# Rice

## Nutrient Disorders & Nutrient Management


Rice ecosystems

Nutrient management

Nutrient deficiencies

Mineral toxicities

Tools and information

Achim Dobermann and Thomas Fairhurst

**Rice: Nutrient Disorders & Nutrient Management**
Handbook Series
A. Dobermann
T.H. Fairhurst



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# Rice

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Achim Dobermann and Thomas Fairhurst

# Foreword

Thirty years ago, persuading rice farmers to use modern varieties and their accompanying fertilizer inputs was easy because the results, in terms of yield increases, were often spectacular. At the same time, governments invested heavily in fertilizer subsidies, and made improvements to irrigation facilities, infrastructure, and rice price support mechanisms that made rice intensification (increased input use, increased number of crops per year) economically attractive.

Further improvements in rice productivity, however, are likely to be much more incremental and 'knowledge-based.' Future yield increases will mostly result from the positive interactions and simultaneous management of different agronomic aspects such as nutrient supply, pest and disease control, and water.

In many countries, fertilizer and other input subsidies have already been removed and it is likely that in the future, the maintenance of irrigation facilities will increasingly become the responsibility of farmers rather than governments. This means that to achieve the required future increases in rice production, extension services will need to switch from distributing prescriptive packets of production technology to a more participatory or client-based service function. Such an approach requires greater emphasis on interpreting farmers' problems and developing economically attractive solutions tailored to each farmer's objectives. Yet extension services are generally ill-prepared for such a change.

This handbook provides a guide for *detecting* nutrient deficiency and toxicity symptoms, and *managing* nutrients in rice grown in tropical and subtropical regions. Some background information on the function of nutrients in rice and the possible causes of nutrient deficiencies are included. Estimates of nutrient removal in grain and straw have been included to help researchers and extension workers calculate the amount of nutrients removed from the field under different management systems. Specific nutrients are discussed in Chapter 3 – Mineral Deficiencies.

In most tropical and subtropical regions, rice farms are small, nutrients are managed 'by hand' and farmers do not have access to more resource-demanding forms of nutrient management, such as soil and plant tissue testing. Therefore, we describe a new approach to calculating site-specific nutrient management recommendations for N, P, and K in lowland rice. The concept described is based on ongoing, on-farm research in the Mega Project on 'Reversing Trends in Declining Productivity in Intensive, Irrigated Rice Systems,' a collaborative project between IRRI and researchers in China, India, Indonesia, the Philippines, Thailand, and Vietnam. As this work progresses, a more complete approach for site-specific nutrient management will evolve.

This handbook has been written primarily for irrigated and rainfed lowland rice systems, because these systems account for about 80% of the total harvested area of rice and 92% of global rice production. Where appropriate, we have included additional information particular to upland rice or rice grown in flood-prone conditions. We hope that this book will help increase the impact of new approaches to nutrient management at the farm level by bridging the gap between technology development and field implementation.

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# Rice Ecosystems

Rice production systems differ widely in cropping intensity and yield, ranging from single-crop rainfed lowland and upland rice with small yields (1–3 t $ha^{-1}$), to triple-crop irrigated systems with an annual grain production of up to 15–18 t $ha^{-1}$. Irrigated and rainfed lowland rice systems account for about 80% of the worldwide harvested rice area and 92% of total rice production. To keep pace with population growth, rice yields in both the irrigated and rainfed lowland environments must increase by 25% over the next 20 years. Currently, upland and flood-prone rice account for less than 8% of the global rice supply, and it is unlikely that production from these systems can be significantly increased in the near future.

### *In this chapter*

# 1.1 Irrigated Rice

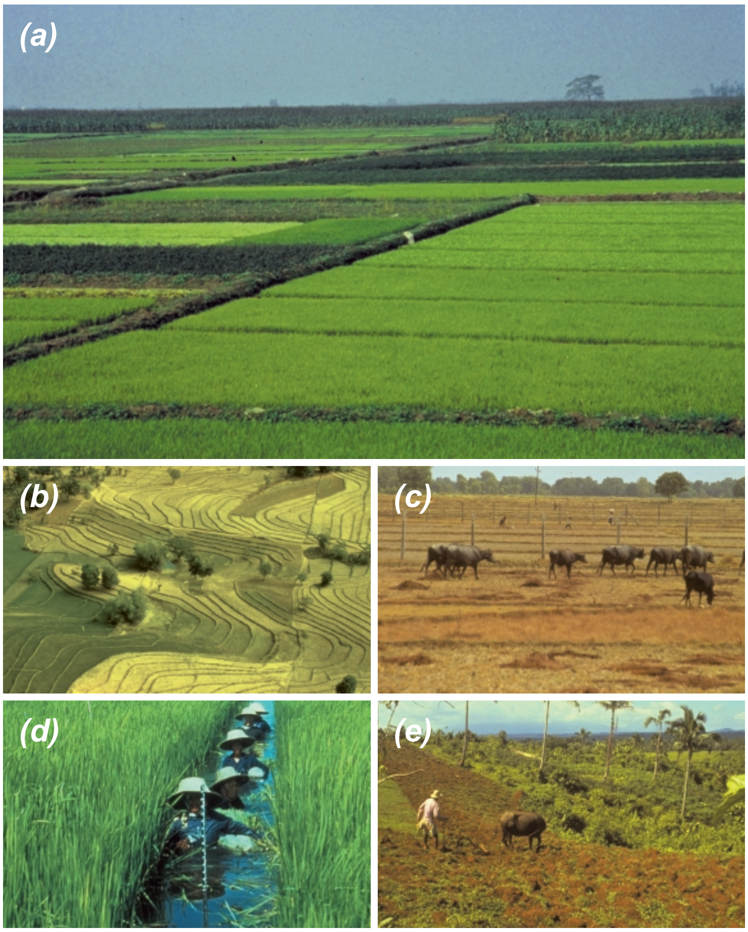
Intensive, irrigated rice-based cropping systems are found on alluvial floodplains, terraces, inland valleys, and deltas in Asia. Irrigated rice is grown in puddled soil in bunded rice fields with one or more crops planted each year. Irrigation is the main water source in the dry season and is used to supplement rainfall in the wet season. Irrigated rice accounts for 55% of the global harvested rice area and contributes 75% of global rice production (~410 M t of rice per year) .

## Area

Worldwide, the total harvested area of irrigated rice is about 79 M ha, with 43% (34 M ha) in East Asia (China, Taiwan, Japan, Korea), 24 M ha in South Asia, and 15 M ha in Southeast Asia. The countries with the largest areas of irrigated rice are China (31 M ha), India (19 M ha), Indonesia (7 M ha), and Vietnam (3 M ha).

## Cropping systems

Irrigated rice systems are intensive cropping systems with a total grain production of 10–15 t ha$^{-1}$ year$^{-1}$. Cropping intensities range from one (in the temperate regions) to three (in the tropical regions) crops grown per year. Examples of intensive rice-based cropping systems are rice-rice, rice-rice-rice, rice-rice-pulses, rice-wheat, and rice-rice-maize rotations. In rice monocropping systems, 2–3




***Rice is grown in a range of contrasting farming systems***

*(a), (b) Irrigated systems and irrigated terraces provide the largest yields. (c) Rainfed rice fields may be affected by drought. (d) Deep water fields are prone to flooding. (e) In upland rice fields, low soil fertility status is the major production constraint.*

short-duration crops are grown per year; at some sites, up to seven crops are grown in 2 years. Fallow periods between two crops range from a few days to 3 months. The major irrigated rice-cropping systems are double- and triple-crop monoculture rice in the tropics, and rice-wheat rotations in the subtropics. Together, they cover a land area of 36 M ha in Asia and account for ~50% of global rice production. Most irrigated rice land is planted to modern semidwarf indica and japonica varieties, which have a large yield potential and respond well to N fertilizer. In China, hybrid rice varieties are used in >50% of the irrigated rice area, and yields are about 10–15% larger than for conventional rice varieties.

Recent changes in production technology include the following:

- the change from transplanting to direct seeding,
- increased use of herbicides for weed control, and
- the introduction of mechanized land preparation and harvesting techniques.

## Yields and major constraints

The global average yield of irrigated rice is 5 t ha$^{-1}$ per crop, but national, regional, and seasonal yield averages vary widely. Large yields (more than 5–6 t ha$^{-1}$) are obtained in the USA, Australia, China, Egypt, Japan, Indonesia, Vietnam, and the Republic of Korea. Medium yields (4–5 t ha$^{-1}$) occur in Bangladesh, northwestern and southern India, Lao PDR, Malaysia, Myanmar, the Philippines, Sri Lanka, and Thailand. Yields are smaller (<4 t ha$^{-1}$) in Cambodia, eastern India, Madagascar, Nepal, and Pakistan.

In the tropics, skilled rice farmers achieve yields of 7–8 t ha$^{-1}$ per crop in the dry season, and 5–6 t ha$^{-1}$ in the wet season when cloud cover reduces the amount of solar radiation and thus the potential yield. The main agronomic problems encountered where intensive rice cultivation is practiced are:

- yield instability due to pests,
- poor input management and unbalanced nutrient use,
- inefficient use of irrigation water, and
- environmental degradation due to misuse of inputs.

## Fertilizer use and fertilizer use efficiency

In intensive rice systems, the indigenous N supply is never sufficient, and mineral N fertilizer inputs represent the largest part of the N cycle. In most Asian countries, irrigated rice farmers apply 100–150 kg N ha$^{-1}$ to dry-season rice crops and 60–90 kg N ha$^{-1}$ to wet-season crops. The cost of N fertilizer usually represents 10–20% of the total variable production costs. More than 20% of N fertilizer produced worldwide is used in the rice fields of Asia, but N recovery efficiency in most farmers' fields is only about 25–40% of applied N. The requirement for mineral fertilizer may be reduced when organic nutrient sources such as farmyard manure, legume green manure, and azolla are used. Green manuring and organic manure use, however, have decreased in recent years as mineral fertilizer has become a more convenient and cost-effective source of N.

Most irrigated rice farmers apply 15–20 kg P ha$^{-1}$ per crop. P balances vary widely, however, and both soil P depletion (e.g., in Cambodia) and excessive P accumulation (e.g., in Java) have been reported.

In the short term, the indigenous K supply in most lowland rice soils is sufficient to sustain average yields of 4–6 t ha$^{-1}$. Farm surveys conducted in various countries, however, suggest an average use of only 15–20 kg K ha$^{-1}$ per crop and negative K balances of 20–60 kg K ha$^{-1}$ per crop. One factor contributing to negative K balances is the increasing trend to remove straw from rice fields, for use as fodder or fuel or to make land preparation easier. Depletion of soil K reserves appears to be a problem in many intensive rice farms in Asia and, if left uncorrected, will limit future yield increases and result in poor N use efficiency.

## *Problems with weeds, insects, and diseases*

Weeds are mainly a problem in areas where direct-seeded rice is grown and hand weeding is not possible due to labor scarcity. This has led to the use of herbicides as a standard practice in regions such as California (USA), South Vietnam, Malaysia, Central Thailand, and Central Luzon (Philippines). In most cases, insecticide application is not necessary during the first 40 days after planting, and integrated pest management techniques using smaller amounts of insecticide have been widely adopted in recent years. The need for larger N fertilizer rates to maintain or increase yields, however, often results in greater pest and disease pressure. The large leaf area required to achieve high yields results in a dense canopy that provides a microclimate environment that favors the development and spread of many rice pests and diseases. K or Si deficiency increases susceptibility to pests, particularly when coupled with excessive N supply.

## *Sustainability and environmental problems*

There have been reports of declining yields in some long-term, double- and triple-crop rice experiments in Asia, where the best management practices have been rigorously followed. There is also anecdotal evidence of diminishing returns to N fertilizer use in farmers' fields. In many countries, the rate of increase in rice yields has decreased in recent years, and this may be related to declining factor productivity from applied inputs. It remains unclear whether yield or productivity decline is widespread in Asia.  Where they occur, they are caused mainly by soil nutrient depletion, changes in soil organic matter, or accumulation of toxic substances in soil, particularly in systems with short and wet fallow periods between two crops.

