or fuel to reduce the turnaround time between crops; nutrients, particularly K, are thereby wasted. Because of the lack of mechanical power, options for better straw management have not received much attention. Interactions with water management and weeds and diseases also need to be considered.

**[IR2, IR3]**


systems. I. Potassium uptake and K balance. Nutr. Cycl. Agroecosys. 46:1-10.

Dobermann A, Cassman KG, Sta. Cruz PC, Adviento MAA, Pampolino MF (1996) Fertilizer inputs, nutrient balance, and soil nutrient-supplying power in intensive, irrigated rice systems. II. Effective soil K-supplying capacity. Nutr. Cycl. Agroecosys. 46:11-21.

Dobermann A, Cassman KG, Sta. Cruz PC, Adviento MAA, Pampolino MF (1996) Fertilizer inputs, nutrient balance, and soil nutrient-supplying power in intensive, irrigated rice systems. III. Phosphorus. Nutr. Cycl. Agroecosys. 46:111-125.

Olk DC, Cassman KG, Carlson RM (1995) Kinetics of potassium fixation in vermiculitic soil under different moisture regimes. Soil Sci. Soc. Am. J. 59:423-429.


**Box I5. Tools for site-specific nutrient management**

We are trying to synthesize our knowledge and understanding of how best to manage nutrients in a set of diagnostic tools and fertilizer recommendation models aimed at extension agents and sophisticated farmers. This set will include methods for predicting the supply of N, P, and K from soil reserves; a fertilizer recommendation and nutrient balance model; a model for optimizing N applications; and tools for optimizing the timing of N applications

**Publications**


Dobermann A, Gaunt JL, Neue HU, Grant IF, Adviento MA, Pampolino MF (1994) Spatial and temporal variability of ammonium in flooded ricefields. Soil Sci. Soc. Am. J. 58:1708-1717.

Dobermann A, Langner H, Mutscher H, Skogley EO, Neue HU, Yang JE, Adviento MA, Pampolino MF (1994) Nutrient adsorption kinetics of ion exchange resin capsules: a study with soils of international origin. Commun. Soil Sci. Pl. Anal. 25:1329-1353.

based on field monitoring with a chlorophyll meter or leaf color chart.

The fertilizer recommendation model is based on the QUEFTS model developed at Wageningen. It predicts nutrient uptake and grain yield from chemical soil fertility indices based on (a) climate-dependent relations between grain yield and N, P, and K uptake, and (b) relations between N, P, and K uptake and measures of their addition in fertilizer, their recovery from fertilizer, and their supply from soil reserves. The latter part is proving the most problematic, particularly for N. We are exploring various soil test measurements for this and the use of fertilizer-omission trials. We have established reasonably robust empirical relations between nutrient uptake and grain yield from a database with 1,500 entries covering yields between 2 and 10 t $ha^{-1}$ in a wide range of environments. The model and associated measurement schemes will be tested in experiments over several years.

**[IR2, IR3, IM2]**

Dobermann A, Oberthuer T (1997) Fuzzy mapping of soil fertility - a case study on irrigated riceland in the Philippines. Geoderma 77:317-339.

Dobermann A, Pampolino MF, Neue HU (1995) Spatial and temporal variation of transplanted rice at the field scale. Agronomy J. 87:712-720.

Dobermann A, Pampolino MF, Adviento MAA (1997) Resin capsules for on-site assessment of soil nutrient supply in lowland rice fields. Soil Sci. Soc. Am. J. 61:1202-1213.

Jimenez RR, Ladha JK (1993) Automated elemental analysis: a rapid and reliable but expensive measurement of total carbon and nitrogen in plant and soil samples. Commun. Soil Sci. Plant Anal. 24:1897-1924.

Oberthuer T, Dobermann A, Neue HU (1996) How good is a reconnaissance soil map for agronomic purposes? Soil Use Manage. 12:33-43.

Peng S, Laza MRC, Garcia FV, Cassman KG (1994) Microwave-oven drying of rice leaves for rapid determination of dry weight and nitrogen concentration. J. Plant Nutr. 17:209-217.

Peng S, Garcia FV, Laza RC, Sanico AL, Visperas RM, Cassman KG (1996) Increased N-use efficiency using a chlorophyll meter on high-yielding irrigated rice. Field Crops Res. 47:243-252.

Skogley E O, Dobermann A (1996) Synthetic ion-exchange resins - soil and environmental studies. J. Environ. Qual. 25:13-24.

**Box I6. Increasing irrigation-water productivity**

We need to produce more rice with less water. We have identified various novel practices for increasing water efficiency at the farm level. These include reducing losses during land preparation and crop growth, and reducing water demand during crop establishment through direct-seeding. These practices have not yet been adopted much beyond experimental and small-scale areas, and we are not able to predict how their wider adoption would improve water use efficiency over irrigation systems or water basins. Large-scale adoption will entail changes in water control in supply canals, and changes in labor inputs, institutional arrangements, weed and fertilizer management, and on-farm infrastructures, and may be costly. For such changes to be made, it will be necessary to demonstrate quantitatively that large-scale adoption of water-saving practices will lead to economic benefits. The challenges are to integrate novel practices into usable technologies, to identify where they are most likely to be successful, and to implement them in such a way as to increase water efficiency over whole systems. For this, it will be necessary to quantify the off-site effects of novel practices.

In collaboration with IIMI, under the auspices of the CGIAR Systemwide Initiative in Water Management, we are developing methodologies to account for water transfer among different components of irrigation systems and to evaluate water balances and water productivity at farm, irrigation system, and basin levels. This will involve a combination of field monitoring, dynamic simulation modeling, and GIS techniques. Continuing research aims to identify

**Publications**


Bhuiyan SI (1993) Irrigation sustainability in rice-growing Asia. Can. Water Res. J. 18:39-52.

