Improving the Efficiency and Sustainability of Fertilizer Use in Drought- and Submergence-Prone Rainfed Lowlands in South-East Asia

R.W. Bell1*, C. Ros2 and V. Seng2

Abstract

In the rainfed lowlands of South-East Asia, rice yields are low and often respond weakly to fertilizers. Studies of soils in Cambodia and North-East Thailand suggest that a complex combination of factors restrict rice yield and nutrient uptake in response to loss of soil-water saturation. Two significant and closely linked constraints are variable rainfall and lack of soil nutrients. Intermittent flooding and drying of soils depresses availability of some nutrients, even when water supply is adequate. Moreover, extreme fluctuations in soil-water levels may impair root activity, further restricting nutrient uptake. The resulting inefficient uptake apparently leads to weak responses to fertilizer nitrogen and phosphorus. Developing management strategies for optimizing the mineral nutrition of rice in drought-prone rainfed lowlands, particularly in the presence of aluminium toxicity and potassium deficiency, thus depends on understanding the function of rice roots in nutrient uptake and their response to temporal and spatial variation in water content and soil properties. This need is particularly relevant for the adoption of direct sowing of rice, which results in a root system developing initially in aerobic conditions, then being exposed to flooded conditions and, during the growing season, returning to aerobic and, in extreme cases, to drought conditions. With the potential increase of fertilizer use in the future, and thus potential pollution of groundwater and eutrophication of water bodies, new management strategies also need to assess risks of such contamination and seek ways of preventing it.

RAINFED lowland rice is grown in a wide diversity of environments, most of which are located in South and South-East Asia (Wade et al. 1999). From the perspective of crop nutrition and rice productivity, the main distinguishing characteristics of the rainfed lowlands are lack of irrigation water and non-continuous flooding of soil during crop growth (Zeigler and Puckridge 1995). While rainfed lowland rice is usually grown in relatively level, bunded fields to retain surface water, the depth and duration of field flooding vary greatly from year to year, within a growing season and spatially over relatively short distances within a field. Rainfed lowland rice is often exposed to an extremely variable water regime during growth.

Yields in rainfed lowlands are typically half those in irrigated rice ecosystems (Wade et al. 1999). The amount and timing of rainfall is considered as the major constraint to rice productivity, followed by low soil fertility, as represented by a range of limiting factors, including salinity, alkalinity, Fe toxicity, sulfide toxicity, N, P, K, and Zn deficiencies, and organic and acid sulfate conditions. The lack of soil fertility is exacerbated by the effects of a changing soil-water regime on nutrient forms and their availability in the soil. Low rates of fertilizer or, as is often the case, no fertilizer, mean that many of these constraints continue limiting rice production in farmers’ fields.

KEYWORDS: Fertilizer, Loss of soil water saturation, Nutrient availability, Deficiency, Nutrient uptake, Root function

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Within the rainfed lowland ecosystem, several subecosystems have been recognized, based on the maximum depth of water accumulating in the fields. Within areas where water depth is <25 cm, a further subdivision is made according to the prevalence of drought and/or submergence during the growing season (Table 1). In each country of South and South-East Asia, most of the subecosystems are represented, but the mix differs so that the main issues for soil fertility management (and breeding) also differ in emphasis from country to country.

About 20% of rainfed lowland rice grows in favourable environments where only minor events of drought or submergence limit rice production. These areas are relatively more prevalent in Indonesia, Philippines, Vietnam, Laos and Myanmar. In contrast, more than half of the rainfed lowlands of India and Thailand occur in drought-prone environments. The drought-prone environments of North-East Thailand (and Cambodia and Laos) differ from those in India because, while the rainy period is long, rainfall has an overall bimodal distribution and, in any given season, is erratic in amount and distribution. In contrast, the drought-prone areas of north-east India are characterized by a short growing season with an end-of-season drought being common. In Cambodia, more than half of the rainfed lowlands are on lands that are susceptible to both drought and submergence, either in different years or possibly the same year. Submergence is a widespread constraint for rainfed lowland rice, particularly in Vietnam, Myanmar and Bangladesh. Medium to deep water levels are most prevalent in the rainfed lowlands of Myanmar, Indonesia, the Philippines and Bangladesh.

In this paper, we focus on the less favourable subecosystems of the rainfed lowlands in South-East Asia and hence emphasize the soil and environmental constraints to efficient and sustainable fertilizer use in Cambodia, Laos and Thailand. Generally, in these areas, only one rice crop is grown per year. A long dry season follows the rice harvest and soils remain dry for several months of the year, with limited plant growth occurring. In Thailand and Cambodia, an early monsoon season from May to June is followed by a short dry period in June-July before the main rainy season (Fukai et al. 1995). Transplanting is often delayed until there is sufficient rainfall at the start of the main rainy season for flooding of the soil to occur.

**Soils**

**Nutrients**

The soils of the rainfed lowlands of South-East Asia usually have low levels of nutrients, especially of N and P and, to a lesser extent, K and S. This is especially so in Cambodia (White et al. 1997; Pheav et al. 1996), Laos (Linquist et al. 1998) and North-East Thailand (Ragland and Boonpukdee 1987). Indeed, given the low rates of fertilizer applied by farmers, the relatively low rice yields in rainfed lowlands of each of these countries can be attributed largely to low soil fertility. In Cambodia, rainfed lowland rice will respond to N on virtually all soils, including even the old marine floodplain soils that receive annual depositions of alluvial sediment, and are inherently more fertile than other rainfed rice soils of Cambodia (Table 2). Similarly, all the soils, except the old marine floodplain soils, are low in P and yield responses to P application on rainfed rice are expected. Many of the soils are low in K, and responses to this nutrient have been reported, especially when the supply of N and P is improved by fertilizer application. Other deficiencies, including S, Mg and B, have been demonstrated in rainfed rice in Cambodia (Wade et al. 1999), for rice production in the Mekong delta, (CaCl2) pH of 5.5 to 6.0 (Seng et al. 1999). At these pH levels, the soil can be rather severe, and for rice may be unclear.

Many of the soil fertility constraints are shared with other crops, especially when the supply of N and P is improved by fertilizer application. Farmers, the relatively low rice yields in rainfed lowlands of each of these countries can be attributed largely to low soil fertility. In Cambodia, rainfed lowland rice will respond to N on virtually all soils, including even the old marine floodplain soils that receive annual depositions of alluvial sediment, and are inherently more fertile than other rainfed rice soils of Cambodia (Table 2). Similarly, all the soils, except the old marine floodplain soils, are low in P and yield responses to P application on rainfed rice are expected. Many of the soils are low in K, and responses to this nutrient have been reported, especially when the supply of N and P is improved by fertilizer application. Other deficiencies, including S, Mg and B, have been demonstrated in rainfed rice in Cambodia (Wade et al. 1999), for rice production in the Mekong delta, (CaCl2) pH of 5.5 to 6.0 (Seng et al. 1999). At these pH levels, the soil can be rather severe, and for rice may be unclear.

