

CROPPING SYSTEMS AND THEIR MECHANISMS OF NUTRIENT UPTAKE

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ABSTRACT

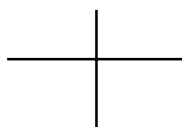
Given the widespread prevalence of nutrient stresses worldwide, a thorough understanding of acquisition, utilization and recycling of both organic and mineral forms of nutrients at the level of the cropping system is essential. This paper outlines selected research advances in nutrient acquisition and management, and identifies a few priorities and strategies to increase the efficiency of nutrients mobilized from all sources. It is recognized that productivity levels of cropping systems cannot be increased and sustained if current practices such as over-or under-application of nutrients and inefficient ways of utilizing crop residues and farm wastes are continued. Although fertilization will continue to be important for alleviating nutrient limitations in many regions, research on biological and chemical processes aimed at optimizing nutrient recycling and recovery, minimizing indiscriminate application of fertilizers, and maximizing the efficiency of nutrient use is expected to provide innovative management alternatives. Further advances in soil fertility evaluation methods, nutrient acquisition models, and site-specific management and phytoremediation technologies, will ultimately provide the most appropriate ways to manipulate nutrient availability and devise strategies for protecting and restoring environmental quality while sustaining farm yields and profitability. It is concluded that research initiatives for sustainable nutrient management must be conceived on the basis of a holistic understanding of location-specific interactions between production and the environmental, social, biological and economic components of cropping systems.

INTRODUCTION

Research on nutrient acquisition and management in cropping systems is entering a critical phase. While developed countries are mainly concerned about the adverse impacts of intensive cropping systems on the environment (soil, water and air) and society (rural displacement, urban sprawl, etc.), developing countries are confronted with an ever-growing demand for greater agricultural production, while needing to sustain their already fragile resource base (Sanchez *et al.* 1997, Smaling *et al.* 1997). Although the concept of sustainability originated mainly in response to pressure from environmentalists in developed countries, concern over the long-term viability of cropping systems is felt for all scales of farming and in all agroecological zones.

Nitrate contamination issues that have recently arisen in north central Europe and the United States have resulted from what seemed to be optimal economic fertilization practices (Fedkiw 1991). Researchers estimate that 20% of the N that humans are putting into watersheds is getting into rivers. In Japan, 670,000 mt of N fertilizer is applied annually to agricultural fields. This constitutes the application of 130 kg N/ha to all arable land. In addition to this, 700,000 mt of N in animal manure and 690,000 mt of various forms of wastes from human activities were also applied, mainly to agricultural fields. This heavy N application is causing nitrate contamination of groundwater and watersheds in and around agricultural areas. To lessen nitrate pollution, and to reduce the application of chemical N fertilizers, we have to develop technologies which utilize organic N for crop production in an efficient way. Improving the use by crops of organic N

Keywords: cropping systems, fertilizers, nitrates, nutrients, root system



would be a key factor in achieving this goal.

In developing countries, where the amount of arable land *per capita* is steadily decreasing, inherently sustainable local practices and knowledge adopted before the Green Revolution era have been systematically replaced. For instance, the subsistence agriculture of the pre-chemical era efficiently sustained the N status of soils by maintaining a balance between N lost with the grain harvest and N gain from biological N fixation. This was possible with less intensive cropping, adoption of rational crop rotations and intercropping systems, and the use of legumes as green manure.

The agriculture of the modern chemical era, however, concentrates on maximum output but overlooks input efficiency. Likewise, the traditional, less intensive wet-dry rotation of rice culture has been gradually replaced by intensive continuous wetland rice culture, leading to a lower available soil N pool (Kundu and Ladha 1995). Depletion in organic carbon was also observed in field experiments conducted in Kenya, in spite of fertilization at optimal rates (Smaling *et al.* 1997). The present challenge is to sustain soil fertility in cropping systems operating at high productivity levels.

Stresses (deficiencies and toxicities) due to availability, acquisition and utilization of nutrients are becoming increasingly widespread in many soils, leading to low crop productivity. For example, the yield potential of cropping systems on acid soils, which cover about 3.95 billion hectares of the earth's surface, is restrained by deficiencies of phosphorus (P), calcium (Ca), magnesium (Mg), and potassium (K), and by toxicities of aluminum (Al), manganese (Mn), and iron (Fe) (Salazar *et al.* 1997).

Conventionally, fertilizers or soil amendments are used to counter such stresses. However, total dependence on fertilizers is neither economical nor pragmatic because of (a) the inability of many farmers to buy enough fertilizer, and (b) the capacity of many soils to fix applied nutrients into forms unavailable to plants (Sanchez and Uehara 1980).

There is also increasing evidence that fertilizer alone cannot sustain yields for long periods. For example, in continuous rice cropping with two to three crops grown annually, the use of fertilizer N increased with time but the yields often remained stagnant (Cassman and Pingali 1995).

This reflects a higher fertilizer requirement to produce the same yields, implying a decline in yield response to nutrients, possibly because of an overuse of fertilizer. This is a reason for concern. As an alternative, tailoring plants to fit the soil through

genetic improvement is considered more economical than changing the soil. It is believed that farmers can more easily adopt a genotype with useful traits, than crop and soil management practices that are associated with extra costs.

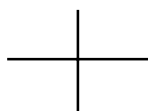
However, the magnitude of nutrient stresses is so severe and widespread that no single remedial measure can effectively solve this problem. For example, it is estimated that as much as 8-26 million hectares of maize, at least 60% of beans in Latin America, and approximately 44% of beans in Africa, are grown on soils that are severely deficient in phosphate (Yan *et al.* 1996). Likewise, it is estimated that at least 50% of the arable land used for crop production worldwide is low in availability of one or more of the essential micronutrients for current varieties (Ruel and Bouis 1997).