Bhuiyan SI, Sattar MA, Khan MAK (1995) Improving water use efficiency in rice irriga- tion through wet-seeding. Irrig. Sci. 16:1-8.

Bouman BAM, Wopereis MCS, Kropff MJ, Tuong TP (1994) Understanding the water use efficiency of flooded rice fields. II. Percolation and seepage losses. Agric. Water Manage. 26:291-304.

Moody K (ed.) (1996) Constraints, opportunities and innovations for wet-seeded rice. IRRI Discussion Paper Series No 10. International Rice Research Institute, Manila.

Tuong TP, Cabangon R, Wopereis MCS (1996) Quantifying flow processes during land soaking of cracked rice soils. Soc. Soil Sci. Am. J. 60:872-879

Tuong TP, Wopereis MCS, Marquez JA, Kropff MJ (1994) Mechanisms and control of percolation losses in irrigated puddled rice fields. Soil Sc. Soc. Am. J. 58:1794-1803.

Wopereis MCS, Bouman BAM, Kropff MJ, ten Berge HFM, Maligaya AR (1995) Understanding the water use efficiency of flooded rice fields. I. Validation of the soil water balance model SWAH. Agric. Water Manage. 26:277-289.

possible policy and institutional reforms that will facilitate wide-scale implementation of water-saving strategies. **[IR4]**

**Box I7. Effects of agrochemicals on soil and water quality**

Water and labor scarcities throughout Asia are forcing a shift from transplanting of rice to less labor-intensive direct-seeding, either on wet, puddled soils prepared as for transplanting, or on dry, tilled soils prepared as for other cereals. Because weed control in direct-seeded rice is more difficult than in transplanted rice, a consequence of this will be a far greater use of herbicides. Also, in many areas, rice farmers are diversifying into high-value upland crops during the dry season in response to increasing water scarcity and decreasing profitability of rice. These new cropping patterns also require high chemical inputs and we have found a high degree of groundwater pollution in rice-wheat and rice-vegetable systems. But our understanding of the effects of agrochemicals on soil fertility and nutrient cycling in flooded intensively cropped rice soils is poor. We also lack tools for monitoring agrochemical effects in the broader environment.

Continuing research at IRRI is assessing the long-term effects of agrochemical use on soil fertility through its effects on biological diversity. It is generally supposed that diversity among soil microorganisms and invertebrates is important for maintaining soil fertility, diversity being equated with stability. It is also widely supposed that with intensification and increasing use of chemicals, population diversity has declined. But there are few irrefutable data with which to test these hypotheses. In

**Publications**

Castañeda AR, Bhuiyan SI (1995) Sediment pollution in a gravity irrigation system and its effects on rice production. Agric. Ecosys. Environ. 45:195-202.

Castañeda AR, Bhuiyan SI (1996) Groundwater contamination by ricefield pesticides and some influencing factors. J. Environ. Sci. Health A31:83-90.

Gumtang RJ, Pampolino MF, Tuong TP (1998) Ground water dynamics and quality under intensive cropping systems. Expl. Agric., in press.

Pingali PL, Roger PA (eds) (1996) Impact of pesticides on farmer health and the rice environment. Kluwer, Dordrecht.

Roger PA, Simpson IC, Official R, Ardales S, Jiminez R (1994) Effects of pesticides on soil and water microflora and mesofauna in wetland ricefields: a summary of current knowledge and extrapolation to temperate environments. Aust. J. Expl. Agric. 34:1057-1068.

Simpson IC, Roger PA, Oficial R, Grant IF (1993) Impacts of agricultural practices on aquatic oligochaete populations in ricefields. Biol. Fertil. Soils 16:27-33.

Simpson IC, Roger PA, Oficial R, Grant IF (1993) Density and composition of aquatic oligochaete populations in different farmers' fields. Biol. Fertil. Soils 16:34-40.

Simpson IC, Roger PA, Oficial R, Grant IF (1994) Effects of nitrogen fertilizer and pesticide management on

terms of soil fertility, the greatest importance of biological diversity is to nitrogen fixation and mineralization of soil organic matter. We are using various techniques for measuring microbial functional diversity, including community-level C source assays and membrane lipid signature compound analyses, and testing whether changes in these assays indicate changes in soil fertility. We are also using sensitive enzyme assays to monitor surface runoff and groundwater for ecotoxic effects of herbicides and pesticides.

We are also investigating strategies for mimimizing herbicide use in direct-seeded crop establishment. These include the use of more weed-competitive cultivars and judicious but weed-suppressing water management during early rice growth.

**[IR4]**

floodwater ecology in a wetland ricefield. I. Experimental design and dynamics of the photosynthetic aquatic biomass. Biol. Fertil. Soils 17:129-137.

Simpson IC, Roger PA, Oficial R, Grant IF (1994) Effects of nitrogen fertilizer and pesticide management on floodwater ecology in a wetland ricefield. II. Dynamics of microcrustaceans and dipteran larvae. Biol. Fertil. Soils 17:138-146.

Simpson IC, Roger PA, Oficial R, Grant IF (1994) Effects of nitrogen fertilizer and pesticide management on floodwater ecology in a wetland ricefield. III. Dynamics of benthic molluscs. Biol. Fertil. Soils 17: 219-227.

**Box I8. Consequences of rice production for the global environment**

Research at IRRI over the past 5 years has quantified emissions of the greenhouse gas methane from irrigated ricefields and other rice ecosystems, and the factors governing these. Though extrapolation from these measurements to the regional scale and beyond is problematic, these measurements indicate that ricefields account for some 12% of total global emissions, which is somewhat lower than originally feared. We are continuing to refine these measurements and to develop management options to reduce emissions, including the possibility of modifying the plant. Management options that reduce emissions to some extent conflict with options for efficient nutrient management, for example, in the management of straw. We are also collaborating in studies of the

**Publications**

Alberto MCR, Neue HU, Lantin RS, Aduna JB (1996) Determination of soil-entrapped methane. Commun. Soil Sci. Plant Anal. 27:5-6.