Global methane ($CH_4$) emissions from flooded rice fields are about 40–50 Tg year$^{-1}$, or ~10% of total global methane emissions. In irrigated rice areas, controlled water supply and intensive soil preparation contribute to improved rice growth but result in the production and emission of larger amounts of $CH_4$. Improved water management techniques can reduce the emission of $CH_4$ from rice fields, but feasible management practices that reduce $CH_4$ emissions *without* increasing N losses and reducing yield have yet to be developed.

As much as 60–70% of applied fertilizer N may be lost as gaseous N, mainly because of $NH_3$ volatilization and denitrification. Nitrous oxide emissions occur as a result of nitrification-denitrification during periods of alternate soil wetting and drying. In irrigated rice systems with proper water control, $N_2O$ emissions are usually small except where excessive amounts of N fertilizer are applied to fertile rice soils. In poorly drained, 'puddled' lowland rice soils, little nitrification takes place and $NO_3$ leaching losses are therefore usually <10% of applied fertilizer N.

## *Future challenges*

N is the main driving force to produce large yields. Because of the wide variation in soil N-supplying capacity between lowland rice fields with the same soil type, however, site-specific soil and fertilizer management practices are required to improve the fit between nutrient supply and crop demand. The main strategies for improving N use efficiency are as follows:

- Adjust fertilizer N rates according to soil N supply.
- Time the split applications precisely according to plant N demand.
- Use novel fertilizer products such as slow-release fertilizers.
- Maintain the proper ratio between N, P, and K through balanced fertilizer use.
- Consider disease-nutrient interactions.
- Use better water management techniques.

# 1.2 Rainfed Lowland and Upland Rice

*Rainfed lowland rice* grows in bunded fields that are flooded for at least part of the cropping season with water to a depth that may exceed 50 cm for no more than 10 consecutive days. The rainfed lowland rice ecosystem can be divided into five subecosystems:

- favorable rainfed lowland,
- drought-prone,
- submergence-prone,
- drought- and submergence-prone, and
- medium-deep water.

Rainfed lowlands are characterized by lack of water control, with floods and drought being potential problems. Rainfed rice accounts for ~25% of the world's total rice land, with a total production of ~85 M t of rice per year (17% of the global rice supply).

*Upland rice* is grown with small amounts of external inputs in unbunded fields. The soil may be cultivated when dry and planted by direct seeding. Upland rice is also dibbled directly into the uncultivated soil after land clearing and burning. Surface water does not accumulate for any significant time during the growing season. Landforms for upland rice vary from low-lying valley bottoms to undulating and steep sloping lands with high surface runoff and lateral water movement. Upland rice constitutes only 10% of the global rice area and 3.8% of total world rice production.

## Area and most important countries

Rainfed lowland rice is grown on ~36 M ha, of which ~34 M ha are found in Asia. It is the most common system in the subhumid subtropics (eastern India, Myanmar, Thailand) and large parts of the humid tropics (Bangladesh, Cambodia, Lao PDR). These are regions where modern rice technologies have yet to make an important impact on productivity and past increases in production have come from an expansion in the area planted. The countries with the largest rainfed lowland rice areas are India (12.8 M ha), Thailand (6.7 M ha), and Bangladesh (4.4 M ha).

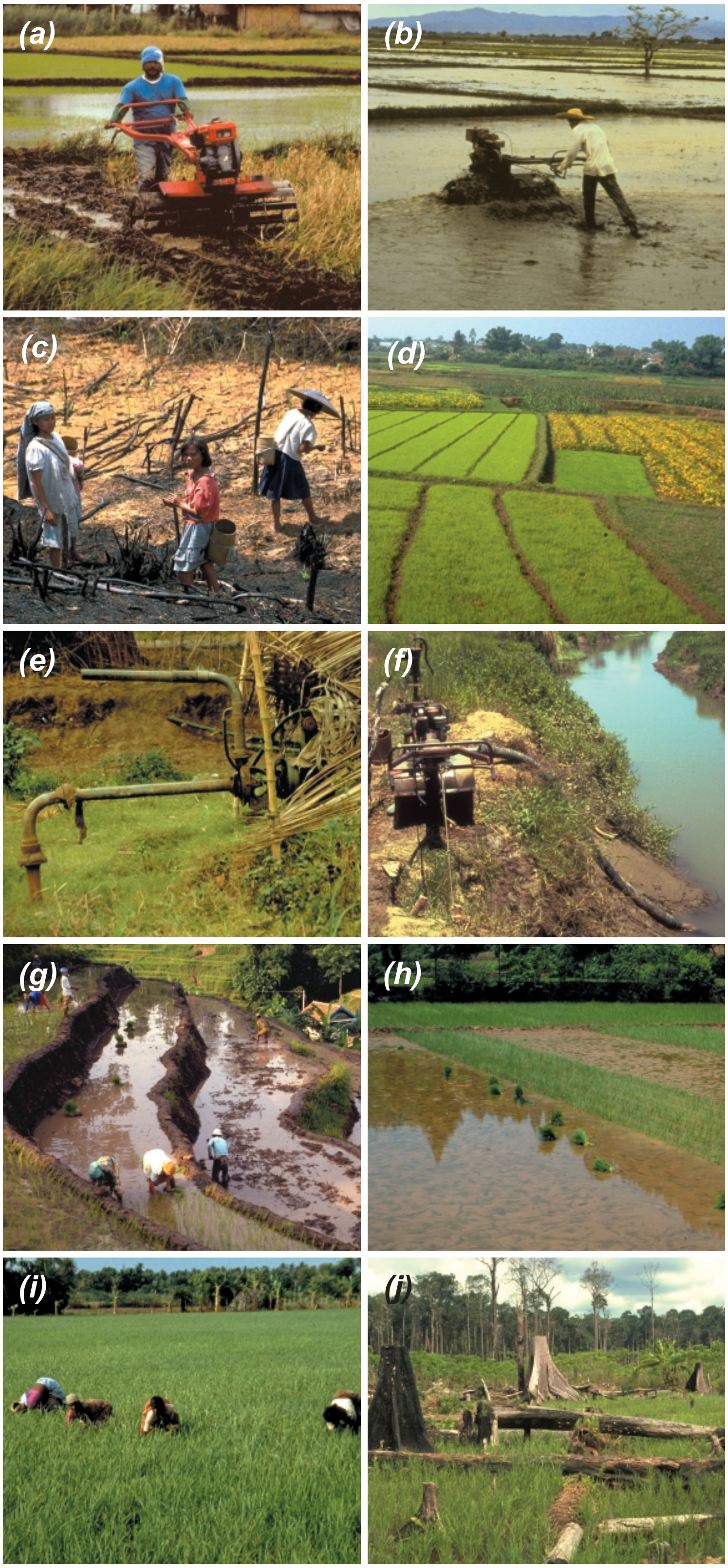
Only ~17 M ha are planted to upland rice worldwide. India (6.2 M ha), Brazil (3.1 M ha), and Indonesia (1.4 M ha) have the largest upland rice areas.

## Cropping systems

Usually only one crop is grown each year in rainfed lowland rice systems and yields are small. In some areas farmers grow rice followed by mungbean, soybean, wheat, maize, or vegetables as a secondary crop. A particular farmer may cultivate rainfed lowland rice at several positions in a toposequence such that on one farm some fields may be drought-prone while others may be affected by flooding in the same season. Because of unstable yields and the high risk of crop failure, rainfed lowland rice farmers are usually poor and typically grow traditional, photoperiod-sensitive cultivars that do not respond well to mineral fertilizer.

Upland rice is an important crop in shifting cultivation (or slash-and-burn) farming systems in Indonesia, Lao PDR, the Philippines, northern Thailand, and Vietnam in Asia, and in forested areas of Latin America and West Africa. Farmers plant rice as a sole crop or mixed with other crops such as maize, yam, beans, cassava, or bananas. An area is farmed for 1–3 years until weed and pest infestations increase because of a decline in soil fertility.

Permanent cultivation of upland rice as practiced in Asia and Latin America is characterized by orderly intercropping, relay cropping, and sequential cropping with a range of crop species.




***Rice cultivation***

*(a), (b) In irrigated rice, land is prepared by plowing and puddling operations to destroy the soil structure. (c) In upland rice, seed is dibbled into cultivated and uncultivated soil after land clearing and burning. (d) Large seedbeds are required for transplanted rice. (e), (f) Poor maintenance of irrigation equipment and channels may result in water shortages during critical growth periods. (g), (h) Transplanted rice requires more labor inputs than direct-seeded rice. (i), (j) Hand weeding is essential to reduce competition from weeds during the early stages of crop establishment up to canopy closure.*


### *Fertilizer application and rice harvesting*

*(k), (l) In Asia, basal and top-dressed fertilizers are broadcast by hand. (m) Rice is usually harvested by hand. (n) Where fields are large, however, combine harvesters have been introduced successfully. (o), (p) In Vietnam and the Philippines, threshing is done in the field using mobile rice threshers. This practice leaves most of the straw as heaps in the field, which are often burned* in situ.

## Yields and major constraints

The world average yield for rainfed lowland rice is 2.3 t $ha^{-1}$ per crop, but under favorable conditions, yields of >5 t $ha^{-1}$ can be achieved. Yields of upland rice have increased slowly over the last 30 years and average about 1 t $ha^{-1}$ in most countries, except in some large and partly mechanized farms in Latin America, where yields can reach 2–3 t $ha^{-1}$. Adverse climatic conditions, poor soils, and a lack of suitable and adapted modern technology are the major constraints to increasing the productivity of rice in rainfed lowlands and uplands. The income of most farmers is small and they have limited and difficult access to credit, inputs, and information about modern technologies. Rice farming in rainfed lowlands is risk-prone because crops can be affected by droughts, floods, pest and disease outbreaks, and weeds, as well as soil constraints. Growing conditions are diverse and unpredictable because most rainfed lowland rice fields depend on erratic rainfall.

Many upland rice soils are acid, vulnerable to erosion, and highly P-fixing. In most cases, P deficiency must be corrected before a response to N is obtained.

## Fertilizer use and fertilizer use efficiency

Because of higher risk and reduced efficiency, most rainfed lowland rice farmers apply fertilizer N to their rice crops in much smaller amounts than in irrigated rice systems. The application of N fertilizer, however, is not common in upland rice, where mineral fertilizer may not be available. K fertilizer is not commonly applied to rainfed lowland and upland rice although a response to K has frequently been shown, particularly on coarse-textured soils. A smaller yield potential and greater uncertainty because of climatic and abiotic stress are two reasons why input use is less in rainfed lowland and upland environments. For example, in rainfed systems, N use efficiency is mainly governed by environmental factors such as drought and flooding, which are beyond the farmer's control. On acid soils in upland rice systems, P deficiency and Al toxicity limit growth and yield. Reduced Si availability under upland conditions increases the susceptibility of rice plants to diseases (e.g., blast) and this reduces the amount of N that can be used safely. These constraints limit the returns to investments in N fertilizer in contrast to irrigated systems where N use efficiency is higher, more consistent, and more reliable. In addition, rainfed soils are characterized by intermittent wetting and drying cycles, even during the wet season, which result in an accumulation of nitrate because of nitrification and the subsequent loss of N by denitrification or leaching. Slow-release fertilizers may have potential to increase N use efficiency in these environments.

## Problems with weeds, insects, and diseases

Weeds are the main production constraint in rainfed lowland and upland rice systems because fields are direct-seeded and do not benefit from the presence of a water mulch to reduce the weed population. Moreover, weeds are also more competitive than rice when soil fertility is poor. Small farmers often cannot afford to implement weed control measures. Estimates of yield losses caused by competition from weeds range from 30% to 100%. Other pest problems include blast, brown spot, nematodes, stem borers, and rice bugs. Nematode infestations can result in yield losses of up to 30%.