There are two approaches to research into nutrient acquisition and management in cropping systems. One approach is to analyze survival mechanisms of crops grown on nutrient-poor soils. Results from such studies must be the foundation for basic process research. The other approach must emphasize basic research for a better understanding of the mechanisms of nutrient acquisition in cropping systems. The study methods for each approach are different, and it is uncommon for researchers working in basic research to have the full competence needed for adaptive research, and vice versa. We believe, however, that to establish sustainable and productive cropping systems, the two different but complementary strategies must be conducted in collaboration with each other.

Evaluation of Soil Fertility

Most methods of evaluating soil fertility are based on the assumption that crop plants absorb nutrients that are already dissolved in the soil solution. Crop activities to acquire nutrients from soil are not usually evaluated. This is one of the main reasons for the lack of explicit methods of evaluating soil fertility in cropping systems, which is perhaps a major factor that has led to over-fertilization in developed countries.

While soil inorganic nitrogen, (NO_3^- or NH_4^+) can be measured rather easily, there is no reliable method for evaluating N mineralized from soil organic matter during the growing season. Poor understanding of the mechanism of crop plants in utilizing organic forms of soil nutrients is perhaps the most important reason, even though several findings or speculations on soil organic uptake mechanisms of plants have been reported. As



mentioned earlier, it has been suggested that some crops may utilize organic forms of nitrogen better than others. Further research is necessary to establish reliable methods of evaluating soil nitrogen fertility.

Methods of testing soil P fertility also need further investigation. For instance, the use of such tests as Bray, Mehlich, or Olsen on soils different from those for which the tests were originally developed provides inaccurate estimates of available soil P. Available P measured by Olsen's method, which uses calcium carbonate (pH 8.5) as an extractant, correlates well with P uptake. However, it gives a lower estimate of available phosphorus for alkaline soils (e.g. Vertisols) and a higher estimate for acidic to neutral soils (e.g. Alfisols) (Ae *et al.* 1991).

It is thus nearly impossible to compare P fertility among different soil types using Olsen's method alone. Olsen's method is especially unsuitable for extracting P from alkaline soils that are rich in Ca-P. Crops such as chickpea, when grown on alkaline soils, can dissolve the less soluble Ca-P in the rhizosphere soil by means of organic acids exuded from its roots (Ae *et al.* 1991). Buckwheat is known to reduce rhizosphere soil pH by releasing proton from its roots. In this way, it can utilize alkaline rock phosphate more efficiently than maize (Bekele *et al.* 1983).

The Truog method, which uses sulfuric acid as an extractant, underestimates the available P in acidic to neutral soils, especially when crops can utilize Fe-P or Al-P solubilized by organic chelating compounds exuded from their roots. In Andisols, for example, no linear relationship exists between soil available P measured with the Truog method and P uptake by crops (Souma 1986).

In recent years, the recommended rates of P fertilizer in cropping systems in some regions have been much higher than the amount of P actually needed by crops, mainly because of poor crop response to applied P. Soil P content in some fields of Hokkaido, for example, was so high that soil particles washed into rivers increased P concentration of water to a critical level, causing algal booms and hypoxia (Tachibana *et al.* 1992).

Sharpley *et al.* (1992) suggested that accounting for the contribution of soil organic N and P to fertility was a major constraint to developing valid soil testing methods. This is especially relevant in the highly weathered soils of southern Africa and India, where mineralization of organic forms may be the main mechanism by which nutrients become available to crops. Methods involving the use of ion exchange resins and iron-oxide impregnated paper

strips have been shown to provide more reliable estimates of plant available soil P (Sharpley *et al.* 1994), but the results need validation in a wider range of soils and cropping systems.

To establish cropping systems suitable for the soil conditions of different locations, a reliable soil test which can standardize soil nutrient availability is necessary. We also need a better understanding of the dynamic mechanisms by which crop plants acquire nutrients from the soil. Both these are indispensable in improving soil tests so that we can evaluate soil nutrient availability.

Research on Novel Mechanisms of Nutrient Uptake: Root Exudates, Cell Walls, Architecture.

In India, chickpea is widely grown on alkaline soils such as Vertisols or Aridisols. Pigeonpea, on the other hand, is grown on acidic soils such as Alfisols or Oxisols. It has been recognized that chickpea and pigeonpea are crops which are not very responsive to P applied to these soils. A sizable fraction of the inorganic P in Vertisols is associated with Ca. This calcium-bound P (Ca-P) is considered to be a largely insoluble compound, mainly in the form of apatite.

The available P level of Vertisols as measured by Olsen's method is generally very low. Chickpea was found to solubilize otherwise insoluble Ca-P in alkaline soil by lowering the rhizosphere pH. It did this by excreting citric acid (Ae *et al.* 1991).

The weak response of pigeonpea to P application in an Alfisol field suggested that pigeonpea was able to efficiently utilize iron-bound P (Fe-P). It was found that pigeonpea can acquire P from Alfisols by excreting an organic acid, piscidic acid and its derivatives, which can specifically chelate from Fe ligands in this soil type (Ae *et al.* 1990). Pigeonpea was later shown to exude significant amounts of malonic and oxalic acids along with piscidic acid. Those acids seem to release P from Fe-P and Al-P in soils of low P fertility (Otani *et al.* 1996a).

Roots of P-stressed white lupin are also known to excrete organic acids, which increases the availability of P. Johnson *et al.* (1996) reported that lateral root development was altered in P-stressed lupin. Clustered tertiary roots, called proteoid roots, formed over 60% of the root mass of P-stressed plants. The P-stressed plants exuded 25 times more citrate and malate than P-sufficient plants. Ae *et al.* showed that groundnut can solubilize Fe-P or Al-P by means of the chelating capability of the cell wall



itself (Ae *et al.* 1996).

In P-depleted farms of Western Kenya, a combination of Minjingu rock phosphate at 250 kg/ha and 1.8 mt/ha of *Tithonia diversifolia*, a common shrub planted for thousands of kilometers along farm boundaries, raised yields by 400%. *Tithonia* apparently helps solubilize P fixed by iron oxides in oxisols. Both *Tithonia* and rock phosphate are indigenous nutrient sources (ICRAF 1997).