Bachelet D, Neue HU (1993) Methane emissions from wetland rice areas of Asia. Chemosphere 26:219-237.

Bronson KF, Neue HU, Singh U, Abao EB (1997) Automated chamber measurements of methane and nitrous oxide flux in a flooded rice soil. I. Residue, nitrogen, and water management. Soil Sci. Soc. Am. J. 61:981-987.

Bronson KF, Singh U, Neue HU, Abao EB (1997) Automated chamber measurements of methane and nitrous oxide flux in a flooded rice soil. II. Fallow period emissions. Soil Sci. Soc. Am. J. 61:988-993.

extent to which natural and managed upland soils are sinks for methane.

The demand for increased rice production is putting pressure on as yet uncultivated natural wetlands in large parts of Asia and Latin America. Natural wetlands are important regulators of regional water balances, as well as being reservoirs of plant and animal biodiversity. They are also important as sinks for carbon. Large-scale conversion of wetlands to irrigated agriculture may therefore have serious consequences for the environment. We are starting work aimed at identifying critical areas, assessing consequences of their conversion, and developing options under which rice and natural wetlands could coexist.

**[IR6]**

Buendia LV, Neue HU, Wassmann R, Lantin RS, Javellana AM, Arah J, Lu W, Wang X, Makarim K, Corton T, Chareonsilp N (1997) Understanding the nature of methane emission from rice ecosystems as basis of mitigation strategies. Appl. Energy 56:433-444.

Buendia LV, Neue HU, Wassmann R, Lantin RS, Javellana AM, Arah J, Lu W, Wang X, Makarim K, Corton T, Chareonsilp N (1998) An efficient sampling strategy for estimating methane emission from rice to assess the impact of potential mitigation options. Chemosphere 36:395-407.

Denier van der Gon HAC, Neue HU (1994) Impact of gypsum application on the methane emission from a wetland rice field. Global Biogeochem. Cycles 8:127-134.

Denier van der Gon HAC., Neue HU (1995) Influence of organic matter incorporation on the methane emission from a wetland rice field. Global Biogeochem. Cycles 9:11-22.

Denier van der Gon HAC, Neue HU (1995) Methane emission from a wetland rice field as affected by salinity. Plant Soil 170:307-313

Denier van der Gon HAC, Neue HU (1995) Oxidation of methane in the rhizosphere of rice plants. Biology Fertil. Soils 22:359-366.

Denier van der Gon HAC, van Breemen N, Neue HU, Lantin R S, Aduna J B, Alberto MCR, Wassmann R (1996) Release of entrapped methane from wetland rice fields upon soil drying. Global Biogeochem. Cycles 10:1-7.

Neue HU, Lantin RL, Alberto MCR, Aduna JB, Javellana MA, Wassmann R (1996) Factors affecting methane emission from rice fields. Atmos. Environ. 30:1751-1754.

Peng S, Ingram KT, Neue HU, Ziska LH (eds) (1995) Climate change and rice. Springer-Verlag, Berlin Heidelberg.
Simpson IJ, Thurtell GW, Kidd GE, Lin M, Demetriades-Shah TH, Flitcroft I, Kanemasu ET, Nie D, Bronson K, Neue HU (1995) Tunable diode laser measurements of methane fluxes from an irrigated rice field in the Philippines. J. Geophys. Res. 100, D4:7283-7290.
Wassmann R, Neue HU, Alberto MCR, Lantin RS, Bueno C, Llenaresas D, Arah JRM, Papen H, Seiler W, Rennenberg H (1996) Fluxes and pools of methane in wetland rice soils with varying organic inputs. Environm. Monit. Assessm. 42:163-173.
Wassmann R, Neue HU, Lantin RS, Aduna JB, Alberto MCR, Flores MJ, Tan MJP, Denier van der Gon HAC, Hoffmann H, Papen H, Rennenberg H, Seiler W (1994) Temporal patterns of methane emissions from wetland rice fields treated by different modes of N-application. J. Geophys. Res. 99:16457-16462.
Wassmann R, Shangguan XJ, Tölg M, Cheng DX, Wang MX, Papen H, Rennenberg H, Seiler W (1996) Spatial and seasonal distribution of organic amendments affecting methane emission from Chinese rice fields. Biol. Fertil. Soils 22:191-195.

## Rainfed lowland and flood-prone rice ecosystems

We discussed the irrigated ecosystem in terms of yield gaps set by the limits of the current best germplasm and management and farmers' practical constraints. By definition, water is not a constraint to yields in irrigated systems, but for rainfed systems, it implicitly is a constraint—either in excess or deficit or both—and this complicates an analogous discussion of yield gaps. Apart from the effects of water stress per se, there are large interactions between water and nutrient availability, and fluctuating water regimes create particular problems for managing nutrients. Severe losses of N occur through denitrification and leaching of nitrate when aerobic soil is flooded, and through volatilization of ammonia from floodwater and microbial and nonmicrobial immobilization. Alternate reduction and oxidation as water levels fluctuate also lead to occlusion of phosphate in iron oxides. Also, nutrient stresses may delay crop development, thus exposing the crop to water stress later on. Water stresses are therefore often compounded by nutrient stresses and to some extent they may be alleviated by overcoming the nutrient stresses. But it is difficult with existing information to quantify the prospects for this over the range of soil types, cultural practices, and seasonal conditions found in rainfed lowland systems.