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**Table 1.** Relative occurrence (as percentage of total area) of the main rainfed lowland rice subecosystems in South and South-East Asia.

<table>
<thead>
<tr>
<th>Country</th>
<th>Shallow (0-25 cm) and prone to:</th>
<th>Medium to deep (25-50 cm)</th>
<th>Total area ('000 ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No water stress</td>
<td>Drought</td>
<td>Drought + submerg.</td>
</tr>
<tr>
<td>Indonesia</td>
<td>58</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>Philippines</td>
<td>51</td>
<td>16</td>
<td>4</td>
</tr>
<tr>
<td>Myanmar</td>
<td>51</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>Vietnam</td>
<td>38</td>
<td>19</td>
<td>0</td>
</tr>
<tr>
<td>Laos</td>
<td>33</td>
<td>33</td>
<td>33</td>
</tr>
<tr>
<td>Bangladesh</td>
<td>16</td>
<td>16</td>
<td>19</td>
</tr>
<tr>
<td>India</td>
<td>12</td>
<td>51</td>
<td>15</td>
</tr>
<tr>
<td>Cambodia</td>
<td>10</td>
<td>29</td>
<td>57</td>
</tr>
<tr>
<td>Thailand</td>
<td>9</td>
<td>52</td>
<td>24</td>
</tr>
<tr>
<td>Total</td>
<td>20</td>
<td>36</td>
<td>15</td>
</tr>
</tbody>
</table>


**Table 2.** Chemical properties of representative rainfed lowland rice soils in South and South-East Asia.

| Property | Percentage of sampled  
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Water-soluble P (mg kg⁻¹)</td>
<td>11.3</td>
</tr>
<tr>
<td>Olsen P (mg kg⁻¹)</td>
<td>14,300</td>
</tr>
<tr>
<td>Total N (mg g⁻¹)</td>
<td>277</td>
</tr>
<tr>
<td>CEC (cmol(+)) kg⁻¹</td>
<td>6,039</td>
</tr>
<tr>
<td>Exch. K (cmol(+))</td>
<td>5,328</td>
</tr>
<tr>
<td>Organic C (mg g⁻¹)</td>
<td>747</td>
</tr>
</tbody>
</table>

Low soil pH is prevalent in lowland soils used for rainfed rice in Cambodia, but the consequence of this for rice production is still unclear. In their oxidized state, pH (CaCl₂) is as low as 3.9, and Al saturation 70% (Seng et al. 1996). However, reducing relatively rapid increases in soil pH to values in the range of 5.5 to 6.0 after 2–3 weeks (Seng et al. 1996, 1999). At these pH values, no KCl-extractable Al can be detected; hence, Al toxicity for rice in flooded soils can be ruled out (Seng 2000). However, as discussed below, the consequences of temporary loss of soil-water saturation for soluble Al levels in the soil and for rice nutrition and water uptake are still unclear.

Many of the same nutrient constraints for rainfed lowland rice production found in Cambodian soils are shared with soils of North-East Thailand. The often extremely sandy nature of the latter soils (clay contents of <5%; Kawaguchi and Kyuma 1977; Mitsuhashi et al. 1986; Willett and Intrawech 1988) is attributed to ferrolysis, which leads to the destruction and leaching of clays. In their oxidized state, the sandy soils are acidic with a pH (H₂O) between 4.6 and 5.0. Despite low levels of N, P, K and S, response to inorganic fertilizer is poor (Ragland and Boonchuay 1997). These conclusions are further supported by a recent international study by Wade et al. (1999), who found that yields of rainfed lowland rice at sites in North-East Thailand were generally lower than at other sites in Bangladesh, Indonesia, India and the Philippines. In addition, in Thai soils, responses to N–P–K or complete fertilizer were generally weaker than in other sites.

In Laos, 85% of rainfed lowland rice crops in the northern region and 100% of those in the central and southern regions responded to N–P–K fertilizer (Linquist et al. 1998). Nitrogen deficiency was the most prevalent, with 40%–50% of crops responding to N alone and another 30% when P also was applied. Some evidence suggests a S deficiency for rice in Laos, and leaf analysis suggest that Mg levels may also be too low for rice.

### Physical properties

Soil physical properties have a significant bearing on soil-water storage and retention, nutrient storage and leaching, the timing and ease of cultivation of soils and root growth. Soils that have been under lowland rice cultivation for several years develop a compacted layer at a depth of 10–40 cm in their profile (Samson and Wade 1998). The layer aids in retaining rainwater but may also restrict root penetration. In North-East Thailand, Laos and Cambodia, at least half of the lowland rice soils are sandy, either throughout the profile or in the surface layers (White et al. 1997; Linquist et al. 1998). This, coupled with the shallow plough pan and the rice crop’s shallow root system, limits water storage and retention in the root zone. Even the presence of a conventional plough pan on coarse sandy soils is not sufficient to retain water for long after the rain stops. Sharma (1992) reported that water stress is evident in rice on sandy soils from North-East Thailand within 1 week after the rains cease.

However, when a significant amount of water in the profile is stored below the plough pan, mechanical impedance in the compacted layer may restrict root access to the stored water. Ahmed et al. (1996) found that increasing root mass density in the 10–20 cm layer of rainfed lowland soils of north-west Bangladesh increased rice yields (Table 3). Deep cultivation of 20 cm or growing a deep-rooted crop like the legume Sesbania aculeata before rice both decreased penetration resistance in the 10–20 cm layer and increased rice yields by 0.5–1.0 t ha⁻¹.

Deep sandy soils in North-East Thailand and Cambodia pose particular problems with water retention that not even the conventional plough pan can resolve in these clays. A long period of permanent waterlogging and plant growth in waterlogged soils, anoxic, anaerobic conditions leading to a deep plough pan, is the main problem. The E horizon is usually not well developed in the soil profile.