Low-grade Florida rock phosphate or BPL61 applied at a 20 cm depth to Andisols was more effective for three years in increasing dry matter production and P uptake of orchard grass and white clover than similarly applied high-grade Florida rock phosphate, BPL 72 or single superphosphate (Kondo *et al.* 1997). The mechanism of the efficient utilization of low-grade rock phosphate by those forage crops is not clear. It may suggest the involvement of AM mycorrhizae for increased dry matter production and P uptake.

Researchers at the International Center for Tropical Agriculture (CIAT) observed promising genetic variation in P efficiency in bean germplasm. They suspected that the variation might be due to the specific capacity of some of the genotypes to obtain P from recalcitrant organic matter. Such a specific adaptation was attributed to the release of phosphatases or other compounds capable of liberating P from organic complexes, as reported in bean and other plants (Helal 1990, Tarafdar and Jungk 1987). Intraspecific variation in excreted phosphatase has been correlated with the depletion of organic P in the rhizosphere, and presumably, P uptake (Asmar *et al.* 1995).

Since recalcitrant soil organic materials often undergo physiochemical interactions with soil minerals, it is imperative that organic matter must be freed from those minerals, perhaps through chelation. While phosphatase itself may have the ability to chelate ions, a combination of other natural chelating substances and phosphatases might release P much faster from recalcitrant soil organic matter.

Pigeonpea showed a higher P uptake from an Andisol of high humic substances than other crops (Otani *et al.* 1996a). This seems to support such a hypothesis, but studies have been limited so far.

Soybean seems to make efficient use of soil N which other plants cannot take up easily. The better growth of maize following soybean, compared to repeated crops of maize alone, has been mainly attributed to the residual effects of N fixed by soybean nodules. In an experiment conducted on an Andisol field, however, maize grown after non-nodulating soybean showed similar growth efficacy

to that after nodulating soybean (J. Arihara, unpublished results). Based on a long-term crop rotation experiment, Vanotti *et al.* 1995) speculated that growth enhancement of maize after soybean was due to the stimulation of soil N mineralizing microbes by soybean, which might gradually deplete readily available soil N. Also, alfalfa was reported to enhance soil N mineralization (Radke *et al.* 1988). It is suggested that some crops such as rice, flowering Chinese cabbage (*Brassica amperistris* L. spp. *Chinensis* (L.)) and carrot absorb organic N directly, and/or solubilize insoluble forms of soil organic N (Yamagata *et al.* 1996; Matsumoto *et al.* 1999). Future research should explore the mechanisms of crop N acquisition, as a first step in establishing a reliable soil N test.

Johnson and Damman (1996) reported that healthy plants in N-deficient habitats such as peat bogs use amino acid N to compensate for a deficiency of N available in inorganic forms. In bogs, the rate of soil N mineralization is among the lowest of any ecosystem. The only source of N is precipitation. Organic N occurs in peat, and in smaller quantities as amino acids. Recent studies have indicated that even upland rice can take up amino acid N. Further studies are necessary to determine if crop plants too can take up novel forms of nutrients besides amino acids.

Nutrient-efficient genotypes may have better root growth and root architecture (Lynch and van Beem 1993, Lynch and Beebe 1995, Yan *et al.* 1995). Mathias *et al.* (1999) found that rice genotypes which had efficient uptake of P from Andisols with low levels of available P had a more vigorous root system than inefficient types. They also identified the position of genes in relation to the efficiency of P uptake. A vigorous, effective crop rooting system is essential for efficient nutrient acquisition, particularly for mobile nutrients. Other general adaptive mechanisms could include better mycorrhizal symbiosis.

With the development of low- or no- tillage systems, agro-pastoral systems which rotate pastures and crops every few years are becoming a practical and promising method for productive agriculture, especially in Brazil and Colombia. In this system, the productivity of pasture is increased after field crops even though no fertilizer is applied to the pasture. Orchard grass grown on volcanic ash soil of very high P-fixing capability, with more than 2500 mg P/kg soil, did not show any P deficiency symptoms once the pasture was established. Rice plants, however, grown in a field adjacent to the



pasture, showed a severe yield reduction from lack of P. Although the dry matter production of ladino clover did not decrease much with lack of P, the rate of reduction was higher than in orchard grass (Kitagishi 1962). In southern Thailand, tropical forage crops of *Stylosanthes*, *Brachiaria humidicola* and *Brachiaria ruzizinesis* grown on a podosolic soil without P produced a dry matter yield comparable to that from forage grown with NPK (Hayashi 1992). Efficient utilization of residual phosphorus by forage crops might be an important reason for this increased production.

Yan *et al.* (1996), however, reported that different bean genotypes did not differ in their ability to mobilize P from organic aluminum or iron sources. This suggests that beans do not have obvious soil specificity in response to low P availability in different soils. However, large-seeded Andean bean genotypes such as G19833 tended to utilize Ca-P better than others.

The superior ability of some genotypes to utilize Ca-P thus opens the possibility of developing bean cultivars that can be fertilized more efficiently with Ca-phosphate or rock phosphate. Lack of specific adaptation of bean to P sources can be interpreted as a positive result from the agronomic point of view. It suggests that bean adaptation to P availability is stable across soil environments. If so, this would make breeding for P efficiency relatively easy.

Role of Soil Fauna (Mycorrhizae, Bacteria, Nematodes etc.) in the Nutrient Balance of Cropping Systems

It is well established that soil fauna play a major role in increasing nutrient availability and uptake, especially in nutrient-poor soils. N-fixing systems, including free-living, symbiotic or associative organisms, contribute significant amounts of fixed N to cropping systems. Rhizobia-legume systems fix N at rates of 50-300 kg N/ha/year. Cyanobacteria fix 15-25 kg N/ha/year and azospirillum-grass associations fix 10-30 kg N/ha/year. The interaction between mineral fertilizers and N-fixing systems needs further study as a way of achieving better integration of the nutrition systems of different crops.