Nonetheless, it is useful to consider yield gaps analogous to those in the irrigated system. The gap between yields with the current best germplasm and absolute yield potentials given climate and water constraints is large. Because the environment is risky, farmers grow traditional photoperiod-sensitive cultivars that are hardy but have low yield potentials and do not respond to fertilizers; the first yield gap is set by these traditional cultivars. In developing improved cultivars, it is important to retain the tolerance of the traditional cultivars of drought, floods, and soil stresses. The improved cultivars need to both perform well under favorable conditions and to at least equal the performance of traditional cultivars under adverse conditions.

With progress in tackling the first yield gap, the adoption of improved management practices will increase. Particularly, there should be a much greater use of fertilizers. Because of the difficulties in N management under fluctuating water regimes, slow-release N fertilizers have a particular niche in rainfed systems. Because costs are currently prohibitive, we need to quantify the potential impact of such fertilizers in rainfed systems to stimulate the private sector into establishing fertilizer plants.

Based on our judgment of the importance of the constraint and the opportunities for making advances, we have focused breeding work for tolerance of adverse soil conditions on improved P and Zn efficiencies and tolerance of Fe toxicity. In focusing on P, our intention is not to provide plants for better mining of native soil P reserves, which is inherently unsustainable. Our aim is to develop plants that are efficient at extracting soil and fertilizer P so as to provide farmers with more incentive to use fertilizer and gradually build up soil reserves.

**Box R1. Interactions between water and nutrient stresses**

We need to quantify the relative importance of water and nutrient stresses as constraints to yield and yield stability in different environments, as a basis for resource management. In a three-year experiment at 30 drought- and submergence-prone sites in the Rainfed Lowland Rice Research Consortium, we found strong interactions between the two stresses. We are applying crop growth models that calculate yield potentials as

**Publications**

Ram PC, Singh BB, Singh VK, Singh HP, Setter TL, Singh VP, Singh RK (1998) Environmental characterization of floodwater in Eastern India: relevance to submergence tolerance of lowland rice. Expl. Agric., in press.

Rama Krishnayya G, Setter TL, Sarkar RK, Krishnan P, Ravi I (1998) Influence of P application to floodwater on oxygen concentrations and survival of rice during complete submergence. Expl. Agric., in press.

functions of climate and water limitations to these sites, and initial indications are that they work reasonably well for the more fertile environments. But in marginal areas, they are wholly inadequate. We now seek to develop models that can take into account nutrient limitations and their interactions with water excess and deficit.

Our approach is based on obtaining two key relationships: that between soil nutrient supply and plant nutrient uptake as affected by soil moisture status; and that between plant nutrient uptake and grain yield as affected by soil moisture status. We have designed experiments to be made at different Consortium sites to obtain these relationships. The experiments will measure the extent to which improved soil nutrient status reduces yield losses due to drought and submergence; the dynamics of soil nutrient release and the associated relationship between potential soil nutrient supply and actual nutrient uptake as affected by soil moisture regime; and the relationship between nutrient uptake and yield as affected by soil moisture regime. **[RL2]**

Tuong, TP, Ingram KT, Siopongco JD, Confesor RB, Boling AA, Singh U, Wopereis MCS (1995) Performance of dry seeded rainfed lowland rice in response to agrohydrology and N fertilizer management. In: Ingram KT (ed.) Rainfed lowland rice - agricultural research for high risk environments. International Rice Research Institute, Manila. p 141-155.

Wade LJ, George T, Ladha JK, Singh U, Bhuiyan SI, Pandey S (1998) Opportunities to manipulate nutrient by water interactions in rainfed lowland rice systems. Field Crops Res., in press.

Wopereis MCS, Bouman BAM, Tuong TP, ten Berge HFM, Kropff MJ (1996) ORYZA_W: Rice growth model for irrigated and rainfed environments. SARP Research Proceedings. Wageningen Agricultural University, Netherlands and International Rice Research Institute, Manila.

**Box R2. Conservation of soil and fertilizer N**

A common cropping sequence in the rainfed lowlandsi s wet-season rice followed by a dry-season upland crop on residual soil moisture or supplemental irrigation, followed by a 60–70-day fallow during the dry-to-wet transition. Alternate soil wetting and drying in this system create particular difficulties for N conservation. Soil N mineralized and nitrified at the onset of rains in the fallow may be lost by leaching and by denitrification when the soil becomes submerged. Commonly high-value vegetable crops are grown in the dry season

**Publications**

Buresh RJ, Chua TT, Castillo EG, Liboon SP, Garrity DP (1993) Fallow and *Sesbania* effects on soil nitrogen dynamics in lowland rice-based cropping systems. Agron. J. 85:316-321.

Buresh RJ, Garrity DP, Castillo EG, Chua TT (1993) Fallow and *Sesbania* effects on response of transplanted lowland rice to urea. Agron. J. 85:801-808.

George T, Ladha JK, Buresh RJ, Garrity DP (1993) Nitrate dynamics during the aerobic soil phase in lowland rice-

with heavy applications of fertilizers, leaving substantial amounts of residual nitrate in the soil. This situation leads to large losses of N before the wet-season rice is established.

We have been studying N balances in an intensified rainfed lowland system of this sort in the Philippines. In studies in farmers' fields, N losse sranged from 240 kg ha$^{-1}$ year$^{-1}$ with a dry-season tobacco crop to 575 kg ha$^{-1}$ year$^{-1}$ with a sweet pepper crop. Much of this N found its way into groundwater: in the sweet pepper areas, some 50% of wells sampled had $NO_3$-N concentrations exceeding WHO limits. Continuing research aims to quantify the contributions of the various pathways involved in these losses and to develop means of alleviating them. We are examining the use of managed weedy fallows to capture $NO_3$-N generated in the fallow or left over from upland crops, the weeds being incorporated into the soil for the wet-season rice crop.

**[RL2]**

based cropping systems. Soil Sci. Soc. Am. J. 57:1526-1532.