## Environmental problems

Methane emissions are smaller and more variable in rainfed lowland rice than in irrigated rice because of periodic droughts during the growing season. Upland rice is not a source of $CH_4$ emissions. Nitrate leaching is common in rainfed rice systems or rice-nonrice cropping systems, particularly on coarse-textured soils, which may result in the contamination of groundwater systems. In addition to the economic loss from N leaching, cumulative $N_2O$ fluxes are 3–4 times larger during the fallow period than during the cropping period. With sufficient residual soil moisture, $NO_3$ losses can be reduced by growing 'nitrate catch crops' which take up and retain $NO_3$ in aboveground biomass during the fallow period. Nitrate accumulation can be reduced by delaying the application of N fertilizer until the onset of permanent flooding, and by splitting the recommended N dose.

## *Future challenges*

The rainfed lowlands offer tremendous scope for increased rice production because the area under this system continues to increase and yields are small. Rainfed rice varieties for the future should be more responsive to mineral fertilizer but should retain the stress tolerance and grain quality built into traditional varieties. Farmers would then be motivated to invest in more productive land preparation and fertility management practices that result in higher yields.

The major requirement for improving the productivity of upland rice is to develop suitable techniques for managing P and soil acidity. Until these problems have been resolved, investments in breeding improved varieties will have little impact on productivity in the upland rice ecosystem.

# 1.3 Flood-Prone Rice

Flood-prone rice is grown in inland and tidal (coastal) wetland areas where the depth of floodwater is >50 cm throughout the growing season. Around 12 M ha of rice lands in South and Southeast Asia are subject to uncontrolled flooding. Rice grown under such conditions must be adapted to temporary submergence of 1–10 days, long periods (1–5 months) of standing (stagnant) water ranging in depth from 50 to 400 cm or more, or daily tidal fluctuations that sometimes also cause complete submergence. Rice yields are very small (~1.5 t $ha^{-1}$) and very variable mainly due to poor soils and the unpredictable incidence of drought and flooding. The flood-prone ecosystem accounts for only 4% of global rice production but is important for food security in some areas.

### *Further reading*

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# 2

# *Nutrient Management*

***In this chapter***

# 2.1 Yield Gaps and Crop Management

Currently, most rice farmers, even those in irrigated areas, achieve less than 60% of the climatic and genetic yield potential of a particular site. To understand why yields in farmers' fields are only a fraction of the potential or maximum yield, a simple model can be used to illustrate the particular factors accounting for the yield gap (Figure 1).

## *Maximum yield, $Y_{max}$*

At $\mathbf{Y_{max}}$, grain yield is limited by climate and genotype only, and all other factors are nonlimiting. $\mathbf{Y_{max}}$ fluctuates from year to year (±10%) because of climatic factors. For most rice-growing environments in tropical South and Southeast Asia, the $\mathbf{Y_{max}}$ of currently grown high-yielding rice varieties is about 10 t ha$^{-1}$ in the dry season (high solar radiation), and 7–8 t ha$^{-1}$ in the wet (monsoon) season, when high humidity leads to greater disease pressure and the amount of solar radiation is smaller due to greater cloud cover. Experimentally, $\mathbf{Y_{max}}$ can be measured only in maximum yield trials with complete control of all growth factors other than solar radiation.

Important points:

- Climate cannot be manipulated, but $\mathbf{Y_{max}}$ varies depending on the planting (sowing) date.
- Grow rice varieties adapted to prevailing climatic conditions (i.e., select genotypes with the highest $\mathbf{Y_{max}}$ under a given climatic regime).

## *Attainable yield, $Y_a$*

At $\mathbf{Y_a}$, grain yield is smaller than $\mathbf{Y_{max}}$ due to limited water and nutrient supply. In irrigated rice, water is usually not a limiting factor (except when the temperature of the irrigation water is very high (i.e., geothermal influence) or very low (i.e., at high altitudes), thus $\mathbf{Y_a}$ represents the attainable yield limited by nutrient supply.

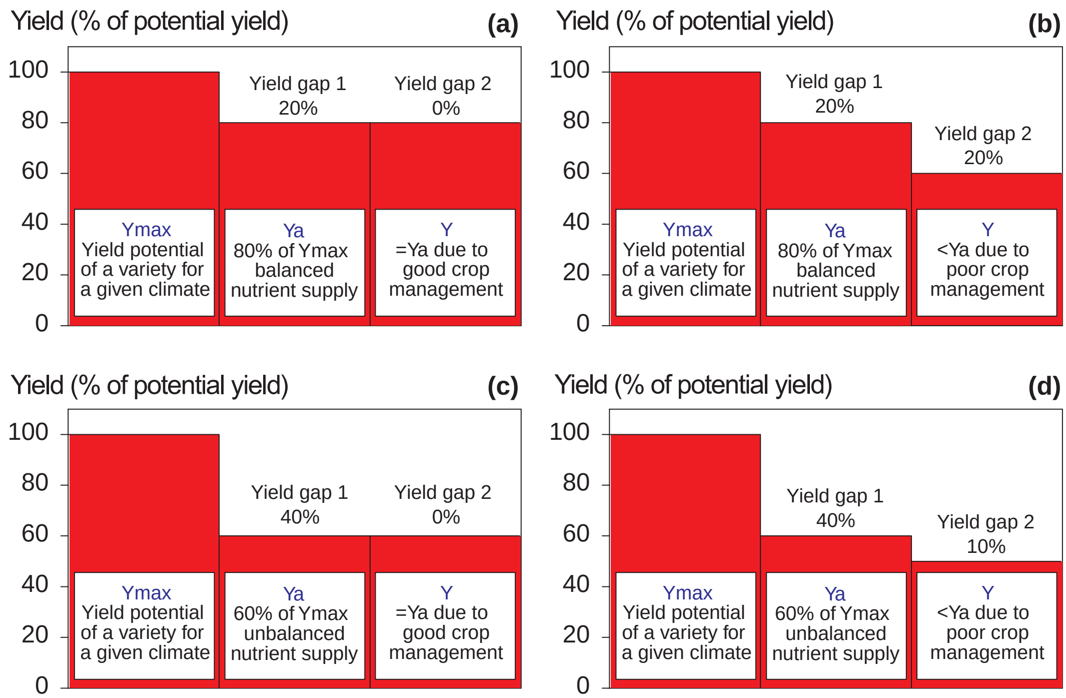
The maximum *economic* $\mathbf{Y_a}$ achieved by the best farmers is about 70–80% of the *potential* $\mathbf{Y_{max}}$ because the internal efficiency of nutrient use decreases when $\mathbf{Y_a}$ >80% of $\mathbf{Y_{max}}$ (Section 2.5). At this point on the yield response curve, larger and larger amounts of N, P, or K must be taken up by the rice plant to produce a given increment in grain yield.

Important points:

- In irrigated rice, Yield Gap 1 ($\mathbf{Y_{max}} - \mathbf{Y_a}$) is mainly caused by an insufficient supply of N, P, K, and other nutrients. To increase and maintain $\mathbf{Y_a}$ at >70–80% of $\mathbf{Y_{max}}$, emphasis must be given to improving soil fertility and ameliorating all constraints to nutrient uptake, balanced nutrition, and high N use efficiency.
- In rainfed lowland and upland rice, Yield Gap 1 is usually caused by insufficient water as well as soil infertility. Therefore, a combined approach of improving water and nutrient management is required to reduce Yield Gap 1. The selection of varieties resistant to biotic and abiotic stresses (drought, weeds, soil stresses), and improvements in soil fertility and water and nutrient use efficiency are important.

## *Actual yield, Y*

$\mathbf{Y_a}$ is reduced to **Y** due to pests and diseases, toxicities, and constraints other than climate, water, or nutrient supply. Yield Gap 2 ($\mathbf{Y_a} - \mathbf{Y}$) results from a reduction in nutrient use efficiency. For example, if Yield Gap 2 is large, the rice plant may take up a large amount of nutrients, but they are not converted efficiently into profitable harvest products (grain) so that the overall profitability of the cropping system remains less than optimal. Crop management in rice must *minimize Yield Gap 2* to achieve efficient nutrient use.




*(a) In a well-managed field, yield gap 2 is close to zero so that the actual yield approaches* $\mathbf{Y}_a$ *at a level of about 80% of* $\mathbf{Y}_{max}$*. Nutrient efficiency and profit are high.*

*(b) Yield losses are large because of poor crop management, inadequate pest control, or mineral toxicities.*

*(c) Yield loss because of poor nutrient management.*

*(d) Yield loss because of poor nutrient and crop management.*

*Figure 1. Maximum yield and yield gaps at the farm level.*

Important points:

- Ameliorate all mineral toxicities (Section 4).
- Implement high standards of general crop management, including selection of suitable, pest-resistant, high-yielding varieties; use of certified seed; optimal land preparation and crop establishment; and efficient control of pests and diseases (insects, rats, snails, birds, weeds) to minimize yield losses.

# 2.2 The Nutrient Input-Output Budget in an Irrigated Rice Field

The nutrient budget for a rice field (Figure 2) can be estimated as follows (all components measured in kg elemental nutrient ha$^{-1}$):

$$B = M + A + W + N_2 - C - PS - G$$

where

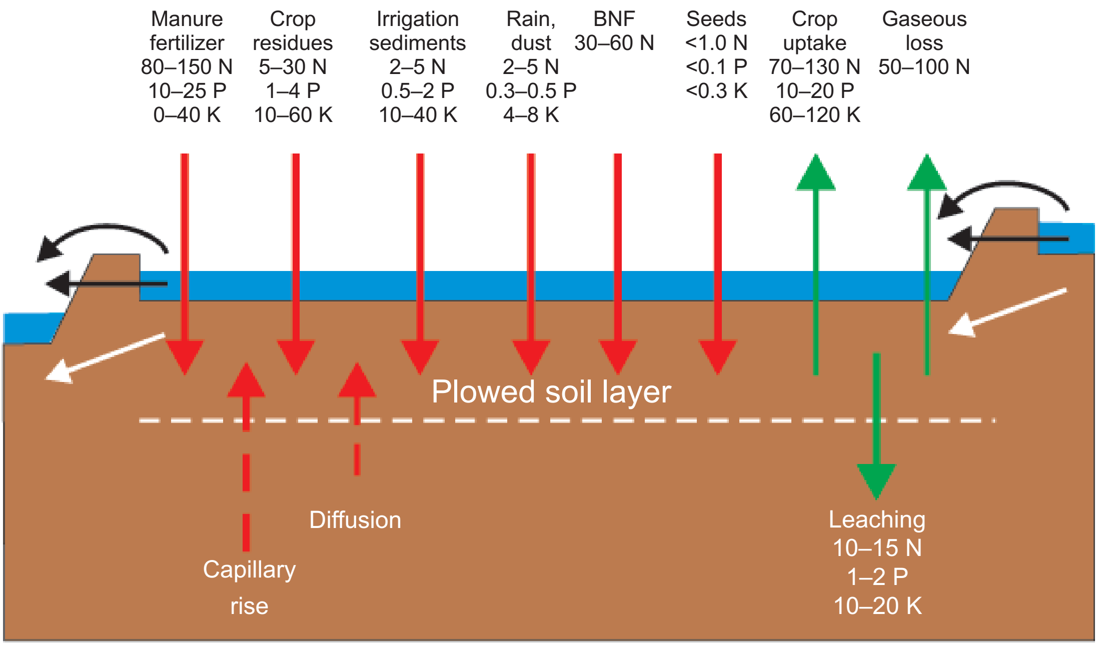
*Inputs*: M is the nutrient source added (inorganic and organic); A is the atmospheric deposition (rainfall and dust); W is the irrigation, floodwater, and sediment (dissolved and suspended nutrients); and $N_2$ is the biological $N_2$ fixation (N only).