It is also indicated that enhanced AM association of crops through cultivation of mycorrhizal crops in the previous season showed significant growth and yield promotion on soils of high P fixation capability (Thompson 1991, Arihara *et al.* 2000).

AM inoculation is expensive, while indigenous AM fungi usually dominate inoculated AM fungi. Increasing indigenous AM fungi through proper cropping systems is a practical way to enhance growth and P uptake of mycorrhizal crops. Soil factors such as P status, soil type and pH, and climatic variables such as precipitation and temperature, determine the growth promoting effects of AM in a cropping system. AM fungal populations and colonization of roots by AM fungi, and their contribution to P uptake, were higher in soils with lower P availability. However, the effect of preceding crops on the growth of following crops varies in different soils, even when P availability was low. This means that differences in indigenous AM fungi in various soils may mediate the effect of preceding crops. High soil moisture also increases the colonization of AM, even in soils with low populations of AM spores. This far outweighs the effect of previous crops on AM colonization (Karasawa *et al.* 2000). Mycorrhizal wheat plants had greater acquisition of P and other nutrients compared to non-mycorrhizal plants grown under water stress (Clark 1996). Similarly, mycorrhizal corn could take up more Fe in alkaline soils than non-mycorrhizal corn. Further studies are, however, necessary to maximize the potential advantages from the mycorrhiza-crop symbiosis through a detailed understanding of mycorrhizal ecology in cropping systems.

Effects of cropping systems on managing harmful soil microorganisms need further examination, in order to realize the positive benefits from nutrient cycling. Researchers at Wageningen reported that when potato was grown as a trap crop, numbers of juvenile potato cyst nematodes decreased by 83%. In contrast, the population of *Trichodorus* spp. increased by 78%. Compared to fallow, the population of *Pratylenchus* spp. decreased under *Tagetes patula* by 78%, but increased under oats by 23%, when these crops were grown as green manure crops in autumn. Likewise, sesame and velvet bean were found to suppress root knot nematodes in Florida and Alabama.

Research on Nutrient Balance and Fertility in Indigenous Cropping Systems

Fertilizer-intensive cropping systems have evolved in only the last 30 to 40 years. To extend these into the next century, some modifications in nutrient management will be required. For this to happen, we must look again at the nutrient

equilibrium of traditional cropping systems, with particular attention to soil and crop health. For instance, studies in the semi-arid tropics of India revealed that the addition of pigeonpea, as a sole crop or as an intercrop in a cropping system, not only helps soil N fertility, but also makes more phosphorus reserves available for subsequent crops (Ae *et al.* 1991, Arihara *et al.* 1991a,b). Based on studies of a 700-year-old practice of Egyptian clover-rice rotation, which covers about 60-70% of the entire rice acreage in Egypt, Yanni *et al.* (1997) reported a unique natural endophytic association between *Rhizobium leguminosarum* *bv.* *trifoli* and rice roots. The N supplied by this rotation replaces 25-33% of the recommended rate of fertilizer application to rice.

Such benefits cannot be explained solely by the increased availability of fixed N through mineralization of N-rich clover crop residues. Yanni *et al.* (1997) found that clover-nodulating rhizobia naturally invade rice roots, and achieve an internal population density of up to 1.1×10^6 endophytes per gram (fresh weight) of rice roots. They reported that inoculation with two endophytic strains (E11 and E12) of *R. leguminosarum* significantly increased grain yield, harvest index and fertilizer N use efficiency of field-grown (Giza 175) hybrid rice (Table 1). Similar studies on natural associations of endophytic diazotrophs in rice roots under rice-sesbania rotation in the Philippines are in progress (Ladha *et al.* 1993).

Research on Nutrient Acquisition in Relation to Environmental Quality and Bioremediation of Contaminated Soils

It is widely recognized that high yields resulting from heavy applications of fertilizer in modern cropping systems have been achieved at some cost to environmental quality. In developed countries, in some places, soil nitrate concentrations have become so high that nitrate leached from agricultural fields has increased the concentration in groundwater to more than 10 ppm, to a level damaging to human health. This is especially important in areas where groundwater is used as drinking water. It is well documented that leaching of nitrate occurs during the period between fall and spring, when the downward flow of water exceeds evapo-transpiration. Cultivating crops during this season is an effective way of preventing leaching of nitrate from the soil profile. It is interesting to note that some crops belonging to the family of *Brassicaceae* seem to directly uptake soil organic

N. This would be beneficial for their growth under low-temperature conditions, when the mineralization rate of organic N is reduced.

Soybean is often cultivated in rotation with maize or other cereal crops, because of its N-fixing capability. However, soybean seems to reduce the nitrate concentration in the soil profile much more than maize does. The difference in the amount of nitrate in the soil profile at 60 cm depth between maize and soybean plots is estimated to be more than 100 kg N/ha when a heavy dose of N fertilizer was applied (Arihara, unpublished data). This surprisingly high figure suggests the possibility of using soybean as a cleansing crops in fields with high nitrate levels, although the mechanisms involved in this phenomenon are still unclear.

Dominique *et al.* (1997) recently reported that plants colonized with VAM fungi showed a greater ability to take up soil nitrate than those that were not. Based on this observation, they reported that induced colonization of crop plants with VAM inoculum in the field could help alleviate nitrate contamination of groundwater.

Crops also vary in their ability to take up metals such as nickel from contaminated soils. Because of their rapid nickel transport rate, ryegrass and cabbage can accumulate high levels of nickel in their shoots. In contrast, maize and white clover have a low influx and transport rate.

Crop Residue Management and its Relation to Fertility Maintenance

Maintaining innate soil fertility through judicious crop residue management is an urgent priority in tropical cropping systems. In highly productive fields, the soil nutrient supply matches the crop nutrient uptake pattern. The yield benefits from high native soil fertility are indeed difficult to replace with fertilizers. Cassman *et al.* (1995) reported that hybrid rice yields in China on a soil with low native N fertility, where 245 kg fertilizer N was applied, was 2.2 mt/ha lower than that obtained on a soil with high native N fertility where only 54 kg fertilizer N/ha was applied. A study in Japan indicated that rice crops depend totally on the soil to meet N requirements from heading to maturity (Wada *et al.* 1986).