George T, Ladha JK, Garrity DP, Buresh RJ (1994) Legumes as nitrate catch crops during the dry-to-wet transition in lowland rice cropping systems. Agron. J. 86:267-273.

George T, Ladha JK, Garrity DP, Torres R (1995) Nitrogen dynamics of grain legume - weedy fallow - flooded rice sequences in the tropics. Agron. J. 87:1-6.

Ladha JK, Kundu DK, van Coppenolle MGA, Peoples MB, Carangal VR, Dent PJ (1996) Legume productivity and soil nitrogen dynamics in lowland rice-based cropping systems. Soil Sci. Soc. Am. J. 60:183-192.

Triphati BP, Ladha JK, Timsina J, Pascua SR (1997) Nitrogen dynamics and balance in intensified rainfed lowland rice-based cropping systems. Soil Sci. Soc. Am. J. 61:812-821.

**Box R3. Germplasm tolerance of mineral deficiencies and toxicities**

This research is aimed at developing molecular markers for component traits for use in breeding programs. Our approach is two-pronged. For P and Zn efficiencies, we are drawing on the results of germplasm screening experiments made over many years at IRRI and elsewhere. We are compiling a database combining the results of screening trials and multilocational yield trials with which to (a) better quantify the genetic variation in efficiency, (b) quantify yield costs and benefits of efficiency at different stress levels, and (c) identify parents of germplasm with desirable traits and, where these parents are already being used to develop mapping populations, to

**Publications**

Begg CBM, Kirk GJD, MacKenzie AF, Neue HU (1994) Root-induced iron oxidation and pH changes in the lowland rice rhizosphere. New Phytol. 128:469-477.

Bode K, Döring O, Lüthje S, Neue HU, Böttger M (1995) The role of active oxygen in iron tolerance of rice. Protoplasma 184:249-255.

Hedley MJ, Kirk GJD, Santos MB (1994) Phosphorus efficiency and the forms of soil phosphorus utilized by upland rice cultivars. Plant Soil 158:53-62.

Kirk GJD, Bajita JB (1995) Root-induced iron oxidation, pH changes and zinc solubilization in the

tag the genes of interest.

Our second approach depends on obtaining a sufficient understanding of the mechanisms governing nutrient efficiency and toxicity tolerance to develop simple mechanism-based screening techniques. These will then be used to identify molecular markers. We are making good progress in this. For Fe toxicity, we have mapped a single major gene controlling tissue tolerance of Fe toxicity, in collaboration with Zhejiang Agric. Univ., China. The mechanism appears to involve enhanced scavenging for $OH^-$ radicals that are formed in $Fe^{2+}$ oxidation in the shoot, and molecular markers for the enzymes involved in this coincide with those for the putative Fe toxicity tolerance gene. We have also identified differences between lines in Fe exclusion from roots; this confers moderate tolerance of toxicity. Continuing research has shown that, in nutrient-deficient Fe toxic soils, Fe exclusion by oxidation in the rhizosphere will lead to impaired uptake of K by the roots, and for these conditions high tissue tolerance is required rather than exclusion ability.

For P deficiency, we have found molecular markers for tolerance of low P within the plant based on screening in nutrient cultures. We are extending this to soil-grown plants to obtain markers for efficient P acquisition. We have established mechanisms for P acquisition in (a) anaerobic soil and (b) aerobic, highly weathered soil or re-oxidized anaerobic soil. In anaerobic soil, rice can solubilize P and thereby increase its P uptake by oxidation and acidification of the rhizosphere. In aerobic soil, rice can solubilize P by exporting organic acids from the roots. With a mathematical model that allows for rates of organic acid release

rhizosphere of lowland rice. New Phytol. 131:129-137.

Kirk GJD, Du Le Van (1997) Changes in rice root architecture, porosity, and oxygen and proton release under phosphorus deficiency. New Phytol. 135:191-200.

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., in press.

Kirk GJD, Saleque MA (1995) Solubilization of phosphate by rice plants growing in reduced soil: prediction of the amount solubilized and the resultant increase in uptake. Eur. J. Soil Sci. 46:247-255.

Kirk GJD, Solivas JL (1994) Coupled diffusion and oxidation of ferrous iron in soils. III. Further development of the model and experimental testing. Eur. J. Soil Sci. 45:369-378.

Neue HU, Quijano C, Senadhira D, Setter TL (1998) Strategies for dealing with micronutrient disorders and salinity in rice systems. Field Crops Res., in press.

Saleque MA, Kirk GJD (1995) Root-induced solubilization of phosphate in the rhizosphere of lowland rice. New Phytol. 129:325-336.

Senadhira D (ed.) (1994) Rice and problem soils in South and Southeast Asia. International Rice Research Institute, Manila.

Senadhira D, Neue HU, Akbar M (1994) Development of improved donors for salinity tolerance in rice through somaclonal variation. SABRAO J. 26:19-25.

Singh VP, Singh RK, Singh BB, Zeigler RS (eds) (1996) Physiology of stress

from roots, their P-solubilizing effects, and their longevity in the rhizosphere, we have shown that observed rates of release are sufficient to account for observed rates of solubilization and uptake. We are attempting to explain germplasm differences with these mechanisms.

For Zn efficiency, we have identified cultivars differing in internal and external efficiencies, and we have established mechanisms for Zn solubilization in the rhizosphere.

**[RL3, FP2]**

tolerance in rice. NDUAT, Faisabad, India and International Rice Research Institute, Manila.

Wu P, Luo A, Zhu J, Yan J, Huang N, Senadhira D (1997) Molecular markers linked to genes underlying seedling tolerance for ferrous iron toxicity. Plant Soil 196:317-320.

Wu P, Zhao B, Yan J, Luo A, Zhu J, Wu Y, Senadhira D (1997) Genetic control of seedling tolerance to aluminium toxicity in rice. Euphytica 97:289-293.