### Table 2. Chemical properties of the main soils used for cultivating rainfed lowland rice, Cambodia.

<table>
<thead>
<tr>
<th>Property</th>
<th>Deep sandy soils</th>
<th>Shallow sand lying over clays</th>
<th>Depression soils</th>
<th>Black soils of rainfed lowlands</th>
<th>Brown plain soils</th>
<th>Old marine and lacustrine floodplain soils</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of shallow-water rainfed rice crop</td>
<td>13</td>
<td>30</td>
<td>13</td>
<td>5</td>
<td>15</td>
<td>21</td>
</tr>
<tr>
<td>pH (1:1 soil:water)</td>
<td>5.6</td>
<td>5.9</td>
<td>5.8</td>
<td>5.1</td>
<td>5.5</td>
<td>5.9</td>
</tr>
<tr>
<td>Olsen P (mg kg⁻¹)</td>
<td>1.3</td>
<td>0.4</td>
<td>1.0</td>
<td>2.6</td>
<td>3.1</td>
<td>4.6</td>
</tr>
<tr>
<td>Total N (mg g⁻¹)</td>
<td>0.5</td>
<td>0.3</td>
<td>0.6</td>
<td>1.1</td>
<td>0.9</td>
<td>1.0</td>
</tr>
<tr>
<td>CEC (cmol(+)+ kg⁻¹)</td>
<td>1.8</td>
<td>1.3</td>
<td>6.3</td>
<td>6.7</td>
<td>18.2</td>
<td>13.5</td>
</tr>
<tr>
<td>Exch. K (cmol(+)+ kg⁻¹)</td>
<td>0.02</td>
<td>0.03</td>
<td>0.07</td>
<td>0.06</td>
<td>0.16</td>
<td>0.19</td>
</tr>
<tr>
<td>Organic C (mg g⁻¹)</td>
<td>4.7</td>
<td>2.9</td>
<td>6.6</td>
<td>10.9</td>
<td>8.8</td>
<td>9.1</td>
</tr>
</tbody>
</table>

overcome. The rapid percolation of water through these soils means that they can lose saturation quickly after rainfall ceases. Garrity and Vejpas (1986) showed that an impermeable plastic sheet installed at 40 cm deep in a sandy lowland soil at Ubon Ratchathani, North-East Thailand, prevented water percolation loss and increased rice yields. Subsoil compaction on the same soil type was also effective in reducing percolation losses of water by 88%, and decreased from 60 to 17 the number of days when loss of soil-water saturation occurred, thus increasing yields by 60%-90% (Sharma et al. 1995).

Table 3. Effect of tillage depth on penetration resistance of soils, root mass density and grain yield of rice in a rainfed lowland soil, north-west Bangladesh.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Tillage depth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6-8 cm 12-15 cm 18-20 cm 6-8 cm with Sesbania as pre-rice crop</td>
</tr>
<tr>
<td>Penetration resistance (MPa)</td>
<td></td>
</tr>
<tr>
<td>0-10 cm</td>
<td>1.25 1.00 0.75 0.6</td>
</tr>
<tr>
<td>10-20 cm</td>
<td>2.20 1.25 1.25 1.1</td>
</tr>
<tr>
<td>Root mass density (kg m^-3 at flowering)</td>
<td></td>
</tr>
<tr>
<td>0-10 cm</td>
<td>3.73 3.75 3.57 3.84</td>
</tr>
<tr>
<td>10-20 cm</td>
<td>0.07 0.15 0.19 0.18</td>
</tr>
<tr>
<td>Grain yield (t ha^-1)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.9 4.3 4.5 4.5</td>
</tr>
</tbody>
</table>

Source: Ahmed et al. (1996).

Fluctuating water regimes comprise the defining characteristic of rainfed lowlands. Loss of soil-water saturation may occur at any time from transplanting onwards and for periods of up to several weeks at a time. Generally, rainfed lowland rice soils will be saturated and flooded at transplanting because, if possible, farmers delay transplanting until there is sufficient water to facilitate transplanting, and to maximize plant survival. An example from Seng et al. (1996) illustrates the variability of the soil-water regime for a rainfed lowland rice crop. In the 6 weeks after transplanting, soils lost saturation at the surface during three periods, each of about 4-7 days (Figure 1) and coinciding with maximum tillering. Thereafter, for 6 weeks, rainfall was adequate to maintain a water level above the soil surface, but for the remainder of the growing season, including panicle initiation, the soil was again exposed to intermittent loss of soil-water saturation. Surprisingly, relatively few studies report on the depth of the perched water table during the growing season so that the effects of loss of soil-water saturation on nutrient availability are poorly defined when comparing experimental results among sites and seasons. Installation and monitoring of observation bores in experimental plots are relatively simple and may add value to many experiments on fertilizer response in the rainfed lowlands.

Flooding has mostly beneficial effects on the availability of nutrients and their uptake by rice (Ponnamperuma 1972). Flooding, by increasing pH and P availability and decreasing levels of soluble Al, particularly and significantly benefits growth and nutrient uptake of rice growing on sandy, acidic, low-fertility, rainfed lowland soils (Ponnamperuma 1972; Willett and Intrawech 1988).

Flooding also has possible negative consequences, including increased levels of Fe^2+ in some soils, loss of NO_3\textsuperscript{-} - N, sulfide toxicity, organic acid toxicity and Zn deficiency. Symptoms of iron toxicity have been reported in rice on some soils of Cambodia but the yield losses associated with this disorder were not quantified (White et al. 1997). Application of S-containing fertilizers to sandy soils in Cambodia and North-East Thailand have been reported to cause toxicity by sulfides forming under flooded conditions, especially when soils are also supplied with organic manures (Willett and Intrawech 1988; White et al. 1997). The management of N under flooded conditions is different from that on oxidized soils. Under flooded conditions, NO_3\textsuperscript{-} - N is subject to losses by leaching, except if an impermeable hardpan exists, and by denitrification in the reduced layers of flooded soils. Thus, NO_3 present in soils at flooding may be lost, whereas NH_4 - N supplied and incorporated into the flooded soil or released by mineralization of organic matter is relatively stable.

When flooded soils lose saturation, re-oxidation reverses the beneficial changes that occurred during flooding. Several studies have examined the effects of draining a previously flooded soil on nutrient forms and availability for upland crops grown after rice (Willett and Higgins 1980; Sah and Mikkelsen 1986).
On acid soils, pH drops and soluble Al re-appears. Oxidation of Fe$^{2+}$ after drainage of flooded soil removes the risk of Fe toxicity, but generates amorphous Fe oxides that react with available forms of P to decrease P availability. Ammonium N oxidizes readily to NO$_3$. These changes in nutrient availability obviously are important considerations for nutrient supply to upland crops grown after rice. Typically, upland crops require more P after a flooded rice crop than after upland rice (Brandon and Mikkelson 1979). This fact has implications for the growing dry-season crops after rice, using stored soil water.