Rice is preferably grown in flooded and puddled soil. This practice has been thought of as an ideal way to conserve soil N. However, a decline in productivity in paddy rice caused by soil N reduction has been noticed in several places in Asia, especially where two to three crops of rice are grown annually.

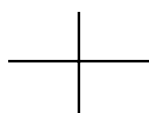


Table 1. Effect of N fertilization and inoculation with *Rhizobium leguminosarum* bv. *trifolii* rice endophytes on production of Giza 175 rice under field conditions

| Fertilization (kg N/ha) | Grain yield (mt/ha) | | | Harvest index (%) | | | Fertilizer use efficiency | | |
|----------------------------|------------------------|-----|------|----------------------|------|------|------------------------------|-------|-------|
| | C | E11 | E12 | C | E11 | E12 | C | E11 | E12 |
| 0 | 4.3 | 6.3 | 6.2 | 30.1 | 35.0 | 35.4 | — | — | — |
| 48 | 5.8 | 7.9 | 7.0 | 30.0 | 40.0 | 38.5 | 121.7 | 165.2 | 145.0 |
| 96 | 5.4 | 7.1 | 7.9 | 31.8 | 36.7 | 37.4 | 56.4 | 74.1 | 81.8 |
| 144 | 6.4 | 7.0 | 7.0 | 31.6 | 30.6 | 30.0 | 44.3 | 48.6 | 48.4 |
| LSD (0.05) | | | | | | | | | |
| Fertilizer (N) | | | 0.31 | | 2.5 | | 3.4 | | |
| Inoculation (I) | | | 0.32 | | 1.9 | | | 4.4 | |
| N x I | | | 0.65 | | 3.9 | | | 8.8 | |

Source: Yanni *et al.* 1996

Soil organic N is continually lost through plant removal, leaching, denitrification, and ammonia volatilization. Continuous rice cropping under wetland conditions thus leads to a low level of soil N, unless it is replenished by biological N fixation. This has the overall effect of reducing the pool of available soil N in the lowlands (Kundu and Ladha 1995). The decline in N supplying capacity of rice is attributed to degradation in the quality of soil organic matter under such a water regime (Cassman *et al.* 1995a, 1995b).

Changing from a continuous wetland rice cropping to judiciously managed multiple cropping systems, with a wet-dry rotation which includes the cultivation of leguminous crops, may rectify such problems.

However, even a wet-dry rotation which includes legumes does not always conserve enough soil N. In Japan, more than 60% of soybean is grown in paddy fields in rotation with rice, wheat or other crops. Soybean yields have been slowly but steadily declining since the middle of the 1980s. As shown above, soybean takes up a large amount of soil N for the production of grain, of which the N percentage is generally more than 8%. A sharp reduction in the level of mineralized soil N caused by the continuous cultivation of soybean is suspected in many paddy fields with a wet-dry rotation. As good yields of grain legumes may exploit soil N more than rice, fertilizers may be required to replenish soil N fertility.

Fertilizer use efficiency is often low in tropical cropping systems, because of the low level of organic matter. The addition of small amounts of high-quality organic matter (with a narrow C/N ratio and

a low proportion of lignin) to tropical soils can substantially improve fertilizer efficiency (Snapp 1995a). Nearly four decades ago, two long-term cropping studies in Kenya and Nigeria indicated that organic plus inorganic inputs sustain fertility at a higher level than the expected effects of either input by itself (Dennison 1961).

Nutrient effects alone do not explain the benefits derived from modest amounts of organic manure combined with inorganic fertilizers. High-quality organic matter provides readily available N, energy (carbon) and nutrients to the soil ecosystem. It also helps retain mineral nutrients (N, S, micronutrients) in the soil and make them available to plants in small amounts over many years, as the organic matter is mineralized. High-quality carbon and N provide a substrate to support an active soil microbial community.

Soil microbes are valuable, not because they supply nutrients directly, but because they enhance the synchrony of plant nutrient demand with soil supply by reducing large pools of free nutrients (and consequent nutrient losses from leaching and denitrification). Thus, microbes maintain a buffered, actively cycled nutrient supply (Snapp 1995). In addition, organic matter increases soil flora and fauna (associated with soil aggregation, improved infiltration of water and reduced soil erosion), complexes toxic Al and manganese (Mn) ions (promoting better root formation), increases the buffering capacity of low-activity clay soils, and increases water-holding capacity.

Examples of yield gains from farmers' fields in southern Africa through inorganic/organic combinations are presented in Table 2. Often the

largest gains are seen on research stations, where soil fertility is already high. On-farm gains are usually lower because of inherently low soil fertility, water deficits, and management compromises. A marked increase in the yield of pearl millet grain after the incorporation of crop residues was reported from field experiments conducted in Sadore, Niger. With the application of crop residues alone, grain yield increased from less than 0.2 mt/ha to nearly 0.8 mt/ha. Crop residues applied with fertilizer increased the grain yield to 2 mt/ha, compared to 1 mt/ha when fertilizer alone was used.

Further research is necessary to study how soil organic matter influences nutrient availability and uptake in various cropping systems. In southern Africa, agricultural intensification is often associated with the diminished availability of animal manure. As pressure on arable land rises, crops encroach on areas previously used for grazing, and livestock production becomes more difficult. This problem is more common in the unimodal rainfall areas of southern Africa, where the long dry season makes zero-grazing techniques difficult or impossible for smallholders, than in the bimodal rainfall areas of eastern Africa. Manure from cattle and other animals is very important for most farmers in Zimbabwe. It is less important in Zambia, and seldom available in Malawi, where livestock are scarce. But even in the best areas, the supply (and, as important, the quality) are inadequate for animal manure to maintain soil fertility on its own.