**Box R4. Efficient rainwater management**

We have studied interactions between water regime, soil physical properties, and plant performance to quantify the effects of water deficit on lowland rice under different methods of crop establishment—transplanting, wet seeding, and dry seeding. We have used the results to develop simulation models for predicting crop performance under water deficits, and we are corroborating the models at different sites in the Rainfed Lowland Rice Research Consortium. We are also in the process of up-scaling these models for predicting yield potentials on a regional scale, and we are developing corresponding methods for measuring input variables. These models will be used in combination with geographic information systems to evaluate land management options for rainfed lowland rice in different environments.

Among these options is dry seeding. Farmers often have to delay planting until sufficient rainfall has accumulated to saturate the soil for transplanting. The delay increases the risk of late-season drought and reduces possibilities for dry-season cropping, depending on cultivars and photoperiod-sensitivity. Dry seeding to establish the crop at the onset of the rains

**Publications**

Bhagat RM, Bhuiyan SI, Moody K (1996) Water, tillage and weed interactions in lowland tropical rice: a review. Agric. Water Manage. 31:165-184.

Bhuiyan SI (ed.) (1995) On-farm reservoir systems for rainfed ricelands. International Rice Research Institute, Manila.

Fujisaka JS, Moody K, Ingram KT (1993) A descriptive study of farming practices for dry seeded lowland rice in India, Indonesia, and Myanmar. Agric. Ecosys. Environ. 45:115-128.

Saleh AFM, Bhuiyan SI (1995) Crop and rainwater management strategies for increasing productivity of rainfed lowland rice systems. Agric. Sys. 49:259-276.

Saleh AFM, Islam MT, Bhuiyan SI (1997) Analysis of drought and its alleviation using on-farm reservoirs in the rainfed lowland rice system of northwest Bangladesh. Expl. Agric., in press.

Sharma PK, De Datta SK (1994) Rainwater utilization efficiency in rain-fed lowland rice. Adv. Agron. 52:85-120.

can overcome this. We have compared transplanting and dry seeding for their water use efficiencies, drought risks, and economic returns: in each of these, dry seeding proved superior to transplanting. We are designing management options to improve the reliability of plant stands, reduce weed competition, and increase yield and yield stability of dry-seeded rice. We are seeking to identify extrapolation domains for the technology using simulation modeling.

Many rainfed lowland rice soils have hardpans formed through frequent cultivation. While hardpans may assist early ponding of water for weed suppression, late-season drought is exacerbated because root access to subsoil moisture and nutrients is restricted. In experiments in Bangladesh, we found a 20% yield gain (0.5 t $ha^{-1}$) by perforating a hardpan using a prerice legume crop. In continuing research, we are studying the ability of roots to penetrate hardpans and to follow earlier root channels, and we are quantifying consequent improvements in nutrient and water balances, in order to devise strategies for using this "biological" tillage.

We have established that on-farm reservoirs to capture excess rainfall and runoff water can produce significant benefits in rainfed lowland rice by ensuring supplemental irrigation water during dry spells. On-farm reservoirs also facilitate the establishment of succeeding upland crops, and fish culture in the reservoirs can also enhance farmers' incomes. We have developed basic design criteria for these reservoirs and identified desirable land features and climatic conditions. Through local initiatives, about 1,000 on-farm reservoirs in Central Java and more than 800 in the Philippines have been built by

Sharma PK, Ingram KT, Hampichitvitaya D, De Datta SK (1995) Subsoil compaction to improve water use efficiency and yields of rainfed lowland rice in coarse textured soil. Soil Till. Res. 36:33-44.

Singh RK, Singh VP, Singh CV (1994) Agronomic assessment of beushening in rainfed lowland rice cultivation in Bihar, India. Agric. Ecosys. Environ. 51:271-280.

Wade LJ (1996) Soil compaction - make it or break it for the rainfed lowland ecosystem. In: Management of clay soils in rainfed lowland rice-based cropping systems. ACIAR Proceedings Number 70. ACIAR, Canberra. p 243-247.

Wopereis MCS, Bouma J, Kropff MJ, Sanidad W (1994) Reducing bypass flow through a dry, cracked previously puddled rice soil. Soil Till. Res. 29:1-11.

Wopereis MCS, Kropff MJ, Maligaya AR, Tuong TP (1996) Drought-stress responses of two lowland rice cultivars to soil water status. Field Crops Res. 46:21-39.

Wopereis MCS, Wosten JHM, ten Berge HFM, Woodhead T, San Agustin AM (1993) Comparing the performance of a soil-water balance model using measured and calibrated hydraulic conductivity data: a case study for dryland rice. Soil Sci. 126:133-140.

Wopereis MCS, JHM Wosten, Kropff MJ, Bouma J (1993) Sampling strategies for measurement of soil hydraulic properties to predict rice yield using simulation models. Geoderma 59:1-20.

farmers during the past 3–4 years. After successful pilot testing in farmers' fields, the M.P. State Govt. of India is developing 5,000 on-farm reservoirs over the next 2 years. Current research focuses on quantifying the impact of the adoption of the technique in terms of regional water savings, and on the development of practical methods of reducing water loss from reservoirs.
**[RL2]**

**Box R5. Managing saline soils, acid sulfate soils, and iron toxic soils**

There are several million ha of flood-prone lowlands in Asia where rice production is almost the only use for the land, but soil toxicities often severely hinder growth in these areas. Ameliorating the toxicities may have side effects downstream and it is necessary to balance rice productivity against environmental quality.