*Outputs*: C is the net crop removal with grain and straw (total uptake less nutrients in crop residues returned); PS is the total loss due to percolation and seepage; and G is the total gaseous loss due to denitrification and $NH_3$ volatilization.

The overall nutrient budget at a particular site varies widely depending on the cropping system, crop management, and climatic season. The N input from biological $N_2$ fixation is smaller where soil N status is high (e.g., due to mineral fertilizer N use) and soil P status is low.

Sediments (W) are a major nutrient input in traditional lowland rice systems, particularly in irrigated rice systems located in river deltas that are regularly affected by natural flooding. The flood prevention structures and dams that are installed to improve irrigation and drainage, however, have decreased the addition of nutrients in sediment inflow.

In the past, organic nutrient sources such as farmyard manure, legume green manure, and azolla were a major source of nutrient inputs, but their use has declined in many regions since the introduction of the Green Revolution technology.




*Values shown are common ranges of inputs and outputs of N, P, and K for an irrigated rice field (kg ha$^{-1}$ per crop).*

*Figure 2. Components of the input-output balance of nutrients in a typical irrigated rice field.*

Crop removal (C) is the largest cause of nutrient removal from the field, but the actual amounts removed depend on the harvest and postharvest technology used. Nutrients contained in the grain are removed from the field, and husks, separated from the grain during milling, may be burned at the mill site (e.g., in Indonesia) or returned to the field. Straw contains almost all of the K and Si, and a large part of the N, P, and S, taken up by the crop. Therefore, straw management markedly affects the field nutrient budget (Section 2.7).

Gaseous losses of N (G) through $NH_3$ volatilization and denitrification often exceed 50% of applied fertilizer N. $NH_3$ volatilization appears to be the major N-loss process for N applied as a topdressing, but nitrous oxide is also emitted from irrigated fields during periods of alternate wetting and drying of the soil. In irrigated rice systems with proper water control, however, nitrification losses, $NO_3$ leaching losses, and $N_2O$ emissions are usually small.

Leaching losses (PS) depend on the concentration in the soil solution and the water percolation rate, both of which vary considerably and are affected by soil texture. In irrigated rice systems where water is properly controlled and percolation is impeded by a compact soil layer beneath the plow sole, leaching losses are usually small. In coarse-textured soils where the plow sole is thin and permeable, however, the amount of nutrients lost due to leaching may be large.

Nitrate leaching losses are large in rice-vegetable systems, where large amounts of N fertilizer are applied to the vegetable crop. In this case, nitrate tends to accumulate in the soil during the vegetable cropping period, and a large amount of N may be leached out into surface water and groundwater during crop irrigation, before the rice crop is sufficiently developed to absorb the $NO_3$-N.

At an average concentration of 1 mg of nutrient $L^{-1}$, 1,000 mm of water adds ~10 kg of nutrient $ha^{-1}$ to a rice field, but this does not necessarily imply a net gain of nutrients to the system. In many cases, the amount of nutrient inputs from rainfall and irrigation is smaller than the amount lost from leaching. For a particular field, we can assume that nutrient losses from seepage are similar to nutrient inputs from seepage coming from neighboring fields.

A simple partial K, P, or S budget can be estimated as:

*Partial input – output budget = M – C*

*= (fertilizer input + straw retained) – total plant uptake*

Table 1 shows an estimated *average* nutrient budget for an irrigated rice crop in Asia. Data used to calculate fertilizer nutrient inputs and crop nutrient removal are based on measurements taken in farmers' fields. In this example, organic manures were not used to reflect the general trend for their replacement by mineral fertilizer use. These calculations underline the importance of straw management in the nutrient balance. This is particularly important for K for which relatively small amounts of fertilizer nutrients are added and large amounts of nutrient may be removed with the straw.

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*Table 1. Nutrient budget for an irrigated rice crop yielding 6 t ha$^{-1}$.*

| Item | N | P | K | Comments |
|---|---|---|---|---|
| | | (kg ha$^{-1}$) | | |
| **Inputs** | | | | |
| Fertilizer (M) | 115 | 17.0 | 15 | No manure applied |
| Rainfall (A) | 2 | 0.3 | 5 | <500 mm, dry season |
| Irrigation (W) | 5 | 0.5 | 20 | Surface water with low nutrient content, 1,000 mm crop$^{-1}$ |
| N fixation ($N_2$) | 40 | 0.0 | 0 | |
| **Outputs** | | | | |
| Grain (C) | 63 | 12.0 | 15 | |
| Straw (C) | 42 | 6.0 | 87 | Harvest index of 0.5 |
| Percolation (PS) | 10 | 1.0 | 10 | About 2–3 mm d$^{-1}$ |
| Gaseous loss (G) | 50 | 0.0 | 0 | $NH_3$ volatilization and denitrification |
| **Net balance** | | | | |
| | -3 | -1.2 | -72 | Cut at surface, straw removed |
| | +30.6 | +3.6 | -2.4 | 80% of straw retained and incorporated |

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# 2.3 Site-Specific Nutrient Management Strategy

Site-specific nutrient management (SSNM) focuses on developing a nutrient management program that takes the following aspects into account:

- Indigenous nutrient supply at each site ('site-specific').
- Temporal variability in plant N status occurring within one growing season ('season-specific').
- Medium-term changes in soil P and K supply based on the cumulative nutrient balance.

## *Management of nitrogen*

To optimize N use efficiency for each season, a dynamic N management strategy is required, in which the *adjustment of the quantity* of N applied in relation to the variation in indigenous N supply is as important as *timing*, *placement*, and *source* of applied N. Nitrogen management should therefore include the following measures:

- An estimate of crop N demand, potential N supply from indigenous sources (soil, biological $N_2$ fixation) and N recovery from inorganic and organic sources applied. These factors are used to estimate the total fertilizer N requirement.
- An estimate of the need for a basal N application according to soil N release patterns, crop variety, and crop establishment method.
- Plant N status monitoring to optimize the timing of split applications of mineral N fertilizer in relation to crop demand and soil N supply.
- Long-term soil and crop management practices to optimize the indigenous nitrogen supply (INS).

## *Management of phosphorus and potassium*

P and K management requires a *long-term management strategy*. It is more important to predict the need to apply P and K, and the amount required, than to attempt to maximize recovery efficiency for fertilizer P and K. This is because these nutrients are not readily lost or added to the root zone by biological and chemical processes that affect N. Management must be geared toward maintaining the available soil nutrient supply, to ensure that P and K do not limit crop growth and thus reduce N use efficiency. Changes in potential indigenous P and K supply can be predicted as a function of the overall nutrient balance. To predict the P and K inputs required for maintaining a targeted yield level, key components of P and K management should include the following:

- An estimate of crop P and K demand, potential indigenous P and K supply, as well as P and K recovery from applied inorganic and organic sources.
- A schedule for timing K applications, depending on soil K buffering characteristics and an understanding of the relationship between K nutrition and pest incidence.
- Knowledge of the relationship between the P and K budget, residual effects of P and K fertilizers, and changes in soil supply over time.

## *Management of other nutrients*

*Prevention*, *diagnosis*, and *treatment* are the key management tools for other nutrients (e.g., Ca, Mg, and S), micronutrients, and mineral toxicities. Over the longer term, prevention through general crop management (e.g., using adopted cultivars), water management, and fertilizer management (e.g., choice of fertilizers containing secondary minerals) is important. Deficiencies can be alleviated by regular or 'one-time' measures as a part of general recommendations. Similarly, diagnostic tools can be used to identify other nutritional disorders (e.g., salinity, Fe toxicity, and B toxicity) and to make adjustments in N, P, and K management. In some cases, it may be necessary to alter soil management practices to reduce the severity of mineral toxicities.

## *A general site-specific nutrient management strategy*

We will now describe a simple SSNM approach for irrigated rice that can be implemented at the farm level even if facilities for chemical soil or plant analysis are not available.

*[Note: A software program to perform the required calculations will be available soon from IRRI. The program will also be able to provide additional options for estimating indigenous nutrient supply and planning nutrient management over several years.]*

The general procedure described here and in Sections 3.1, 3.2, and 3.3 (under specific nutrients) is equally applicable.

Implementing an SSNM requires the following steps (Figure 3):

1. Identify and alleviate all nutritional constraints other than N, P, and K (e.g., improved crop management to prevent toxicities or deficiencies of nutrients other than N, P, and K).
2. Estimate (in kg $ha^{-1}$) the farm- or field-specific potential indigenous supply of N (INS), P (IPS), and K (IKS) (Section 2.4).
3. Develop a farm- or field-specific recommendation for NPK use to achieve a defined target yield, by optimizing the balance between N, P, and K in the rice plant (Section 2.5):

   *Fertilizer rate = (crop nutrient requirement – indigenous nutrient supply)/first-crop recovery of fertilizer*

4. Optimize the timing and amount of N fertilizer applied based on plant growth. Decisions about the timing of N application and the number of splits required can be based on the following factors:
   - 2–4 split applications (i.e., following basic agronomic principles),
   - regular monitoring of plant N status up to the flowering stage, using tools such as the chlorophyll meter (with the help of a village technician) or green leaf color charts (Section 5.6), or
   - prediction of N split applications using simplified simulation models.
5. Calculate the amount of fertilizer nutrients applied; measure the grain yield and the amount of straw and stubble returned to the field. These data are then used to predict the change in INS, IPS, and IKS during the previous crop cycle based on an estimated nutrient budget. For nutrients such as P and K, reasonable estimates of the nutrient budget can be obtained by estimating nutrient inputs (manure, fertilizers, and crop residues) and nutrient removed (grain and straw).

   Changes in the INS tend to be small over 3–5 years. Therefore, frequent adjustments based on the nutrient balance are not required.
6. Specify a fertilizer recommendation (repeat calculation as in Step 3) for the subsequent crop cycle. The modified INS, IPS, and IKS values resulting from Step 5 are used for this.
7. Continue using this procedure (Steps 5 and 6) for a succession of crops. After about 3–5 years, a new measurement of INS, IPS, IKS and other constraints may be necessary (Steps 1 and 2) to restart the whole recommendation cycle.