Nutrient Acquisition and Management in Organic Cropping Systems

Recently, there has arisen a tremendous interest in organic agriculture, especially in developed countries. Soil fertility research in organic cropping systems is, however, still in its infancy and further studies are necessary. For instance, research on organic onions at the University of California showed that organic farms have lower soil and plant nitrate levels than conventional farms, even though their yields were much the same. Soil nitrate levels were similar at the beginning of the season (about 20 ppm), but by mid-June nitrate in the conventionally farmed soils had increased to 76 ppm, and remained significantly greater than in the organic system until the end of the season. Nitrate levels on the organic farms remained constant at about 15 ppm through the entire cropping season. A similar pattern was found with soil ammonium. Nitrate-N in the onion roots and tops was also lower in the organic system than in the conventional system.

The question is how organic onions obtained adequate supplies of N despite the low nitrate levels in the soil and plants. The results suggest that nutrient acquisition and uptake patterns in conventional cropping systems in cropping patterns may differ from those in organic ones (Table 3). Although the pool of inorganic nutrients in the organic system may be fairly small, the nutrient supply may be sufficient to support crop growth because of the continual re-supply of nutrients by high turnover rates mediated by soil microbes.

Moreover, if farmers rely on organic sources of N such as compost and cover crops to meet the entire nutrient demand, it is important to determine how nutrient release from such materials can be synchronized with the nutrient demands of crops. Synchronizing nutrient release with nutrient demand using organic residues is technically challenging.

Laboratory incubation studies have shown that high-quality residues (with e.g. a low C/N ratio and a low percentage of lignin) supplied in combination with low-quality residues (e.g. a high C/N ratio and/or a high lignin content) can provide a continuous nutrient supply. N is released from high-quality residues first (Snapp *et al.* 1955a). This synchrony may also be influenced by plant genotypes and climatic patterns of daylight and rainfall (Ladha *et al.* 1993). Under cold, wet conditions, for example, surface mulches increase soilborne plant diseases, promote weed infestation, impede tillage and alter plant nutrient availability. Preliminary indications are that plants with a high lignin and polyphenolics content, and other anti-quality factors, may not release nutrients until after several growing seasons. Thus, these residues may be unsuitable for use as organic soil amendments (Myers *et al.* 1994). More research is necessary on how to increase plant access to nutrients in such situations. Humification parameters and electrophoretic procedures can be used to establish quality criteria for soil organic matter, and to follow the stabilization and turnover rate of organic amendments.

Pallant *et al.* (1997) reported that corn develops a larger root system under low-input/organic agriculture than in conventional systems. As a result, corn yields tend to be higher on average, especially during years when there is drought or nutrient stress. The reason is because the larger root systems of organically grown corn are more efficient in extracting whatever moisture and nutrients are available. Moreover, the team found some of the differences between systems to be surprisingly significant. For example, root density for low-input



Table 2. Examples of gains in maize yield obtained through a combination of organic and inorganic fertilizer at levels practicable on farmers' fields in Malawi and Zimbabwe

| Organic fertilizer | Inorganic fertilizer | Location & season | Maize grain yield (mt/ha) | | | | Yield of combined organic/inorganic as a % of single treatments |
|---------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------|---------------------------------------------------------------------------------|---------------------------|---------------|-----------------|-------------------------|-----------------------------------------------------------------|
| | | | No fertilizer | Organic alone | Inorganic alone | Organic + inorganic mix | |
| <i>Leucaena leucocephala</i> alley cropped with maize. 1.5 - 2.5 mt/ha of <i>Leucaena</i> prunings applied to maize | 30 kg N/ha applied to maize | Chitedze Research Station, Malawi, 1988-90 | 2.24 | 3.32 | 2.72 | 3.6 | 119 |
| Pigeonpea intercropped with maize in previous season; Pigeonpea residues incorporated into the soil | 48 kg N/ha applied to maize crop | Luyangwa Research Station, Malawi, 1993-95 | 0.87 | 1.70 | 1.98 | 2.31 | 126 |
| Cattle manure: 112 kg N, 13-25 mt/ha broadcast and plowed in before planting | 17 kg P, and 16 kg K/ha split between a basal dressing and topdressing | 6 communal farms, Wedza and Chinyika, Zimbabwe, 1994/95 season (a drought year) | 0.79 | 1.11 | 1.30 | 1.93 | 160 |

Note: These gains are from the first cropping season after fertilizer application. Additional gains can be expected in the

systems based on livestock were 5.51 cm root/cubic cm of soil, compared to 2.99 in conventionally fertilized corn/corn systems.

It must be borne in mind, however, that increasing needs of agricultural production in developing countries cannot be met either by "low input" schemes or by "organic farming" alone. This is because crop nutrient uptake tends to exceed nutrients applied in the form of fertilizer.

Research on Agronomic Strategies to Improve Nutrient Use Efficiency in Cropping Systems

Because chemical fertilizers are not practicable in many regions for economic and other reasons, an integrated approach using germplasm efficient in nutrient acquisition and use seems appropriate. Adoption of genotypes with a higher nutrient uptake efficiency (NUE) is relatively easy, since no

additional costs are involved, and no major changes in cropping systems are necessary. Also, nutrient efficient varieties contribute to sustainability in many other ways. They have a greater degree of disease resistance (thereby a reduced use of fungicides) due to enhanced membrane function and cell integrity, a greater ability to develop deep roots to penetrate subsoil in infertile soils, and greater seedling vigor which in turn gives higher seed yields (Graham and Welch 1996).

NUE is defined in several ways, such as efficiency of acquisition (plant nutrient content/available nutrient) or the physiological efficiency with which a nutrient is used to produce biomass (plant biomass/plant nutrient content) or grain (grain yield/plant nutrient content). It is also defined as the amount of additional grain yield per unit of fertilizer applied. Efforts to improve it must be guided by a thorough understanding of the soil and plant processes that govern NUE.