In the rainfed lowlands, the water regime is more complex and dynamic than the above cases where soils planted to irrigated rice are drained after harvest and planted to upland crops. Significant periods of loss of soil-water saturation occur intermittently throughout the growing season (e.g. Seng et al. 1996; Trebuil et al. 1998). The implications of the temporary periods of loss of soil-water saturation for nutrient availability are not fully understood, although growth may be depressed as nutrient availability decreases (Fukai et al. 1999). Laboratory studies show that intermittent flooding of soils results in a significant loss of soil N (Patrick and Wyatt 1964). Oxidation of NH$_4$ to NO$_3$ occurs during loss of soil-water saturation, and the NO$_3$ is then subject to leaching as the soil water drains below the root zone, and to denitrification once re-flooding of the soil occurs. In rainfed lowlands, where loss of soil-water saturation may occur on several occasions during the critical early growth stages, including tillering and panicle initiation (Figure 1), significant losses of N are expected to occur.

Seng et al. (1999) tested the effect of a 3-week period of loss of soil-water saturation on P uptake by rice in a pot experiment with two acid rainfed lowland soils from south-eastern Cambodia. They found that temporary loss of soil-water saturation led to decreased P uptake and shoot dry matter, whether with and without P fertilizer application. The decreases were attributed to the decreased availability of P during the period of loss of soil-water saturation. Subsequent field experiments on the same soil also suggested that the period of loss of soil-water saturation also depressed P uptake by rice (Seng 2000). However, Willett and Intrawech (1988) and Seng (2000) suggested that the increase in soluble Al following re-oxidation of the soil was a possible additional factor limiting P uptake during periods of loss of soil-water saturation.

**Improving the Efficiency of Fertilizer Use**

The weak responses of rainfed lowland rice to fertilizers, despite low soil fertility, suggest that the
efficiency of fertilizer use can be increased, but taking into account not only soil factors limiting nutrient uptake but also plant factors.

Root biology

Rice roots can greatly modify their rhizosphere and in doing so, improve the availability of nutrients for uptake. However, optimal benefit from these root characteristics can only be captured if the roots are able to access the pools of water and nutrients available in the soil by appropriate root exploration. Limitations on root exploration are a function of both the genetics of a cultivar that determine the structure of the root system and its distribution in the soil, as well as soil physical and chemical factors that limit root growth. Developing management strategies to optimize mineral nutrition of rice in drought- and submergence-prone rainfed lowlands depends on understanding the function of rice roots in nutrient and water uptake and their response to temporal and spatial variation in water content and to soil physical and chemical properties.

Extreme fluctuations in soil-water levels may impair root activity, thus restricting nutrient uptake either temporarily or in the longer term. However, the function of the root system in nutrient uptake under changed water regimes is not well understood (Samson and Wade 1998). The dynamic nature of the soil-water regimes in rainfed lowlands may also mean that there is a distinct advantage in roots having a rapid and plastic response to changing water supply and redox potential.

Lowland rice has an unusually shallow root system. Generally, 70% or more of the roots are in the 0-10 cm layer, 90% in the 0-20 cm layer, and very few roots penetrate below 40 cm (Sharma et al. 1994; Figure 2). In contrast, upland rice can have rooting depths between 70 and 80 cm (Morita and Abe 1996). The shallow rooting behaviour of lowland rice is clearly controlled partly by genetics and partly by the soil's physical and chemical properties. Sharma et al. (1994) suggest that lowland rice cultivars show genotypic differences for root length density, although no differences were found among three cultivars for depth of maximum root penetration.

Sharma et al. (1994) also compared three cultivars, KDML 105, RD6 and IR46, at three sites representing high and low topographical positions, and clay and loamy sand textures. Measurable differences in root length density among the cultivars were most consistently found in the 10-30 cm layer. Cultivar differences in root length density were most obvious in the loamy sand and less so in the clay soil. Somewhat surprisingly, root density was greater in the 0-10 cm layer in the high fields, where the perched water table was below the soil surface for most of the season, than in the low fields where the soil surface was flooded. Unfortunately, the effects of root length density on nutrient uptake were not examined, although anoxic conditions can markedly alter nutrient availability in the rhizosphere.

To grow under anoxic conditions, rice roots carry \( \text{O}_2 \) to respiring tissues through longitudinal gas channels (known as aerenchyma) found in the cortex. Aerenchyma development and \( \text{O}_2 \) flux to root tips increase in response to anoxic conditions (Colmer et al. 1998). Oxygen may leak along the root axis, with excess leaking occurring from the older basal roots, thus limiting the amount of \( \text{O}_2 \) that can be delivered to the root tips. Hence, under flooded conditions, the depth of root growth may be limited by the amount of \( \text{O}_2 \) that can be delivered to the root tips. Cultivar selection for decreased \( \text{O}_2 \) leakage from basal roots under anoxic conditions may be advantageous.

![Figure 2. Decrease, with soil depth, in root length density of rice at heading, in a rainfed lowland soil. (After Samson and Wade 1998.)](image-url)
Colmer et al. (1998) suggested that cultivars differ in the degree of aerenchyma development. They found two lowland cultivars that responded to stagnant anoxic solutions by decreasing \( O_2 \) leakage to negligible levels at 20-25 mm from root tips. In contrast, neither of the two upland cultivars showed any decline in \( O_2 \) leakage along the root axis in response to anoxic conditions. However, even if \( O_2 \) leakage in basal roots can be decreased, Kirk and Du (1997) showed that a significant proportion of \( O_2 \) leakage also occurred from fine lateral roots, and that these roots can proliferate from basal as well as apical parts of the root axis.

Kirk and Du (1997) also reported that P deficiency increased both root porosity and the rate of \( O_2 \) released per plant into the rhizosphere. Releasing \( O_2 \) into the rhizosphere is beneficial under anoxic conditions because it oxidizes Fe\(^{2+}\) and causes the soil pH of the rhizosphere to decline by 1 or 2 units. The excess uptake of cations relative to anions by rice under anoxic conditions also contributes to rhizosphere acidification. Collectively, these mechanisms increase P availability to rice because, in the acid rhizosphere, extractable-P levels increase. Rhizosphere acidification also appears to increase Zn uptake, but decreases uptake of NH\(_4^+\) and K (Kirk et al. 1994).