While necessary input data such as grain yield, stubble left in the field, and fertilizer use can easily be obtained from the farmer, other data required are:

- an estimate of the climatic yield potential,

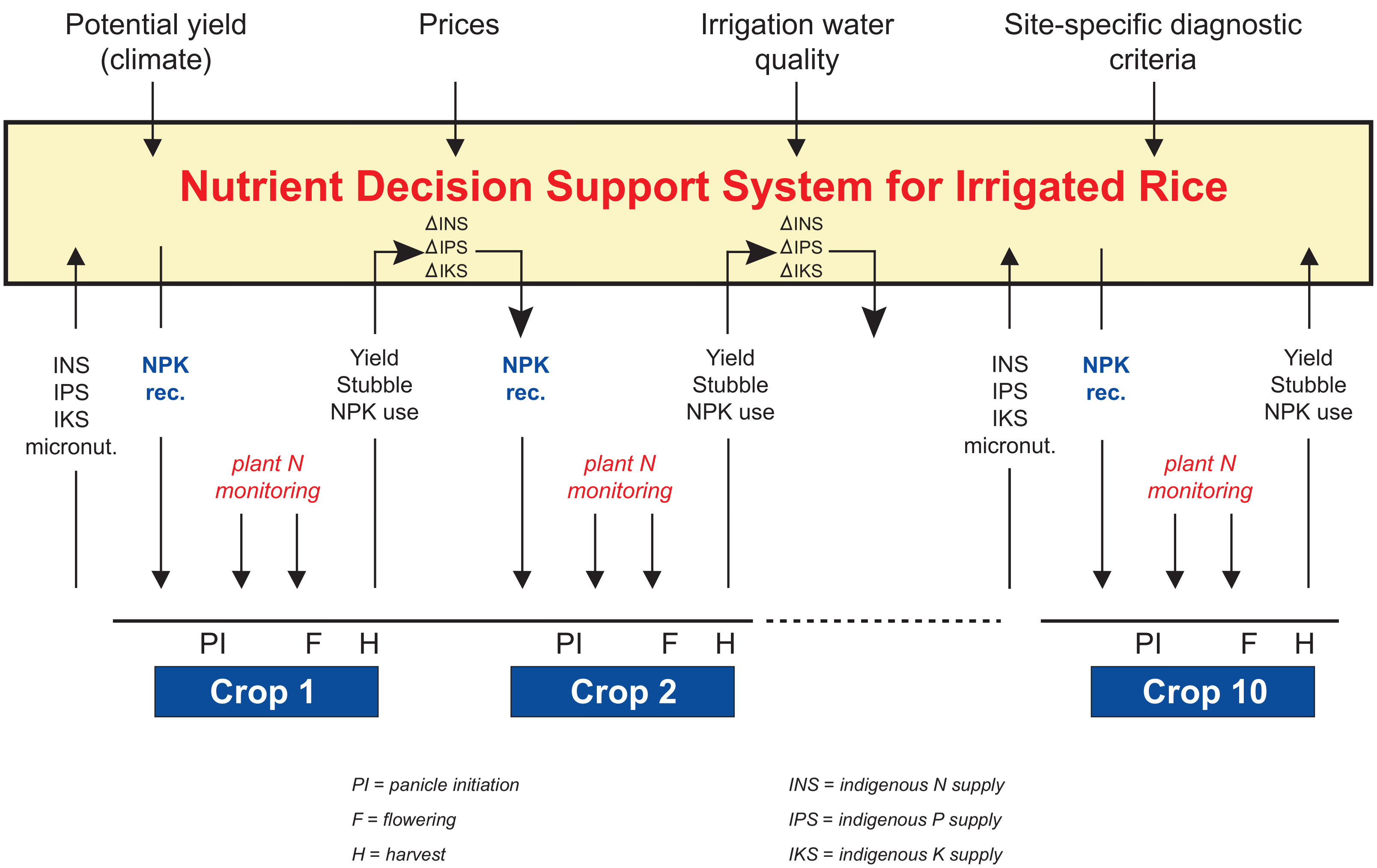


*Figure 3. Strategy for site-specific nutrient management in irrigated rice.*

- prices for harvested grain and fertilizer inputs,
- the source, amount used, and nutrient content of irrigation water, and
- a farm- or field-specific estimate of the indigenous N, P, and K. This is the most sensitive input in the model, and can be estimated using a variety of methods depending on the facilities available at the site (Section 2.5).

Additional important parameters involve:

- the relationship between grain yield and nutrient uptake, i.e., the crop nutrient demand for a specified target yield (Section 2.5), and
- the recovery efficiency and residual effects of applied fertilizer nutrients (i.e., the change in potential nutrient supply).

The necessary information for this is provided in Sections 3.1, 3.2, and 3.3.

In principle, the same approach can be used for rainfed lowland or upland rice, or any other upland crop. However, crop-specific and cropping system-specific data for modeling the relationship between grain yield and nutrient uptake (Section 2.5) and estimating INS, IPS, and IKS (Section 2.4) are required. Unpredictable changes in soil moisture availability in upland and rainfed systems may make this difficult, because one of the major assumptions for the model is that water availability does not limit growth. More research is required to develop a similar approach for rainfed environments that allows adjustments for different levels of moisture availability.

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# 2.4 Estimating Indigenous N, P, and K Supplies

## Definition

The indigenous nutrient supply is the cumulative amount of a nutrient originating from all indigenous sources that circulate through the soil solution surrounding the entire root system during one complete crop cycle.

For practical purposes, the potential indigenous nutrient supply of N (INS), P (IPS), and K (IKS) is defined as the amount of each nutrient taken up by the crop from indigenous sources when sufficient amounts of all other nutrients are supplied, and other limitations to growth are removed. It can be measured as the total plant nutrient uptake in a nutrient omission plot (provided that no other factors such as water, other nutrients, or pests affect growth):

***INS** = total N uptake in N omission plots*

(i.e., plots receiving P, K, and other nutrients, but no N).

***IPS** = total P uptake in P omission plots*

(i.e., plots receiving N, K, and other nutrients, but no P).

***IKS** = total K uptake in K omission plots*

(i.e., plots receiving N, P, and other nutrients, but no K).

The potential indigenous supply as defined earlier is a crop-based measure that integrates the supply of nutrients from *all indigenous sources under field conditions*, including:

- soil supply across the whole rooting depth,
- irrigation water,
- atmospheric deposition (rainfall, dust),
- biological $N_2$ fixation (only in the case of INS), and
- crop residues.

## Estimating INS, IPS, and IKS from grain yield

We will now describe a simple approach for estimating INS, IPS, and IKS based on grain yield only. Other data, such as nutrient uptake measured in omission plots and soil test results, can also be used to arrive at an estimate of how much N, P, and K are available from indigenous sources during one cropping season (in kg $ha^{-1}$), but the three methods described in the following paragraphs are usually most applicable in the field, where field experiment and soil analysis data may not be available.

***Nutrient omission plots***

*This is the most suitable method for estimating indigenous N supply (INS). Note the pale green color in the plot where N fertilizer was not applied.*

1 In a cropping season where favorable weather conditions and good yields are expected, two steps are required:

*(i)* In a farmer's field, establish three small (5 x 5 $m^2$) nutrient omission plots: 'no N,' 'no P', and 'no K'. In the remaining area, apply all three macronutrients N, P, and K. Choose a balanced fertilizer ratio for N:P:K of 3:1:3 (i.e., for 3 kg N, apply 1 kg fertilizer P and 3 kg fertilizer K). Assuming fertilizer recovery fractions of 0.50 kg N uptake $kg^{-1}$ N applied, 0.25 kg P uptake $kg^{-1}$ P applied, and 0.50 kg K uptake $kg^{-1}$ K applied, this would result in the optimal uptake ratio for plant N:P:K of 6:1:6 (based on on-farm data collected in Asia).

*(ii)* Measure grain yield (GY) in the omission plots (0 N, 0 P, and 0 K) and in the fertilized field (NPK). If possible, oven-dry grain at 70°C for 48 hours (i.e., ~3% moisture content) and adjust GY to 14% moisture content:

*GY 14% = oven-dry GY x 0.97/0.86*

Otherwise, sun-dry the grain and assume a moisture content of 14%.

If it is not feasible to establish nutrient omission plots, collect data on grain yield in a farmer's field and record the amounts of fertilizer N, P, and K applied for a cropping season with favorable weather and good yield.

2 If nutrient omission plots were established, follow the decision tree in Figure 4 and calculate the indigenous nutrient supply for each nutrient. The factor by which the grain yield in the respective nutrient omission plot is multiplied refers to the average amount of a nutrient (kg $ha^{-1}$) taken up by the plant to produce one ton of grain in fields, according to whether the nutrient is limiting or not (based on on-farm data collected in Asia). We make the following assumptions:

- A full supply of nutrients other than the element missing in the omission plots, e.g., a full supply of N and K in a 0 P plot.
- The harvest index is approximately 0.5 (modern rice variety with no severe yield-reducing factors).
- If the grain yield in a plot (field) with a full NPK supply is less than 70% of the potential yield ($Y_{max}$), factors other than NPK are limiting. Improve crop management first before estimating INS, IPS, and IKS.

3 If nutrient omission plots were not established but fertilizers were applied in

| | | |
|---|---|---|
| **Estimation of INS** from grain yield (t $ha^{-1}$) in N omission plots (0 N plots) | | |
| GY(NPK) = GY(0 N) | N supply not limiting in 0 N plots | INS = GY(0 N) x 15 |
| GY(NPK) > GY(0 N) | N supply limiting in 0 N plots | INS = GY(0 N) x 13 |
| **Estimation of IPS** from grain yield (t $ha^{-1}$) in P omission plots (0 P plots) | | |
| GY(NPK) ≤ GY(0 P) | P supply not limiting in 0 P plots | IPS = GY(0 P) x 2.6 |
| GY(NPK) > GY(0 P) | P supply limiting in 0 P plots | IPS = GY(0 P) x 2.3 |
| **Estimation of IKS** from grain yield (t $ha^{-1}$) in K omission plots (0 K plots) | | |
| GY(NPK) ≤ GY(0 K) | K supply not limiting in 0 K plots | IKS = GY(0 K) x 15 |
| GY(NPK) > GY(0 K) | K supply limiting in 0 K plots | IKS = GY(0 K) x 13 |

*GY(NPK) is the grain yield in t $ha^{-1}$ (GY, t $ha^{-1}$, 14% moisture content) in a farmer's field receiving N, P, and K fertilizer. $Y_{max}$ is the maximum potential yield (Section 2.1).*

*Figure 4. Estimation of indigenous nutrient supplies of N, P, and K (INS, IPS, and IKS) from grain yield in nutrient omission plots (0 N, 0 P, and 0 K plots).*

a balanced NPK ratio as suggested earlier, calculate the indigenous nutrient supplies according to Equations (N1), (P1), and (K1):

$$INS\ (kg\ N\ ha^{-1}) \approx (GY \times 17) - (RE_N \times FN) \quad (N1)$$

$$IPS\ (kg\ P\ ha^{-1}) \approx (GY \times 3) - (RE_P \times FP) \quad (P1)$$

$$IKS\ (kg\ K\ ha^{-1}) \approx (GY \times 17) - (RE_K \times FK) \quad (K1)$$

where GY is the grain yield in t ha$^{-1}$ (14% moisture content); the factors 17, 3, and 17 are the average amounts of N, P, and K (kg ha$^{-1}$) taken up by the plant to produce 1 t of grain in fields that received NPK fertilizer (based on on-farm data collected in Asia); $RE_N$, $RE_P$, and $RE_K$ are the apparent recovery efficiencies of applied N (0.4–0.6 kg kg$^{-1}$, Section 3.1), P (0.2–0.3 kg kg$^{-1}$, Section 3.2), and K (0.4–0.6 kg kg$^{-1}$, Section 3.3); and FN, FP, and FK are the amounts of fertilizer N, P, and K that were added (kg ha$^{-1}$).

These equations are mentioned in Sections 3.1, 3.2, and 3.3 in Boxes 1, 4, and 6, respectively.

## NOTES:

- Calculations based on nutrient omission plots are more accurate than the indirect estimates using Equations (N1), (P1), and (K1) mentioned above. Equation (N1) should only be used as a last resort because *estimates* of $RE_N$ are not very reliable.
- Plant-based measures of indigenous nutrient supply are affected by:
  - cultivar differences in harvest index, rooting patterns, and nutrient uptake/ nutrient use efficiency,
  - crop establishment method,
  - seasonal variability in climate, and
  - pests and other unquantified yield-limiting factors such as lodging.
- The use of omission plots is only valid for modern high-yielding varieties with a harvest index of about 0.50. If large yield losses were detected (e.g., due to lodging), grain yield should be corrected (e.g., by calculating straw yield/2, assuming a harvest index of 0.50).
- For a particular soil, INS, IPS, and IKS measured in wet broadcast-seeded rice are smaller than in transplanted rice.
- The indigenous nutrient supply is the *potential* supply of a nutrient from indigenous sources. Thus, it can only be measured accurately in a season with favorable climatic conditions and proper crop management and assuming that factors such as the supply of other nutrients, water supply, and pests and diseases do not limit plant growth. For rice grown in a tropical climate, the indigenous nutrient supply is best measured in the dry season.
- In some countries, there is a continuous transfer of soil fertility from border areas to the center of the field (or *vice versa*), where threshing is done and where straw and chaff are later burned. Misleading information on indigenous nutrient supply may therefore result from the use of small omission plots.
- The same principles can be used for estimating the indigenous supply of other nutrients.