For example, an ideal and cost-effective approach to improving NUE in acid soils might be a combination of liming to neutralize soil acidity, coupled with selection for crops more tolerant to Al toxicity. In cropping systems where fertilizer use is already high, cost-effective technologies that improve NUE are necessary. In cropping systems with low fertilizer use, however, the most promising way of improving NUE is to add small amounts of high-quality organic matter and use crop varieties with a higher NUE.

Fertilizer use efficiency in many developing countries is generally low, seldom exceeding 25-30%. Modifications in fertilization methods, use of biological resources (e.g. *Azolla* and legumes as green manures), and genetic improvement can all help increase NUE. Although there are many fertilization technologies (effective formulations;

split applications; specification of suitable timing, particle size, and placement methods; development of slow-release materials and nitrification inhibitors; combined use of organic and inorganic fertilizers, etc.) which have long been established, they are not always accepted and adopted by farmers. Similarly, despite the knowledge that *Azolla* and *Sesbania* have high N supply potential to support higher yields, most rice farmers are averse to using them. Research must be initiated, therefore, to examine why farmers are not adopting these technologies, and find ways to make adoption easier.

A deficiency in secondary and micronutrients is another factor reducing N and P use efficiency. This is becoming more common in cropping systems worldwide. A good supply of secondary and micronutrients can improve the yield response to macronutrients considerably. In Malawi, for example, average maize yields improved by 40% as compared with the standard N-P recommendation when the deficiencies of B, Zn, S, and K were satisfied (Kumwenda *et al.* 1996).

Micronutrients can be included in common fertilizer blends, or applied directly as chelated powders and suspensions. However, research on how to optimize their supply from a cropping systems perspective is limited. For example, the existence of a regulatory interplay between S and N acquisition has been known for a long time. There are few studies, however, on how to use this knowledge in formulating S recommendations for various cropping systems.

Research on Physiological Mechanisms and Genetic Improvement of Nutrient Use Efficiency

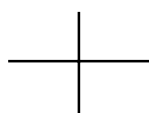
How to achieve genetic enhancement of NUE

Table 3. Selected rice genotypes that showed similar N uptake but different grain yield and NUE

| Genotype | Grain yield | N uptake (g m ²) | NUE |
|----------------------|-------------|------------------------------|-------|
| IR 50363-61-1-2-2 | 6.3* | 8.3 | 64.4* |
| IR 51009-155-2-3-3 | 4.7 | 7.4 | 55.3 |
| BG 380-2 | 6.5* | 8.0 | 70.0* |
| IR 50391-100-2-3-3-2 | 4.4 | 6.7 | 56.3 |
| IR 27325-63-2-2 | 6.6* | 8.5 | 69.7* |
| BR 51-46-1-C1 | 4.9 | 7.3 | 57.9 |

Source: Tirol-Padre *et al.* 1996

*Value is significantly different from the one below it at the 5% level



in crops used in a cropping season depends mainly on the diversity within each crop for acquisition and internal use of a particular nutrient. For example, genotypic variation in N acquisition results from differences in:

- Root characteristics such as surface area, weight, distribution and architecture;
- Amount and rate of uptake of N from various soil depths, including the efficiency of absorption and assimilation (Tirol-Padre *et al.* 1996);
- N-fixation (Shrestha and Ladha 1996), *and*
- Rhizosphere effects on the extent and pattern of N mineralization, transformation and transport in the soil.

Likewise, variation in the internal N use can arise from differences in:

- Internal N requirements for growth and development (Singh and Buresh 1994);
- The ability to translocate, distribute and remobilize absorbed N (Ladha *et al.* 1993);
- Flag leaf N import/export and leaf senescence patterns, *and*
- The efficiency of N use in converting CO₂ to carbohydrates.

Efficient genotypes often possess more than one of these characteristics. Tirol-Padre *et al.* (1996) speculated that N use efficiency in rice was a more stable and suitable criterion than N uptake. Their studies suggested that root properties influencing rates of N absorption and assimilation can limit the rates of N acquisition from the soil. Therefore, genetic modification of roots to increase the efficiency of absorption and assimilation is a useful objective.

As far as P use efficiency is concerned, plants adopt at least four different mechanisms to increase their access to native or applied soil P. These include:

- Modification of soil exploration by roots (through increasing absorptive area);
- Better symbiosis with soil microbes (such as arbuscular mycorrhizal fungi);
- Modification of the rhizosphere to increase nutrient availability (through release of enzymes or other compounds capable of liberating P from metal-P compound or organic complexes); *and*
- Reduced tissue P requirements (Marschner 1998).

In order to improve adaptation of a crop to low P conditions, it is important to explore genetic

variation for all these characteristics. While we have known for a long time that crops/varieties differ in the pools of soil P they can exploit, we still have a rudimentary understanding of the effects of such differences on the cropping system. In general, breeding for P use efficiency is considered easy in a crop which has wide genetic variation in P use efficiency, and which is stable in adaptation in terms of response to low P availability in different soils. Because of such characteristics, attempts to breed for increased P use efficiency were successful in the development of a navy bean cv. Sanilac (Schettini *et al.* 1987). Substantial diversity in P use efficiency parameters was also found in maize, rice and field bean (Baligar *et al.* 1997). The superior ability of some crops and genotypes, such as the large seeded Andean bean accession G19833, to utilize Ca-P more efficiently than others also offers the possibility of developing varieties that can be fertilized with Ca-phosphate or rock phosphate (Hoffland *et al.* 1992, Yan *et al.* 1995, 1996).

Besides low P availability, aluminum (Al) toxicity is considered a major constraint to crop growth in the acid soils which occupy nearly 30% of the world's land area. Tolerance to Al toxicity has been regarded as one of the most important traits for crops grown in these areas. However, field experiments conducted on Oxisols in Colombia indicated that rice growth was limited, not by Al toxicity, but by the low Ca content of the soil. They also indicated that rice genotypes adapted to acidic soils can tolerate conditions of low Ca (Okada, K., personal communication). Careful surveys and agronomic studies on such aspects are needed before we study Al tolerance mechanisms of crops.