While root nutrient and water uptake processes under oxic or anoxic conditions is reasonably well understood, very little is known about how nutrient and water uptake by rice roots responds to a changing soil-water regime. In rainy lowlands, roots may be exposed for most of the growing season to anoxic conditions, interspersed with periods of loss of soil-water saturation. Alternatively, the roots may be mostly exposed to oxic conditions with periods of anaerobia. The transition from oxic to anoxic conditions appears to result in increased root porosity in only some cultivars (Colmer et al. 1998). Whether adaptive responses in root structure or physiology occur as conditions change from anoxic to oxic is unclear. Neither is it clear whether roots adapted to anoxic conditions effectively absorb nutrients and water when exposed to oxic conditions. Response to loss of soil-water saturation may require rapid initiation and growth of new roots adapted to these conditions. The dynamics of root response and the functional efficiency of roots for nutrient and water uptake under changing soil-water regimes require further research.

The problems of root adaptation to changing soil-water regimes are compounded in direct seeding. The roots of direct-seeded rice initially develop under oxidized conditions, then are exposed to anoxic conditions and, during the growing season, return to oxic conditions, which, in extreme cases, can mean drought. Fertilizer rates and methods of application developed for transplanted rice may have to be re-examined for direct-seeded rice. Detailed studies of root biology and physiology during the various transitions between oxic and anoxic soil conditions are needed to develop a rational basis for modifying existing fertilizer recommendations for direct-seeded rice crops.

**Cultivars**

Breeding for nutrient efficiency and adaptation to the variable growing environments of rainfed lowlands may be a cost-effective approach towards making a major impact on the productivity of drought- and submergence-prone rainfed lowlands, provided traits associated with efficiency in that environment can be identified. Ample evidence exists of variation in nutrient efficiency among rice germplasm in low-fertility rainfed lowlands in Laos and Thailand (Fukai et al. 1999). However, selection of germplasm for such conditions is difficult (Cooper et al. 1999), as is the management of water use and nutrient availability. Fortunately, nutrient efficiency appears to be expressed whether plants are grown with or without fertilizer application, thus simplifying the task of selecting because only one nutrient regime needs to be tested rather than two.

The results of field-screening studies for adaptation to low-fertility soils of the rainfed lowlands in Laos suggest that internal efficiency is a genetically determined trait that, overall, is consistent across environments (Fukai et al. 1999). Low nutrient concentration in the plant and higher nutrient allocation to grain were identified as potential selection criteria for nutrient-use efficiency.

**Soil physical properties**

Shallow rooting depth is a major constraint to productivity for rainfed lowland rice. Alleviating soil physical constraints to root penetration may therefore increase rice productivity by increasing access to stored water and nutrients in the deeper layers of the soil profile. If roots can penetrate the shallow plough pan, then rice crops can extract significant amounts of N from below 20 cm (Ventura and Watanabe 1984). Kundu and Ladha (1999) reported that deep cultivation increases rice yields. In Korea, increasing cultivation depth from 14 to 19 cm increased root depth from 27 to 36 cm and rice yield from 4.5 to 8.1 t ha\(^{-1}\). Increasing cultivation depth from 15 to 40 cm on a soil with a hardpan at 15 cm increased both N uptake and grain yield (Kundu et al. 1996). The scope for increasing cultivation depth with draught animals is of course limited. In Cambodia, a pair of working animals can achieve a cultivation depth of 7–10 cm (Rickman et al. 1997). However, increasing availability of tractors for primary cultivation is making deeper cultivation possible on rainfed
lowland soils with shallow hardpans. In 1996, for example, about 12% of primary cultivation in Cambodia was by tractor (Rickman et al. 1997). In contrast to the above, studies at Ubon Ratchathani, North-East Thailand, suggested that subsoil compaction of deep sandy soils helps increase grain yield (Trebuil et al. 1998). Compaction in the 10–80 cm layer of soil was achieved by 10 passes with a 12-t vibrating roller. On such deep sandy soils, percolation is so rapid that the soil drains very quickly after rain. The primary benefit of compacting this deep sandy soil was to decrease saturated hydraulic conductivity from 38 to 12 cm day$^{-1}$ and to increase the duration of surface flooding of soils from 1 to 9 weeks. However, even on these deep sandy soils, the importance of deep root penetration was still evident. Deep cultivation to 20 cm following compaction increased yields relative to shallow cultivation (7–10 cm) of the compacted profile.

However, apart from the practical consideration of how to achieve subsoil compaction at a reasonable cost to small farmers, the benefits were season dependent. In a season where water supply was adequate throughout, crops failed to respond to subsoil compaction + conventional fertilizer rates, requiring higher nutrient supply to benefit fully from the improved water retention (Trebuil et al. 1998). The decrease in percolation rates with subsoil compaction was insufficient to retain water in the soil profile after the rice harvest, hence providing no opportunity for growing a post-dry-season rice crop on the residual moisture.

**Soil water–nutrient interactions**

Nutrient losses from the root zone and decreases in availability of nutrients to rice roots are the two key processes that need to be managed if fertilizer-use efficiency is to be increased in rainfed lowlands.

**Nitrogen**

Considerable scope exists for decreasing N losses. Nitrate N that accumulates during the dry season may be substantially lost during early season rains, even before the rice is transplanted (Kundu and Ladha 1999). On deep sandy soils with high percolation rates, leaching losses are difficult to prevent with conventional practices. One strategy is to grow pre-rice crops in the early rainy season to capture NO$_3$–N and recycle it for the rice crop as organically bound N. The N mineralizes and is supplied as NH$_4$–N to the rice (George et al. 1994). Pulse crops like mung beans that mature in 65 days can be planted in May and harvested before the main rainy season in July–August. However, in many parts of Cambodia, crops grown during the early rainy season were unsuccessful because of temporary flooding of soils. Sesbania, in contrast, tolerates waterlogging and, in 45–60 days, produces 1–18 t of aboveground fresh biomass per hectare (CIAP 1994). Incorporating sesbania into the soil before transplanting rice increased rice yield by 40% in on-farm trials in Cambodia (Nesbitt 1997). The benefits are usually attributed to improved N supply for rice from N$_2$ fixation by sesbania. However, the capture and recycling of accumulated soil NO$_3$–N may also be a significant benefit of growing sesbania during the early rainy season, because the amount of N$_2$ fixation is usually related to soil N supply. If the supply is high, then N$_2$ fixation is typically low and vice versa (George et al. 1994).