## *Further reading*

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# 2.5 Crop Nutrient Requirements – The Nutritional Balance Concept

## *Internal nutrient use efficiency and nutrient removal*

In a situation where crop growth is not limited by water supply, weed problems, or pest infestations, biomass production is mainly driven by N supply, the most limiting nutrient in irrigated rice. Thus, the rice plant's demand for other macronutrients mainly depends on the N supply. Considerable uncertainties about crop N, P, and K requirements may arise, however, because the internal nutrient use efficiency (kg grain produced per kg nutrient in aboveground plant dry matter) varies widely depending on nutrient supply, crop management, and climatic conditions.

*[NB: Nutrient removal (kg nutrient $t^{-1}$ grain) = 1,000/ internal efficiency (kg grain $kg^{-1}$ nutrient).]*

Based on a large number of field observations, we have estimated the total nutrient removal per ton of grain (Table 2). These values include extreme situations in which nutrients are either under maximum dilution or accumulation in the plant, i.e., where nutrients are either limiting or available in surplus.

## *Nutrient accumulation and dilution*

The relationship between grain yield and nutrient accumulation in total aboveground dry matter at physiological maturity of irrigated lowland rice can be investigated for particular target yields using a modeling approach based on QUEFTS (QUantitative Evaluation of the Fertility of Tropical Soils) developed by Bert Janssen and his colleagues in Wageningen, The Netherlands. The model requires the empirical determination of two boundary lines describing the maximum accumulation (YNuA) and dilution (YNuD) of nutrients in the plant (Figure 5). YNu represents the optimum nutrient uptake requirement to achieve a particular grain yield target for the given boundary lines.

This concept assumes a linear relation between grain yield and nutrient uptake at lower uptake levels when nutrient uptake is at its maximum under conditions of limited nutrient supply. The *actual* plant nutrient accumulation under such conditions should theoretically be close to the line of maximum dilution of the respective nutrient in the plant (YNuD in Figure 5), but it is unlikely that *all*


***Nutritional balance***

*Response to N and P fertilizers may be small because of K deficiency. Balanced fertilization requires that all nutrient deficiencies be eliminated by proper nutrient management.*

*Table 2. The effect of nutrient availability on the removal of N, P, and K (in kg) per ton of rice grain for the linear part of the relationship between grain yield and nutrient uptake (<80% of the potential yield).*

| Nutrient availability | Nitrogen | Phosphorus | Potassium |
|---|---|---|---|
| | | (kg nutrient $t^{-1}$ grain) | |
| Maximum nutrient limitation | 10 | 1.6 | 9 |
| Nutrient limitation | 11–13 | 1.7–2.3 | 10–13 |
| Nutritional optimum | 14–16 | 2.4–2.8 | 14–16 |
| Nutrient surplus | 17–23 | 2.9–4.8 | 17–27 |
| Maximum nutrient surplus | 24 | 4.9 | 28 |

major nutrients can be diluted to the maximum at once. At least one macronutrient is probably not limiting but may even be available in surplus and, therefore, accumulate to the maximum in the plant. Thus, internal nutrient use efficiency for all three nutrients would be between their maximum and minimum values in an ideal situation of balanced N, P, and K nutrition where none of these nutrients is limiting or taken up in surplus. This situation of nutritional balance is the most economical and is depicted by YNu in Figure 5.

When yields are large and approach the potential yield, however, internal nutrient use efficiency decreases in a nonlinear fashion. The nonlinear part of the relation between grain yield and nutrient accumulation (as predicted by the QUEFTS model) depends on:

- the definition of the boundary lines describing the 'envelope' of maximum and minimum accumulation, and
- the genetically determined maximum potential yield ($\mathbf{Y}_{max}$ in Figure 5).

If we assume that the internal nutrient use efficiency of modern high-yielding varieties does not vary greatly, standard boundary lines appear to be valid for all indica varieties with a harvest index of approximately 0.50. The derived nutrient requirements shown below and in Sections 2.6, 3.1, 3.2, and 3.3 can therefore be used for all tropical and subtropical sites with irrigated lowland rice in Asia regardless of the method of crop establishment.

## Nutrient requirements

Provided plant growth is limited by nutrient supply only, the optimal nutritional balance is achieved with an uptake of ~14.7 kg N, 2.6 kg P, and 14.5 kg K per ton of grain yield.

These nutrient uptake rates are valid up to the point where the yield target is about 70–80%

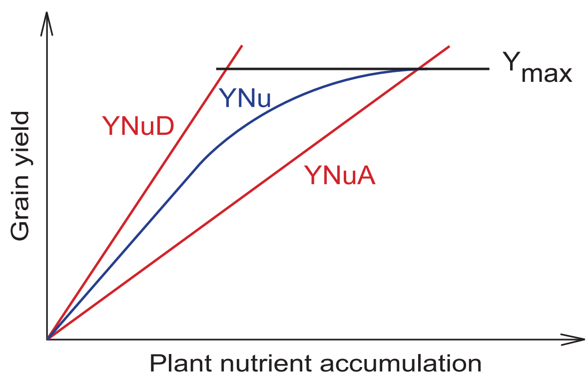


*Figure 5. Schematic relationship between grain yield and plant nutrient accumulation in total aboveground plant dry matter of rice as affected by potential yield.*

*Table 3. Optimal internal use efficiency for N, P, and K in irrigated rice.*

| Nitrogen (kg grain $kg^{-1}$ N) | Phosphorus (kg grain $kg^{-1}$ P) | Potassium (kg grain $kg^{-1}$ K) |
|---|---|---|
| 68 | 385 | 69 |

of the climate-adjusted potential yield (i.e., Y = $Y_a$ = $Y_{max}$ x 0.80). Optimal internal nutrient use efficiency values are shown in Table 3.

Irrespective of the selected potential yield, the N:P:K ratio in plant dry matter (as recommended by the QUEFTS model) is about 5.7:1:5.6. This is similar to the average plant N:P:K ratio of 5.3:1:5.4 calculated from a large data set on grain yield and plant nutrient accumulation collected in six Asian countries.

Using these nutrient requirements for a site-specific nutrient management approach in irrigated rice, no other site-specific or season-specific information is required other than the climate-adjusted potential yield (which can be obtained from crop simulation models, long-term experiments, or local experts). Thus, this approach allows the estimation of nutrient requirements to achieve a particular yield target and provides a useful tool for identifying economical yield targets such as the attainable yield, $\mathbf{Y_a}$ (Section 2.1).

## NOTES:

- The internal nutrient use efficiency as calculated by QUEFTS is based on the average values of numerous modern, high-yielding indica varieties grown at various experimental sites in Asia.
- If the internal nutrient use efficiency of a particular variety is greater than that of other varieties, the boundary lines describing the 'envelope' must be adjusted.
- If new varieties with a greater potential yield are released, internal nutrient use efficiency may be greater even at lower yield levels, resulting in an upward shift of the 'envelope'.

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# 2.6 Recovery Efficiencies of Applied Nutrients

## *Definition*

The recovery efficiency (RE) of applied fertilizer is defined as the amount of fertilizer nutrient taken up by one crop, divided by the amount of fertilizer applied. The first-season RE (or recovery fraction) can be estimated in fertilizer trials using the difference method:

$$RE\ (kg\ kg^{-1}) = (U_2 - U_1)/(F_2 - F_1)$$

where RE is the recovery efficiency (kg of nutrient uptake per kg of nutrient applied); U is the total nutrient uptake with grain and straw (kg $ha^{-1}$), and $F_1$ and $F_2$ are the amounts of fertilizer nutrient added (kg $ha^{-1}$) in two different treatments.

Treatment 2 receives a higher fertilizer nutrient rate than Treatment 1. A zero-fertilizer control can be used as the reference (Treatment 1).

An estimate of recovery efficiency is necessary to calculate the amount of fertilizer nutrient required to meet plant nutrient demand for a grain yield target using the general formula:

$$F\ (kg\ ha^{-1}) = U - IS/RE$$

where F is the amount of fertilizer nutrient required to meet nutrient uptake demand (U) to support the grain yield target (Section 2.5); U is the total nutrient uptake with grain and straw (kg $ha^{-1}$); IS (kg $ha^{-1}$) is the indigenous supply of the respective nutrient (Section 2.4); and RE is the recovery efficiency (kg of nutrient uptake per kg of nutrient applied).

Examples of the application of this formula are given in Sections 3.1, 3.2, and 3.3.

## *Determinants of recovery efficiencies*

If other factors do not limit crop growth, the RE of a nutrient is related to the following:

- the indigenous nutrient supply,
- the amount of fertilizer nutrient applied, and
- plant uptake or sink potential, which in turn depends on the availability of other nutrients and the climate-adjusted potential yield of a particular rice cultivar.

This is explained in greater detail using the relationship between the actual plant P accumulation at maturity and the potential P supply to the crop as an example (Section 2.5). The potential nutrient supply is defined as the amount of a nutrient that originates from indigenous and/or fertilizer sources and passes through the soil solution during the entire growing season. This theoretical nutrient pool cannot be directly measured, but the relationship between nutrient accumulation and potential supply can be modeled using the following assumptions:

- The measured indigenous supply is equal to the uptake of a nutrient up to maturity under optimal conditions in a nutrient omission plot (Section 2.4). The actual (potential) indigenous nutrient supply, however, is usually greater than the nutrient uptake in such an omission plot because optimal conditions are rarely achieved under field conditions. Furthermore, a certain amount of nutrients will never be taken up by the crop and will remain in the soil solution, especially when nutrient concentrations are large.
- All applied fertilizer nutrients are potentially available to the crop. This assumption holds for many irrigated soils cropped to rice, in which fixation of P and K is substantially smaller than in aerated soil. The assumption is not valid for N, where recovery efficiency depends not only on the total amount of applied fertilizer N but also on the number of

splits and the timing of applications. Fertilizer N that is not immediately taken up by the plant is prone to losses due to volatilization.

The potential P supply is the sum of the indigenous P supply (IPS) and fertilizer P (FP). For practical reasons, P uptake in a P omission plot ($UP_{0P}$) is often assumed to be equal to the actual IPS (Section 2.4).

In general, the relationship between nutrient accumulation at maturity and potential supply can be expected to follow a curved line with a transition from source to sink limitation of nutrient uptake, as illustrated in Figure 6. Plant P uptake would be source-limited in a situation of low potential P supply (e.g., IPS + FP 1). Hence, available P will be most efficiently used by the plant so that UP 1 is relatively close to the 1:1 line, representing the situation where all supplied P would be taken up by the crop. With increasing potential P supply (e.g., if FP 2 was chosen instead of FP 1), the recovery efficiency decreases because plant P uptake becomes increasingly restricted by the genetically determined seasonal yield potential, until plant P uptake (or plant growth) does not increase further with increasing P supply. In this situation of nutrient uptake or sink limitation, plant P uptake has reached its maximum ($UP_{max}$).

The greatest recovery efficiencies of fertilizer nutrients can be expected in situations where sink potential ($UP_{max}$) is large (i.e., favorable climatic conditions, sufficient water supply, low pest pressure, etc.) and indigenous nutrient supplies and fertilizer rates are small. A large sink potential would force the line describing the relationship between plant nutrient accumulation and potential nutrient supply to follow a steeper curve, bringing it closer to the 1:1 line. Increasing the fertilizer rate, however, will eventually lead to a decrease in nutrient recovery efficiency.

The lowest recovery efficiencies can be expected at low sink potentials (flat curve describing the relationship between plant nutrient accumulation and potential nutrient supply) and high levels of indigenous supplies. In this situation, recovery efficiencies may be low even at small fertilizer application rates.