Research on how to improve micro-nutrient use efficiency from a systems perspective has also received inadequate attention so far. There is substantial plant genetic diversity in acquisition of trace minerals from soils, but this has not been exploited widely by breeding programs. Nearly all micronutrient use efficiency traits so far studied seem to arise from a superior ability to extract the limiting micronutrient from the soil, rather than a capacity to survive on less of that nutrient. From the viewpoint of sustainability, it is especially important to develop genotypes with the latter trait. This can be done by investigating micronutrient acquisition mechanisms of wild forms and ecotypes. For example, in soils with low Cu availability, rye is more efficient than wheat in terms of Cu acquisition but its acquisition mechanisms are not entirely clear. Within a single crop, landraces of rice [Jalmagna (India), Xua Bue Nuo (China) and Zuchem (Bhutan)]

produced grains with 50, 60 and 70% more Fe than IR 36, which has an average concentration of Fe of 12.1 ppm. Madhukar, a rice variety from eastern India, and other aromatic varieties such as Milagrosa and Basmati, consistently produce grain with the highest amount of Zn (IFPRI 1996). Remobilization and retranslocation of micronutrients within plants also needs further research.

In certain cropping systems, phyto-siderophores (non-proteinaceous amino acids), rhizosphere microorganisms (through release of microbial siderophores) and root exudates are known to improve Fe and Cu mobilization through chelating insoluble Fe and Cu from the soil (Jolley and Brown 1989; Romheld and Marschner 1990). Research on ways to enhance the release of siderophores in different cropping systems may help in improving micronutrient use efficiency.

Research on implications of cultivating crops/genotypes that are very efficient in nutrient acquisition and utilization is important. Highly efficient crops may in fact contribute to soil mining, in which nutrient outflow exceeds inflow. This can adversely affect the sustainability of the system in the long run. It must be remembered that more effective mining of soil nutrient reserves is only a medium-term solution. Research on suitable methods for soil recapitalization in each cropping system is essential.

Models and Decision Support Systems for Nutrient Management in Cropping Systems

Rapid advances have been made in the development and application of quantitative and mechanistic crop models that allow a simultaneous evaluation of complex physical, chemical, and biological processes related to nutrient acquisition and dry matter production. For example, Beyrouthy *et al.* (1997) developed a mechanistic model which satisfactorily predicts N, P, and K uptake by rice, to examine the influence of each of 11 soil and crop parameters on nutrient uptake. Models also provide a means to simulate nutrient uptake by crops grown in rotations and mixed cropping systems, once basic parameters (nutrient supplying capacity of soil, root morphology, nutrient absorption kinetics, *etc.*) have been adequately defined. Models enable us to determine how far root and soil characteristics limit nutrient acquisition. This in turn is useful in developing site-specific nutrient recommendations. For example, fertilizer amounts for each homogenous area (in terms of soil and crop characteristics) can be

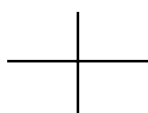
estimated using simulation models for crop growth and nutrient dynamics.

Most of the models developed to date are fairly robust in describing a single process (e.g., N dynamics) for an individual crop, but they need improvements if they are to be able to handle the multiple factors operating in a cropping system. Rather than discarding existing mechanistic models because of imperfections, we should continue to improve them by utilizing available data on soil nutrient levels and crop nutrient responses. Development of multi-criteria decision support systems such as Interactive CropSys (Caldwell and Hansen 1993), which links simulation models, databases, graphics programs, *etc.*, should be promoted. This may make possible the rapid analysis of nutrient use and requirements in cropping systems.

Nutrient Mapping and Sensor-Based Technologies

Site-specific nutrient management (optimizing the nutrient supply for individual sections of the field), based on critical analysis and quantification of inherent spatial and temporal variation in soil fertility and crop nutrient status, will be increasingly important from both the economic and the environmental point of view (Srinivasan 1999). Even in developing countries, where the farm size is usually small, marked differences in soils are often ignored in implementing a local cropping system. Geospatial information technologies such as geographic information systems (GIS) and remote sensing and global positioning systems (GPS) permit us to create nutrient status and recommendation maps for various cropping systems more easily than before.

For example, the spatial variability of N deficient areas within a field can easily be mapped using N reflectance index of canopy, GPS and GIS. However, further refinements in mapping and interpretation techniques are necessary to allow optimal management of nutrients. Likewise, advances in the development of both invasive (e.g. ion-selective field-effect transistors) and non-invasive (e.g. near infrared reflectance) sensing technologies will significantly contribute to more accurate determinations of in-field variability of soil nutrient status, and allow continuous data acquisition, processing, and input control. Practical use of nutrient sensing technologies in the field has so far been limited, mainly because of the cost and complexity of such technologies.



CONCLUSION

Sustainable crop production will obviously require enhanced flows of nutrients to crops. This in turn will involve larger nutrient reserves in soils, and higher nutrient uptake and utilization by crops. The productivity of current cropping systems, and the protection of environmental quality, cannot be sustained for long if we continue such practices as the application of too many or too few nutrients, and inefficient utilization of crop residues and wastes. Research must be intensified, so that we can quantify measurable sustainability indicators such as levels of organic carbon, soil microflora and fauna, nutrients lost through runoff and leaching, and the rates of change in those variables as affected by specific nutrient management practices in cropping systems.

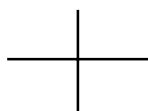
Since such indicators and their responses are likely to vary with each cropping system, due to the many interactions among soils and crops in diverse climates, the adoption of location-specific strategies for nutrient management is essential. Design and development of comprehensive nutrient management plans for various cropping systems will also require an integrated approach, which concentrates on processes and links various scientific disciplines.

Research initiatives for sustainable nutrient management at the level of the cropping system must be conceived, therefore, on the basis of a holistic understanding of interactions among production, environmental, social, biological and economic components. Sensitivity to the needs of ultimate users (farmers and the public) is also important when research and implementation is being planned, and in assessing the value of system adjustments for achieving sustainable nutrient management.

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