A second strategy, carried out in most of Cambodia, Laos and North-East Thailand, is to leave the soils fallow after the rice harvest. Animals usually graze the rice stubble during the dry season. In addition, volunteer weed and pasture plants may grow if residual soil water is sufficient, or in the early rainy season. P.F. White (pers. commun., 1999) noted that leguminous pasture species growing in the early rainy season increased in biomass, using residual P from fertilizer applied to rice. The N$_2$ fixed during the early wet season may therefore be a significant spin-off benefit to the farming system from P fertilizer application. Equally important may be the uptake by volunteer pasture species and weeds of NO$_3$–N that accumulates in the soil during the dry season (George et al. 1994). Further research is needed to improve the management of the annual pasture-fallow period to increase nutrient availability to rice.

The third alternative for increasing the capture and recycling of NO$_3$–N accumulating in the soil after the dry season is to direct sowing rice during the early rainy season.

**Phosphorus**

If P uptake is restricted during growth, particularly at transplanting, loss of soil-water saturation may impair growth and final yield (De Datta et al. 1990; Seng et al. 1999; Seng 2000), although the relative sensitivity of yield to P deficiency at different stages of crop growth is poorly understood. Improved understanding would permit better tactical decisions on correction during the growing season. Options for minimizing the impact of periods of loss of soil-water saturation are either to use cultivars that are efficient in P uptake and use and presumably would be best able to cope with a temporary decline in P availability (Fukai et al. 1999); or to treat soil with straw (Seng et al. 1999). Straw keeps the redox potential lower during the period of soil-water
saturation loss, thus apparently decreasing the extent of Fe$^{3+}$-oxidation and minimizing losses in P availability due to reaction with Fe oxides. Other forms of organic matter added to the soil at planting, including cow manure, or residues from pre-rice pulse crops or green manures like sesbania, can help minimize losses of P during periods of soil-water saturation loss. The minimum amount of organic matter required to make a difference is not known, but Seng et al. (1999) had applied the equivalent of 5 t of straw per hectare.

Loses of P in leachate from lowland rice soils have not been adequately quantified, although Cho et al. (2000) estimate that 0.2 kg ha$^{-1}$ of P are leached. On sandy soils, however, recent findings suggest higher rates of P leaching. Lindquist et al. (2000) examined residual availability of P fertilizer on sandy lowland rice soils in Laos and found that 48% to 85% of the P was not used in the first crop, probably because of significant leaching of P through high percolation rates and low P sorption. Leaching of P has not usually been considered a significant issue for P nutrient management, but the prevalence of sandy lowland rice soils in North-East Thailand, Cambodia and Laos suggest that P leaching needs to be more thoroughly studied. The low residual effectiveness of P fertilizer due to P leaching suggests that annual P rates need to be matched with expected crop demand because any extra P would only exacerbate P losses. Alternatively, where available, rock phosphate could be used to minimize P leaching. In Cambodia, local rock phosphate is a potentially effective source of P for lowland rice (White et al. 1999) but, until the marketed product shows consistent quality, its use is not recommended (CIAP 1999).

**Acidity**

Aluminium toxicity has generally been ruled out as a significant limiting factor for rice under flooded conditions. However, several possible consequences of Al toxicity during temporary loss of soil-water saturation may warrant further attention to acid soils of rainfed lowlands (Willett and Intrawech 1988; Seng 2000). One consequence is to directly inhibit root elongation, thus limiting plants' capacity to access water stored deeper in the profile of a drying soil. A second consequence is, by limiting root extension, the uptake of nutrients, especially P, would also be limited. Finally, soluble Al may react with P, thus decreasing the availability of soil P for uptake by roots.

**Nursery fertilizer use**

In Cambodia, farmers in the rainfed lowlands often apply fertilizer and manures to the seedling nursery rather than to the main fields (Lando and Mak 1994; Ros et al. 1998). On the low-fertility soils of Cambodia, fertilizer applied to both nursery and main fields increased rice yield (Ros 1998; CIAP 1998). Fertilizer applied to the nursery increased seedling vigour, which generally increased subsequent rice yields by 5%-10%, regardless of whether the main field was treated with fertilizer or not. Cow manure at 3 t ha$^{-1}$ and inorganic fertilizer at 50 kg N ha$^{-1}$ and 22 kg P ha$^{-1}$ were recommended for increasing seedling vigour (CIAP 1998).

Other low-cost strategies suggested by Ros et al. (1997, 2000) for increasing seedling vigour include seed coating with crushed rock phosphate and increasing seed P concentration in nursery-planted seed. The strategy adopted by Cambodian farmers of applying most of the fertilizer to the nursery was an efficient use of nutrients because applications to the main field could not replace the need for nursery fertilizer to produce vigorous seedlings.

Another P management strategy in the nursery phase, reported from India, is to dip seedlings in a P slurry before transplanting. This localizes P directly around roots and, in one study, improved P-use efficiency by 50% (Katyal 1978).

**Managing the variability of soil-water regime**

Unevenness in the soil surface is a significant source of variability in a field's soil-water regime (CIAP 1997). Elevation differences between 7 and 33 cm are not uncommon in farmers' fields (CIAP 1997). These differences are sufficient to cause some parts of the field to experience intermittent loss of soil-water saturation during the growing season while other parts of the field are continuously flooded. Variation in surface elevation affects decisions on when to transplant, seedling survival after transplanting, and weed control. In addition, such microvariability aggravates the problem of efficiently managing nutrient supply and fertilizer applications to rainfed lowland rice. Laser levelling has been developed in Cambodia, leading to increases in rice yields between 400 and 1000 kg ha$^{-1}$ in farmers' fields (CIAP 1996, 1997, 1998). While laser levelling may not be an option for poor lowland rice farmers, the research showed the benefits of level fields, suggesting the need for greater attention to manual levelling during land preparation.

**Sustainability of Fertilizer Use**

**Cropping systems**

Two major changes anticipated for the cropping systems found in rainfed lowland ecosystems will have a major bearing on the sustainability of fertilizer use. The first is the increased adoption of direct sowing of rice across the rainfed lowland ecosystems
as the reduced availability of labour makes transplanting a less attractive option. Direct-seeded rice is planted earlier, under essentially upland conditions, after the early rainy season. Subsequently, soils experience a variable soil-water regime, with periods of flooding interspersed with loss of soil-water saturation for intermittent intervals of variable duration. The variation in the soil-water regime under a direct-sowing system of crop establishment will require a re-examination of optimal methods and timing of fertilizer use, compared with establishment by transplanting. Secondly, the increased prevalence of dry-season cropping through direct sowing increases the intensity of crop production on these soils and, hence, the overall demand for nutrients and stored soil water. In areas other than rainfed lowlands, increased access to water for supplementary irrigation in the dry season permits the production of either a dry-season rice crop, or pulse or vegetable crops.