We have been investigating water management strategies for rice production on acid sulfate soils. We have assessed the effectiveness of leaching in removing acidity from the cultivated soil, in relation to soil hydraulic and chemical properties and their management. Practices that minimize iron oxidation and the accumulation of acidity in the rooting zone will minimize the amount of leaching required and consequent downstream pollution. Such practices include mulching and shallow tillage to reduce capillary rise. Poor-quality water may accumulate at depth during the dry season and may contaminate surface soils if the water table is allowed to rise too rapidly at the onset of the rainy season. Thus, it may be necessary to delay planting until receding floodwater can be used to flush the ricefields effectively. Future work will focus on the process of pollutant transport in canal and

**Publications**

Minh LQ, Tuong TP, van Mensvoort MEF, Bouma J (1998) Soil and water table management effects on aluminium dynamics of acid sulphate soils. Agric. Ecosys. Environ., in press.

Minh LQ, Tuong TP, van Mensvoort MEF, Bouma J (1997) Tillage and water management for increasing riceland productivity in flood prone acid sulphate soil areas of the Mekong delta, Vietnam. Soil Till. Res. 42:1-14.

Minh LQ, Tuong TP, van Mensvoort MEF, Bouma J (1997) Contamination of surface water as affected by land use in acid sulphate soils in the Mekong delta, Vietnam. Agric. Ecosys. Environ. 61:19-27.

Minh LQ, Tuong TP, Booltink HWG, van Mensvoort MEF, Bouma J (1997) Bypass flow and its role in leaching of raised beds under different land use types on an acid sulphate soil. Agric. Water Manage., 32:131-145.

river networks and the pollution impact on aquaculture and biodiversity on a regional basis. We will investigate productive and sustainable land use systems, including agroforesty and agro-aquaculture for coastal areas.
**[FP1]**

## Upland rice ecosystem

Upland rice has a niche in upland agricultural systems by virtue of its tolerance of poor soil conditions, particularly high acidity and low phosphorus. Traditionally, this tolerance has been exploited in subsistence farming in which little lime and fertilizer are used, but these systems are unsustainable under increased population pressure. We consider the main niche for upland rice in the future to be as a component of transition systems in which a gradual long-term improvement in soil conditions is sought with farmers in the long run diversifying into higher value crops. In the interim, it may be possible to harness rice's adaptation to poor soil conditions to enhance the soil improvement process and also to provide short-term returns to investments. An example of this type of system is the rehabilitation of *Imperata* grasslands in Indonesia using zero-tillage production of upland rice under estate crops, principally oil palm and rubber. Another example is the upland rice-pasture rotations developed for the acid savannas of Latin America. We seek to understand how such rehabilitation systems can be made effective.

**Box U1. Managing P fertility**
We are studying long-term cumulative responses to P fertilizer in upland systems with the aim of being able to predict long-term P dynamics and synergistic effects on other components of soil fertility. Residual effects are particularly marked in strongly P-fixing soils where additions must necessarily greatly exceed removals by the crop. As soil P fertility and plant growth improve, soil carbon and nitrogen dynamics may also improve, particularly in legume rotations where biological N inputs are enhanced. If sufficient benefits accrue with each crop cycle, repeated applications of moderate amounts of P may be attractive to resource-poor farmers. Long-term studies are being made with a rice-soybean rotation at sites in the Philippines, Indonesia, India, and Thailand. Phosphorus

**Publications**

Cassman KG, Singleton PW, Linquist BA (1993) Input/output analysis of the cumulative soybean response to phosphorus on an ultisol. Field Crops Res. 34:23-36.
Sanyal SK, De Datta SK, Chan PY (1993) Phosphate sorption-desorption behaviour of some acidic soils of South and Southeast Asia. Soil Sci. Soc. Am. J. 57:937-945.

is applied to each crop at 0–200% of the quantity required to maintain a specified critical level in the soil. Measurements of plant growth, yield, and nutrient uptake and of various soil P pools are made. This will provide a unique dataset on P dynamics in tropical upland soils with which to develop economical P management strategies.
**[UR2]**

**Box U2. Managing subsoil acidity**
In many upland areas, subsoil acidity restricts access of roots to subsoil moisture and nutrients, and its amelioration is necessary for reasonable yields of most crops. We have been studying ways to ameliorate subsoil acidity by manipulating the leaching of surface-applied calcium and using acid-tolerant rice cultivars to help capture the leached calcium in the subsoil. In experiments in an ultisol in Sumatra, the degree of movement of calcium into the subsoil followed the mobility of the accompanying anion: nitrate > sulfate > carbonate. Rooting depth increased in accordance with the degree of calcium movement. Significant quantities of nitrate were sorbed on soil particles in the subsoil, though not in the surface soil, favoring its accumulation in the subsoil. Uptake of leached nitrate by roots in the subsoil presumably further enhanced calcium accumulation; acidity will have been neutralized by base released from the roots to balance the nitrate taken up. Although calcium nitrate fertilizer is expensive, calcium and nitrate can be generated cheaply from urea and lime. The dataset being produced in these experiments will be used to develop a model of the leaching and acidity amelioration process for determining where and how a technology based on these ideas would be useful.
**[UR2]**

**Publications**
Kirk GJD, Zeigler RS (1994) The use of adapted cultivars in acid-soil improvement. In: Trans. 15th Cong. Int. Soc. Soil Sci., Vol. 5a. Int. Soc. Soil Sci., Acapulco. p 567-578.