## *Estimates of recovery efficiencies*

Clearly, a large variation in recovery efficiencies can be expected among farmers' fields and in the same field over time, depending on differences in general soil properties, cropping history, current crop management, and climatic conditions. Additional variation may be introduced because of problems in water supply, weeds, and pests. This makes it difficult to specify a representative RE, which is needed for estimating fertilizer rates as described in Sections 3.1, 3.2, and 3.3 for N, P, and K.

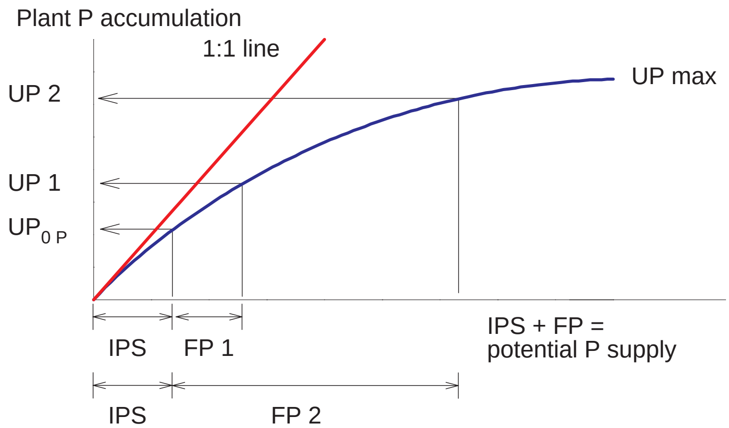


*Figure 6. Schematic relationship between actual plant P accumulation (UP) with grain and straw at maturity of rice and potential P supply for a particular maximum P uptake potential ($UP_{max}$). IPS = indigenous P supply, FP = fertilizer P.*

In irrigated lowland rice fields with good crop management and grain yields of 5–7 t $ha^{-1}$, typical fertilizer recovery efficiency ranges are 0.30–0.60 kg $kg^{-1}$ for N (median: 0.40), 0.10–0.35 kg $kg^{-1}$ for P (median: 0.20), and 0.15–0.65 kg $kg^{-1}$ for K (median: 0.35).

*[NB: Interquartile ranges and medians of about 320 on-farm trials with site-specific fertilizer management conducted in 1997–98 in six countries of Asia.]*

For practical decision making, we suggest using these average recovery efficiencies when calculating fertilizer requirements of P and K (Sections 3.2 and 3.3). For nitrogen, we recommend using an RE of about 0.50 kg $kg^{-1}$ when calculating fertilizer N rates, where management options are used to increase N efficiency (Section 3.1), particularly in cases where tools for dynamic, real-time N management are available (Section 5.6).

## NOTES:

- Estimates of RE of fertilizer N topdressed at different growth stages are given in Section 3.1 and information on practical measures to improve $RE_N$ is given in Section 5.6.
- Particularly for P and K, it may not be advisable to calculate fertilizer requirements according to the general equation F = U - IS/RE when the gap between plant nutrient demand for a yield target and indigenous nutrient supply is small. A maintenance dose of P and K would be sufficient in this situation to replenish the soil nutrient pool and avoid nutrient mining.
- The given 'typical' recovery efficiencies for P and K are only valid for irrigated lowland rice systems in Asia, i.e., for given fertilizer rates, yield levels, and crop management practices (including method of fertilizer application and cultivars used). In soils with high P-fixation potential (e.g., Ultisols, Oxisols) or K-fixation potential (e.g., K-depleted Vertisols), the RE of P or K may be much smaller, particularly under upland conditions or rainfed lowland conditions where prolonged flooding does not occur.
- As P and K demand is largely driven by potential yield and the availability of N, recovery efficiencies of P and K may be improved through improved N management and a more balanced nutrient use.
- The recovery efficiencies of P and K also depend on the *method* of fertilizer application. In rice, the recovery efficiencies of P and K are probably smaller for fertilizer incorporated into the soil (typical for TPR) than for topdressed application of P or K (typical for DSR in the tropics).

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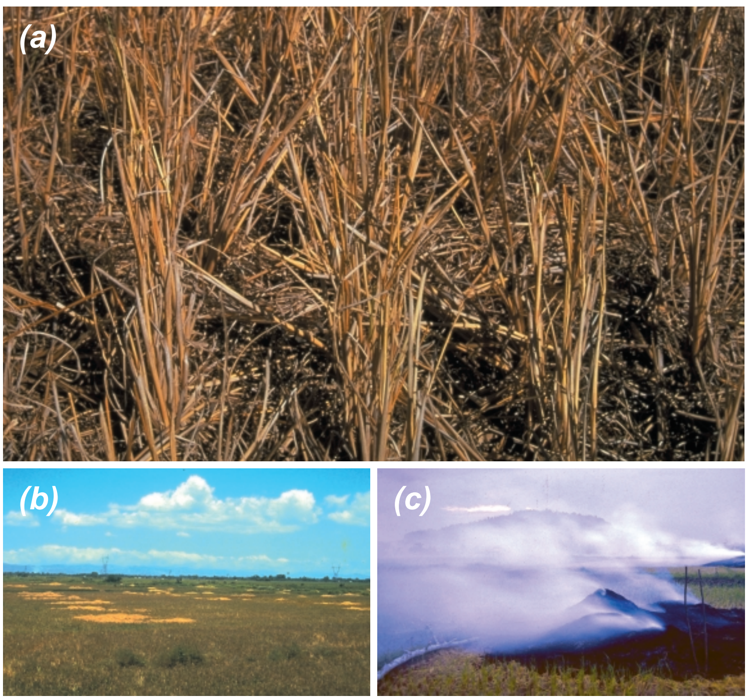
# 2.7 Managing Organic Manures, Straw, and Green Manure

Prior to the introduction of mineral fertilizers, all the N and other nutrients used to grow rice in flooded soils were provided by irrigation water, sediments, biological $N_2$ fixation, and animal manure. N fertilizer use became widespread following the invention of the Haber Bosch process, which is used to convert atmospheric $N_2$ into mineral fertilizer. Traditional rice varieties, however, did not respond well to added fertilizer N. It was only with the introduction of modern, N-responsive, high-yielding varieties that the demand for N and other nutrients became greater than that which could be supplied from indigenous and cycled sources. Over the past 30 years, governments have subsidized N fertilizer manufacture and distribution to safeguard food supplies during periods of rapid economic and population growth. This and the greater convenience of mineral N fertilizer use have led to a decline in the use of most organic nutrient sources.

Where possible, nutrient sources such as farmyard manure, straw, and green manure should be used in combination with mineral fertilizers to satisfy part of the rice crop's requirement for nutrients and to sustain soil quality in the long run. In many areas, however, the supply is not sufficient, and using organic manure is more costly than applying equivalent amounts of nutrients as mineral fertilizer. Organic rice farming is practiced in small areas but depends on the following:

- the availability of organic inputs, and
- a price premium to compensate for smaller yields and greater production costs.

So far, we have not seen convincing evidence that the supply of nutrients from organic sources to intensive rice-cropping systems can be managed on a large scale. In most areas, insufficient organic manure is available to balance nutrient removal. The problem of




***Straw management***

*(a) Most of the total uptake of K and Si is contained in the straw. For this reason, straw management is of great significance in rice nutrition. (b) When threshing takes place in the field, straw is left behind in heaps. (c) Some of the K returned to the soil beneath the fire spots is lost by leaching, and no straw K is returned to most of the soil surface. Nutrients may also be removed from the field when straw is fed to cattle but this depends on how cattle manure is managed.*

transporting of bulky organic manure materials is another concern.

It is important to understand the fundamental differences in decomposition patterns of organic inputs and the role of organic matter (OM) in different rice-based cropping systems:

- **In rice-nonrice crop systems** (e.g., rice-wheat rotations), or rainfed lowland or upland rice systems, longer aerobic periods cause a more rapid and complete turnover of organic matter. Under continuous cropping, this may result in a ***decrease* in soil organic matter content**. The replenishment and buildup of soil OM are important in maintaining soil structure for crops grown under aerobic conditions in the rotation. Under upland conditions, the main functions of OM are as follows:
  - to increase the water-holding capacity of the soil,
  - to improve soil structure and water percolation,
  - to reduce erosion,
  - to stimulate the activity of soil flora and fauna (earthworms), and
  - to improve the use of soil and fertilizer P.

  The effect of OM on soil fertility depends on the amount applied and the material used:
  - Carbon-rich sources with a wide C:N ratio (e.g., straw, compost) should be used if soil organic C content is to be increased.
  - Green manures with a narrow C:N ratio have little potential for increasing soil organic matter over time, but may improve soil physical properties.

  Catch crops (legumes, other green manures, managed weeds) should be grown in fallow periods to *conserve* N and produce additional OM and income (grain legumes) if soil moisture and farm economics allow.

- **In rice-rice (-rice) systems** with short aerobic fallow periods, anaerobic decomposition leads to the development of more stable OM compounds so that soil OM is well conserved. The total soil OM content tends to remain constant or, in heavy clay soils, ***increases* over time** until it reaches a new equilibrium, even if no OM has been applied and straw is removed. Because soil structure is deliberately destroyed during puddling, possible positive effects of increased OM content on soil physical properties are less important than in upland crops. The role of OM is reduced to its direct and indirect effects on nutrient supply. Occasionally, OM-increased soil content can even have negative effects that lead to mineral deficiencies (e.g., Zn) or toxicities (e.g., Fe, sulfide), and poor root health. The buildup and maintenance of soil OM are therefore less critical for sustaining soil fertility in lowland systems. OM management must instead focus on maintaining the *quality* of soil OM by avoiding the accumulation of highly complex organic matter compounds with slow N mineralization rates.

The *timing of OM incorporation* is also very important. Organic nutrient sources may form part of an integrated nutrient management strategy, but large OM inputs before flooding should be avoided. Green manures have an N fertilizer substitution value, but are less cost-efficient than mineral N fertilizer and have little long-term residual benefit.

## *Organic manures*

Organic manures differ widely in their composition and effect on soil fertility and nutrient supply (Table 4). Where available, 2–10 t $ha^{-1}$ (or more) of farmyard manure (FYM) can be applied, but FYM use has decreased in recent years due to the increased use of straw as fuel for cooking, lack of labor, and the specialization of rice farms that has caused a reduction in livestock numbers per hectare of arable land. In intensive rice-rice systems,

*Table 4. Typical nutrient contents of organic materials.*

| Organic material | Water (%) | C | N | P | K | Ca |
|---|---|---|---|---|---|---|
| | | (% of fresh material) | | | | |
| Human feces | | | 1.0 | 0.2 | 0.3 | |
| Cattle feces | | | 0.3 | 0.1 | 0.1 | |
| Pig feces | | | 0.5 | 0.2 | 0.4 | |
| Fresh cattle manure | 60 | 8–10 | 0.4–0.6 | 0.1–0.2 | 0.4–0.6 | 0.2–0.4 |
| Composted cattle manure | 35 | 30–35 | 1.5 | 1.2 | 2.1 | 2.0 |
| Pig manure | 80 | 5–10 | 0.7–1.0 | 0.2–0.3 | 0.5–0.7 | 1.2 |
| Poultry manure | 55 | 15 | 1.4–1.6 | 0.5–0.8 | 0.7–0.8 | 2.3 |
| Garbage compost | 40 | 16 | 0.6 | 0.2 | 0.3 | 1.1 |
| Sewage sludge | 50 | 17 | 1.6 | 0.8 | 0.2 | 1.6 |
| Sugarcane filter cake | 75–80 | 8 | 0.3 | 0.2 | 0.1 | 0.5 |
| Castor bean cake | 10 | 45 | 4.5 | 0.7 | 1.1 | 1.8 |

*kg nutrient $t^{-1}$ fresh manure = % nutrient content x 10*

the effect of organic manures on rice yields is mainly due to their nutrient input, including the secondary nutrients and micronutrients that may not be contained in mineral NPK fertilizers used. Improvements in soil fertility through the use of organic manures (e.g., increased soil OM content and cation exchange capacity [CEC], and improved soil physical properties) are more important in rice-nonrice and rainfed lowland and upland rice systems.