For rainfed lowland rice crops, the accumulation of nutrients, especially N, from the mineralization of organic matter during the long dry season represents a significant nutrient resource that needs to be managed. In areas such as Cambodia and North-East Thailand, where fields mostly lie fallow during the dry season, significant losses of NO$_3$ – N may occur during the early rainy season, although no quantitative data exist on the likely rates. These soils are relatively low in organic matter, and mineralization may not be that high, compared with soils in Ilocos Norte (Philippines), where high rates of NO$_3$ – N accumulate in the dry season. Furthermore, weeds often grow up during the early wet season before tillage, and are either grazed or incorporated during tillage. Hence, a significant proportion of NO$_3$ – N may already be recycled in these rainfed lowland rice ecosystems. The same may be true for SO$_4$ – S and K on sandy soils, but few data are available on this point.

In this environment, the most promising technologies for better using plant-available nutrients that accumulate during the dry season are planting a pre-rice crop or direct sowing rice early. In both cases, the aim is to encourage plant uptake of these nutrients to prevent their loss. In the case of a pre-rice crop, the mineralization of crop residues releases nutrients for rice at a time when the root system of the transplanted rice is capable of absorbing them. In the case of early direct-seeded rice, the nutrients absorbed are used directly for growth. In either case, appropriate adjustments in the rates of fertilizer applied at sowing and later will need to be worked out.

Nutrient budgets

Increasing concerns about the sustainability of the fertility status of rainfed lowland rice soils has prompted several studies on nutrient budgets. On a national scale, for example, Lefroy and Konboon (1998) estimated N-P-K budgets for Thailand and concluded that much more K was being exported from rice fields in harvested grain than was being replaced by fertilizer. In contrast, a positive balance was found for N and P, making the simple assumption that no other losses of nutrients occurred, except through harvested grain. Similarly, Lefroy and Konboon (1998) estimated nutrient budgets on regional and farm scales in North-East Thailand and concluded that N and P were, on the whole, positively balanced for rice production but that K was being depleted under the current cropping regime. Negative K balances were also reported for sandy soils in central Java (Indonesia; Wiharidjaka et al. 1998). The removal of stubble from rice fields significantly depletes soil K. Few reports of S balances are available for rainfed lowlands. Low-S soils are relatively widespread in North-East Thailand, Cambodia and Laos and so depletion of soil S in harvested grain may significantly affect the productivity of rainfed lowland rice. However, S in rain may significantly offset losses through harvested grain (Lefroy and Hussain 1991).

The calculation of nutrient budgets as a tool for managing nutrient supply for rainfed lowland rice has considerable promise because of its relative simplicity, compared with alternative approaches such as soil and plant testing, and simulation modelling. However, Lefroy and Konboon (1998) pointed out that many of the assumptions underlying calculation of nutrient budgets need more rigorous support from field research.

Environmental consequences of fertilizer use

The application of fertilizer to rice has potential unintended consequences that are of increasing concern in many parts of the world (e.g. Mishama et al. 1999; Xing and Zhu 2000). Negative effects on the quality of surface and ground water comprise the most common environmental impact (Shrestha and Ladha 1999). In rainfed lowlands with access to supplementary irrigation, dry-season cropping is becoming more common, especially where population density is high and increased output per unit area can be most readily achieved by dry-season cropping, using surplus labour (Pandey 1998). The environmental impact of these systems is under examination and may be a possible precursor of more widespread concern for agrochemical use in rainfed lowlands.

At present, fertilizer rates in rainfed lowlands are generally still low, leading Crosson (1995) to suggest that the negative environmental impact of fertilizer use on rice fields in these areas could be further reduced by making better use and application of the nutrient budgets. Hence, there is need to be more aware of the consequences of fertilizer use on rice fields. In these waterlogged environments, the losses of nutrients in drainage water are potential...
use on rice production is probably minimal. However, because nutrient deficiencies are prevalent and farmers are being advised to increase their fertilizer use and application rates, the possible future consequences of implementing these recommendations need to be considered. Villagers usually access stream water or shallow groundwater for domestic cleaning, cooking and drinking. Degraded quality of these water resources would be a matter of considerable concern for public health. In addition, artificial and natural wetlands in rainfed lowlands are often significant food resources for villagers. Loss of water quality in these wetlands likewise needs to be guarded against.

Because these problems generally do not exist yet in most rainfed lowland rice environments, now is an opportunity time to set in place strategies to prevent it from becoming a concern. Periodic monitoring of water quality and identifying areas in catchment basins that contribute most to nutrient enrichment of water bodies should be implemented.

Nitrogen accumulation in surface and groundwater has been reported as a consequence of fertilizer applications to irrigated-rice crops. Intensification of production in rainfed lowlands by growing dry-season vegetables, using supplementary irrigation, is also causing similar high losses of NO₃⁻-N through leaching into groundwater (Shrestha and Ladha 1999). In Ilocos Norte (Philippines), annual losses of up to 550 kg of N ha⁻¹ were reported. In 50% of wells surveyed on farms practising the rice-sweet pepper rotation, nitrate concentrations exceeded the World Health Organization's (WHO) limits for drinking water. The high rates of N fertilizer use in these intensive production systems are driven by the high economic returns from dry-season vegetables and are not currently typical of the drought-prone and emergence-prone rainfed lowlands. However, even in Cambodia, installation of wells and pumps for dry-season cropping is spreading and may eventually lead to intensive production systems like those of Ilocos Norte.

In the irrigated-rice fields of central Korea, annual P losses in run-off were estimated to be 4.3 kg P ha⁻¹ in water and 0.9 kg P ha⁻¹ in sediments (Cho et al. 2000). Increasing P concentration in surface and groundwater also has potential environmental consequences. Most aquatic ecosystems are P limited, so that increases in P concentration in runoff water and groundwater can greatly increase the biological productivity of these systems. Eutrophied wetland systems may generate algal blooms that would harm fisheries by impeding movement of boats and killing fish—some algal species in blooms are potentially toxic.

Adoption of Improved Nutrient Management Strategies

Traditionally, rainfed lowland farmers use little fertilizer, probably to avert risks. Pandey (1998), for example, reported that rates of N-P-K fertilizer use across Asian countries correlate with percentages of rice crops irrigated. In Cambodia, farmers in irrigated areas have adopted modern methods of rice production to a much greater extent than those in rainfed lowlands. Surveys by Jahn et al. (1997) showed that only 1.2% of rainfed rice farmers grow IRRI varieties, representing only 0.9% of the rice-growing area. In terms of inorganic fertilizer use, only 27% of rainfed rice farmers use inorganic fertilizers, compared with 70% of dry-season rice farmers.