**Box U3. Managing N fertility and nutrient-by-water interactions**
As in the rainfed lowlands, we are investigating the extent to which alleviating nutrient stresses can lessen the impact of water deficits in drought-prone areas. We are studying how root morphology and function are influenced by mineral nutrition under varying water regimes. We are studying how the depth-distribution of N and P and the use of slow-release N fertilizers might be manipulated to foster deep rooting as a buffer against periods of drought. In experiments in India and Thailand at sites with poor soil N fertility but only moderate acidity, we found that root growth was enhanced by N application and allowed a greater extraction of soil water at depth. Nitrogen uptake, yield, and root development were greater with controlled-release urea than with split applications of an equal quantity of soluble urea.
**[UR2]**

**Publications**
Dobermann A, Goovaerts P, George T (1995) Sources of soil variation in an acid Ultisol of the Philippines. Geoderma 68:173-191.
Kurschner E, Bonman JM, Garrity DP, Pabale D, Tamisin MM, Estrada BA (1995) Effects of nitrogen timing and split application on blast disease in upland rice. Plant Disease 76:384-389.
Ladha JK, Peoples MB, Garrity DP, Capuno VT, Dart PJ (1993) Estimating dinitrogen fixation of hedgerow vegetation using the nitrogen-15 natural abundance method. Soil Sci. Soc. Am. J. 57:732-737.
Prot JC, Villanueva LM, Gergon EB (1994) The potential of increased nitrogen supply to mitigate growth and yield reductions of upland rice cultivar UPLRi-5 caused by *Meloidogyne graminicola*. Fund. Appl. Nematol. 17:445-454.

## Cross-ecosystems
Large parts of Asia are undergoing rapid land use changes driven by market forces and economic growth as well as by population increase. Agricultural systems are being challenged by the requirements of increased productivity, more diversified products, and environmental protection, and multiple claims on natural resources are being made. To address these issues, it is necessary to consider regional levels of integration, beyond the rice ecosystems discussed above. An analysis of land use and natural resource management options at regional levels is needed to guide changes in agricultural and environmental policies, and to assess the scope for rice technologies beyond the constraints of current policies. Moreover, regional level studies help in setting research priorities at lower levels of integration.

**Box C1. Ecoregional research**
We are developing methodologies and tools for land use planning in Asia at the subnational level in an ecoregional network called SysNet. These tools include simulation models, technical coefficient

generators for formulating constraints and policies as mathematical functions, geographic information systems, and linear programming models. Studies are being made in four regions: Haryana State, India; Kedah-Perlis Region, Malaysia; Ilocos Norte Province, Philippines; and Cantho Province, Vietnam. The aim for each region is to explore different pathways for agricultural development allowing for different socioeconomic, biological, and physical limitations. This should reveal the extent to which different goals can be met and the trade-offs between costs and benefits. Thereby, we will develop options for sustainable land use under different sets of multiple goals.
**[CE6]**

# Appendix 1. IRRI projects by program, 1998-2003 planning period

## Contents

## IRRI Discussion Paper Series

No. 1 Matheny EL, Raab RT, Navarro EL, eds. 1994. Current status and future directions of rice-related group training programs in Asia.

No. 2 Quick GR, Yabes S, eds. 1994. Microenterprise development—small-scale farm equipment manufacturing: entrepreneurship and employment.

No. 3 Denning GL. 1994. Farmers as customers: a service management approach to designing an agricultural research and development institution.

No. 4 Senadhira D, ed. 1994. Rice and problem soils in South and Southeast Asia.

No. 5 Calvero SB, Coakley SM, McDaniel LR, Teng PS. 1994. A weather factor searching program for plant pathological studies: Window Pane Version W1B0003.

No. 6 Devendra C, Sevilla C, eds. 1995. Crop-animal interaction.

No. 7 Raymundo ME, Mamaril CP, Aragon EL. 1995. Characteristics and classification of wetland rice soils in India, Indonesia, and Thailand.

No. 8 Quick GR, Paris TR, eds. 1995. Enhancing incomes of rural women through suitably engineered systems.

No. 9 Tinsley RL. 1995. Rice research and production in the Commonwealth of Independent States (CIS).

No. 10 Moody K, ed. 1995. Constraints, opportunities, and innovations for wet seeded rice.

No. 11 Pingali PL, Paris TR, eds. 1995. Competition and conflict in Asian agricultural resource management: issues, options, and analytical paradigms.

No. 12 Zheng K, Huang N, Bennett J, Khush GS. 1995. PCR-based marker-assisted selection in rice breeding.

No. 13 Cuyno RV, Lumanta MF, Manza MR, Carretas AC. 1996. What IRRI personnel say about the matrix management system 5 years after its adoption.

No. 14 Yap IV, Nelson RJ. 1996. WinBoot: a program for performing bootstrap analysis of binary data to determine the confidence limits of UPGMA-based dendrograms.

No. 15 Ranaweera NFC, ed. 1996. Impact of farming systems research.

No. 16 Piggin C, Courtois B, Schmit V, eds. 1996. Upland rice research in partnership.

No. 17 Moody K, ed. 1996. Rice weed management research at IRRI.

No. 18 Savary S, Elazegui FA, Teng PS, 1996. A survey portfolio for the characterization of rice pest constraints.

No. 19 Chancellor TCB, Teng PS, Heong KL. 1996. Rice tungro disease epidemiology and vector ecology.

No. 20 Savary S, Elazegui FA, Pinnschmidt HO, Castilla NP, Teng, PS. 1997. A new approach to quantify crop losses due to rice pests in varying production situations.

No. 21 Datta SK, Torrizo LB, Tu J, Oliva NP, Datta K. 1997. Production and molecular evaluation of transgenic rice plants.

No. 22 Gregorio GB, Senadhira D, Mendoza RD. 1997. Screening rice for salinity tolerance.

No. 23 Olk D, ed. 1998. Reversing trends of declining productivity in intensive irrigated rice systems.

No. 24 Coloquio E, Tiongco RC, Cabunagan RC, Azzam O. 1998. Evaluation of two mass screening methods for tungro disease resistance.

No. 25 Piggin C, Courtois B, George T, Lafitte R, Pandey S. 1998. Directions and achievements in IRRI upland rice research.

No. 26 Piggin C, Wade L, Zeigler R, Tuong TP, Bhuiyan S, Ladha JK, Pandey S, Garcia L. 1998. Directions and achievements in IRRI rainfed lowland rice research.