As discussed above, rainfed lowlands have several significant characteristics that distinguish them from irrigated rice-growing areas where significant gains in technology adoption and productivity have already been achieved. These are a high degree of spatial and temporal variability both in terms of soil type and water availability (Zeigler and Puckridge 1995); the soils often have poorer chemical and physical properties than soils in irrigated systems; and farmers in rainfed lowlands also have fewer resources for capital expenditure and limited access to credit than do farmers in irrigated systems (Zeigler and Puckridge 1995) and therefore their ability to invest in innovative technologies is limited. The range of options for improved management are consequently few; with a greater chance of crop failure. When crops fail, rainfed-rice farmers have fewer options to generate supplementary food or income. Risk avoidance, therefore, occupies a more important position in decision making for rainfed-rice farmers than it does for irrigated-rice farmers (Zeigler and Puckridge 1995). Once again, the range of technologies that rainfed lowland farmers are willing to adopt is further restricted.

Traditionally, fertilizer recommendations have been based on average responses for particular soils and ecosystems (Dobermann and White 1999). The high degree of spatial and temporal variation of soil conditions in the rainfed lowlands raises two questions: firstly, how useful are blanket recommendations and generalized advice on fertilizer use; secondly, how can site-specific nutrient management strategies be developed (Dobermann and White 1999). Current strategies need to be better targeted than were past strategies to specific environments that have relatively small recommendation domains (Pingali et al. 1998). Because many such recommendation domains exist in the variable rainfed lowlands, the cost of developing these strategies, using
normal empirical experimentation for each particular environment, is expensive and time consuming.

A major reason for this is the difficulty of identifying appropriate technologies that can feasibly be applied by a farmer, given his or her particular set of constraints and expectations. Predicting the magnitude of a response to management inputs for any given situation is therefore difficult unless prior knowledge exists for each individual circumstance. In an effort to solve this problem, emphasis in much of Asia is currently placed on improved characterization of the environment and development of mechanistic and empirical simulation models that will predict crop performance in a given environment (Zeigler and Puckridge 1995).

While simulation models can now make good predictions of crop yield (e.g. Alagarswamy and Virmani 1996), the process depends on data for calibrating the models. Such data are frequently not available in the many local environments of the rainfed lowlands because of limited research infrastructure and knowledge base. Indeed, even the simplest data sets, such as daily rainfall, that are needed for simulation models such as APSIM (McCown et al. 1996) are unavailable for many Cambodian environments. Furthermore, the crop simulation approach takes no account of the difficult-to-quantify farmer circumstances and other such constraints that significantly determine the adoption of improved technologies.

Management strategies, particularly for nutrient supply by fertilizer applications, must be flexible and capable of modification, depending on the progress of the season and/or the outcome of the previous season. Farmers need to maximize the advantage gained from a better-than-average season while also being able to minimize the risk and losses associated with a poor season. Farmers need to be able to make informed decisions about changing their strategies to suit the seasonal progress and other changed circumstances.

Farmer participatory research, which follows a bottom-up approach and aims at working with farmers to identify their problems and solutions, can give farmers the necessary knowledge to dynamically manage their system. Experience, nevertheless, has shown that this type of research has difficulty moving beyond the diagnostic and design stages and few practical solutions have been developed that can be applied outside the project area (Pillot 1988).

Improved management strategies must also accommodate the farmer’s aims, which, because of economic circumstances or personal preferences, may favour management strategies or fertilizer types that do not necessarily maximize yields or economic returns. For example, some Cambodian farmers are reluctant to apply inorganic fertilizer to traditional varieties grown for their own consumption because they believe it degrades the flavour of cooked rice. Similarly, in areas of low population density, farmers with large farms (2–4 ha) place little emphasis on higher yield but stress yield stability and decreased labour requirements (Pandey 1998). Alternatively, farmers in remote locations may not be able to purchase fertilizer at the recommended times for application but need to know the likely benefits from application at other times in the growing season.

These factors have been well studied by social scientists and economists. And the modelling and integration of social, economic and biophysical data for specific systems has been possible, but again, application to the varied environment of the rainfed lowland rice-growing ecosystem has been difficult.

Finally and importantly, there is a need for a formal and organized mechanism whereby knowledge and experience about soil fertility and fertilizer response can be stored and shared at all levels within the agricultural sector. The system must allow for incremental improvements of the technologies as lessons are learnt, and for the entry of new technologies as they are developed. Drawing on this background, researchers are developing a model of rice farming in Cambodia that integrates information from a range of sources, including farmer experience (Bell et al. 2000). The model developed will predict the likely outcomes of given actions. Advisers can therefore use the model to identify the optimal technology for the particular circumstances of a farmer. By better targeting advice, the model will help facilitate the improved adoption of technology by farmers. The system will also facilitate the storage and transfer of farmers’ knowledge between localities. Finally, the model’s outputs can be represented spatially in a geographic information system. This will contribute to improved strategic planning on a provincial and district basis.

Conclusions

The rainfed lowlands comprise a complex environment for managing soil fertility. Contrary to previous views that drought was the major limiting factor for rice yield, recent research and simulation modelling suggest that nutrients and nutrient-water limitations are more significant. Breeding for nutrient efficiency and adaptation to these variable growing environments has been suggested as the most cost-effective approach towards making a major impact on the productivity of the drought- and submergence-prone rainfed lowlands. However, a deeper understanding of soil chemical changes due to the various transitions between oxic and anoxic conditions is needed to discover mechanisms of cultivar adaptation. Similarly, to better understand nutrient and water uptake by rice, adaptation to different water regimes is needed.

Rice production is limited by a threshold of nutrients and water. Increased fertilizer and water inputs can achieve high yields, but overuse is too late. The farmer’s experiences are responsible for the management of these inputs.

uptake by rice, an improved knowledge of root function, adaptation and turnover under the variable water regimes in rainfed lowlands is needed. Rice production in rainfed lowlands stands at the threshold of major changes in nutrient management. Increased fertilizer use is expected. This has potential to generate benefits and harm. Elsewhere in the world, fertilizer practice has been developed to achieve high production but without considering the potential negative environmental consequences until too late. The opportunity exists to learn from these experiences by taking a more environmentally responsible approach to fertilizer use and nutrient management in the rainfed lowlands.

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