## Straw management

Straw is the only major organic material available to most rice farmers. About 40% of the N, 80–85% of the K, 30–35% of the P, and 40–50% of the S taken up by rice remains in vegetative plant parts at crop maturity.

Straw is removed from the field, burned *in situ*, piled or spread in the field, incorporated in the soil, or used as mulch for the following crop. Each of these measures has a different effect on the overall nutrient balance and soil fertility in the long term. Where S-free mineral fertilizers are used, straw may be an important source of S. Thus, straw burning should not be practiced. In contrast, burning effectively transforms straw into a mineral K nutrient source and only a small amount of K is lost in the process. The effect of straw removal on long-term soil fertility is much greater for K than for P (Table 5). Spreading and incorporation of straw, however, are labor-intensive tasks, and farmers consider burning to be more expedient. Straw is also an important source of micronutrients (Zn) and the most important influence on the cumulative Si balance in rice (Section 3.6).

*Removal* of straw from the field is widespread in India, Bangladesh, and Nepal. This explains the depletion of soil K and Si reserves observed at many sites. Straw can be used as fuel for cooking, ruminant fodder, and stable bedding or as a raw material in industrial

*Table 5. Typical nutrient concentrations of rice straw at harvest.*

| | N | P | K | S | Si |
|---|---|---|---|---|---|
| Content in straw DM [a] (%) | 0.5–0.8 | 0.07–0.12 | 1.2–1.7 | 0.05–0.10 | 4–7 |
| Removal with 1 t straw (kg $ha^{-1}$) | 5–8 | 0.7–1.2 | 12–17 | 0.5–1.0 | 40–70 |

[a] DM = dry matter

processes (e.g., papermaking). In the process, some or all of the nutrients contained in the straw may be lost to the rice field, particularly where animal manure is used in other parts of the farming system where the response is greater than in rice.

*Incorporation* of the remaining stubble and straw into the soil returns most of the nutrients and helps to conserve soil nutrient reserves in the long term. Short-term effects on grain yield are often small (compared with straw removal or burning), but long-term benefits are significant. Where mineral fertilizers are used and straw is incorporated, reserves of soil N, P, K, and Si are maintained and may even be increased. Incorporation of straw and stubble into wet soil (during plowing) results in temporary immobilization of N and a significant increase in methane emission from rice paddy, and therefore contributes to global climate change. Incorporation of large amounts of fresh straw is either labor-intensive or requires suitable machinery for land preparation, and may result in the buildup of disease problems. Transplanting should be carried out 2–3 weeks after straw incorporation.

Recent research results from experimental farms indicate that early, dry shallow tillage at 5–10 cm depths (to incorporate crop residues and enhance soil aeration during fallow periods) has beneficial effects on soil fertility in intensive rice-rice systems. Shallow tillage of dry soil requires a 4-wheel tractor and should be carried out up to 2–3 weeks after harvest in cropping systems where the dry-moist fallow period between two crops is at least 30 days. Beneficial effects include:

- Aerobic decomposition of crop residues (~50% of the carbon within 30–40 days), thereby minimizing negative effects of the products of anaerobic decomposition on early rice growth. A more complete carbon turnover is achieved.
- Improved soil aeration (i.e., reoxidation of $Fe^{2+}$ and other reduced substances that accumulate during the flooding period).
- Increased N mineralization and soil P release to the succeeding rice crop, up to the panicle initiation stage.
- Reduced weed growth during the fallow period.
- Reduced irrigation water requirement during rice land preparation (i.e., less soil cracking and bypass flow water losses in heavy clay soils).
- Easier wetland preparation for rice (i.e., there is often no need for a second plowing operation).
- Smaller $CH_4$ emissions compared with straw incorporation during land preparation for the rice crop.

*Burning* causes almost complete N loss, P losses of about 25%, K losses of 20%, and S losses of 5–60%. The amount of nutrients lost depends on the method used to burn the straw. In areas where harvesting has been mechanized (e.g., Thailand, China, northern India), all the straw remains in the field and is rapidly burned *in situ*. Therefore, losses of S, P, and K are small.

In Indonesia and the Philippines, straw is heaped into piles at threshing sites and burned after harvest. The ash is usually not spread on the field, and this results in large losses of minerals (K, Si, Ca, Mg) leached from the ash piles, although nutrients contained in the relatively long stubble (30–40 cm) remain in the field. Moreover, such a practice results in a significant transfer of nutrients from the periphery of the field to the center, or even from surrounding fields to the center field where, after threshing, the residues are burned. Over time, this practice results in the accumulation of some nutrients (K, Si, Ca, Mg) in some parts of the field and nutrient depletion in other parts.

Burning causes atmospheric pollution and results in nutrient loss, but it is a cost-effective method of straw disposal, and also helps to reduce pest and disease populations that may occur due to reinfection from inoculum in the straw biomass.

## *Green manuring*

The practice of green manuring has been abandoned in most areas following the introduction of intensive cropping systems. Only fast-growing, short-duration legumes such as the stem-nodulating *Sesbania rostrata* are now used in intensive rice systems, because of the short duration of the fallow period (40–60 days). Many green manure legumes accumulate N rapidly in 45–60 days of growth (80–100 kg N $ha^{-1}$) and most of the accumulated N (~80%) is derived from biological $N_2$ fixation. The amount of N accumulated by green manures may be sufficient to substitute for the total mineral fertilizer N requirement. N use efficiency for fertilizer N and green manure is similar; mineral fertilizer N losses are larger, but the long-term residual effects of green manure on soil productivity are usually small. Green manuring is effective in accelerating the reclamation of saline and sodic soils. In China, several green manure plants that contain a large amount of K have proved useful as potash fertilizer substitutes and provide additional benefits such as enhanced grain protein content. Such green manure plants, however, do not provide a net *addition* of K to the soil, but may exploit K from deeper in the soil profile, capture K from irrigation water, or reduce leaching of K on coarse-textured soils.

Worldwide, the use of pre-rice green manure legumes for lowland rice production has decreased dramatically over the last 30 years due to scarcity of land (increasing population pressure) and the low price of urea N. Post-rice green manure in rice rotations has been replaced by high-yielding early maturing grain legumes. Other constraints to green manure use include unreliable performance, poor availability of seeds, and high labor requirements. Local hydrology and soil texture also affect the agronomic effectiveness of green manure compared with N fertilizers and alternative cash crops. In addition, green manure crops require sufficient P for effective biological $N_2$ fixation.

In general, the niche for pre-rice green manuring is the relatively short time span available for green manure growth when the soil moisture regime is unfavorable for cash cropping (e.g., flood-prone rainfed lowlands with coarse-textured soils). Ultimately, socio-economic factors such as the cost of land, labor, and mineral N fertilizer determines the cost-effectiveness and adoption of pre-rice green manure technology by farmers. Given these constraints, green manure use is expected to decrease further in the future in favorable rice-growing environments.

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# 2.8 Economics of Fertilizer Use

This brief discussion of the economic aspects of fertilizer use is restricted to the estimation of optimal fertilizer rates and profit for a single rice crop. For nutrients with long-term residual effects such as P and K, the economic contribution of applied fertilizer must also be considered over time periods in years or even decades.

For a single nutrient, profit ($\pi$, gross return above fertilizer cost) and the increase in profit compared with no fertilizer applied ($\Delta\pi$) can be calculated using

$$\pi = G_P \times Y - P_F \times F$$
$$\Delta\pi = G_P \times (Y - Y_0) - P_F \times F$$

where $\pi$ is profit (\$ ha$^{-1}$ crop$^{-1}$); $G_P$ is the average farm-gate price of rice (\$ kg$^{-1}$); Y is the grain yield with nutrient applied (kg ha$^{-1}$); $Y_0$ is the grain yield without nutrient applied (kg ha$^{-1}$); $P_F$ is the market price of fertilizer nutrient (\$ kg$^{-1}$); and F is the amount of fertilizer nutrient applied (kg ha$^{-1}$).

Profits for different combinations of N, P, and K fertilizer can be calculated and compared using

$$\pi = G_P \times Y - (P_N \times FN + P_P \times FP + P_K \times FK)$$

where FN, FP, and FK are the respective amounts of fertilizer applied; and $P_N$, $P_P$, and $P_K$ are the respective prices of each fertilizer.

The optimal rate of fertilizer application to a crop is that rate which produces the maximum economic returns at the minimum cost, and this can be derived from a nutrient response curve. Different models for response curves are in use, but linear response-plateau models and curvilinear models (e.g., quadratic, exponential, inverse hyperbolic) are the most widely used. A typical example is a quadratic response function of the following form:

$$Y = b_0 + b_1F - b_2F^2$$

where Y is grain yield (kg ha$^{-1}$); $b_0$, $b_1$, and $b_2$ are constants fitted by regression; and F is the amount of fertilizer nutrient applied (kg ha$^{-1}$).

The advantage of quadratic response models of this form is that they allow incremental responsiveness of the crop to decline as larger amounts of fertilizer are used. Refer to Section 5.5 for a detailed discussion of response curves and the factors affecting them.

The optimal fertilizer rate ($\Delta\pi/\Delta F = 0$) is the point on the response function where the slope of the function ($\Delta Y/\Delta F$) equals the ratio of the fertilizer price to the price of rice (paddy):

$$\Delta Y/\Delta F = P_F/G_P$$

where $P_F$ represents the price per kg of fertilizer; and $G_P$ represents the price per kg of paddy.

For a standard quadratic response function ($Y = b_0 + b_1F - b_2F^2$), the optimal fertilizer rate is given as

$$F = (P_F/G_P - b_1)/2b_2$$

where F is the amount of fertilizer nutrient applied (kg ha$^{-1}$); $P_F$ represents the price per kg of fertilizer; $G_P$ represents the price per kg of paddy; and $b_1$ and $b_2$ are constants fitted by regression.

## NOTES:

- As a rule of thumb, optimal rates determined on an economic basis are smaller than those required to produce maximum crop yields. Economic yield targets usually do not exceed 80% of the maximum potential yield ($Y_{max}$, Section 2.1). The ‘nutritional balance’ approach described in Section 2.5 focuses on achieving the physiological optimum in terms of crop nutrient uptake. In most cases, this physiologically optimal yield is not very different from the optimal economic yield.
- The benefit-cost ratio, BCR = $\Delta\pi/P_F \times F$, is often used to assess fertilizer rates or fertilization technologies. For a nutrient that follows a diminishing response form

**Example:**

A fertilizer experiment with five N rates (N, kg $ha^{-1}$) was conducted and grain yields (Y, kg $ha^{-1}$) were fitted to the response function

$$Y = 3125 + 18.5\,N - 0.06\,N^2$$

The average price of N fertilizer ($P_N$) was \$0.22 $kg^{-1}$, whereas the price of rice ($G_P$) was \$0.12 $kg^{-1}$. The optimal N rate obtained is

$$F_N = (0.22/0.12 - 18.5)/-0.12$$
$$= 139 \text{ kg N ha}^{-1}$$

of the profit function, however, this ratio is both misleading and inappropriate if applied in relation to benefits gained from fertilizer use, because it tends to overestimate economic fertilizer rates.

- Whatever model of response curve is chosen, it is important to consider the model fit as well as sensitivity to price changes.
- The approach described does not take into account other economic variables such as labor costs associated with fertilizer use or interest to be paid on loans for purchasing fertilizer. These need to be included for a full economic assessment.
- Colwell (1994) describes the determination of optimal rates for multiple nutrients and their interactions. Ali (1999) presents an approach for evaluating organic fertilizers.

## *Further reading*


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3

# Mineral Deficiencies

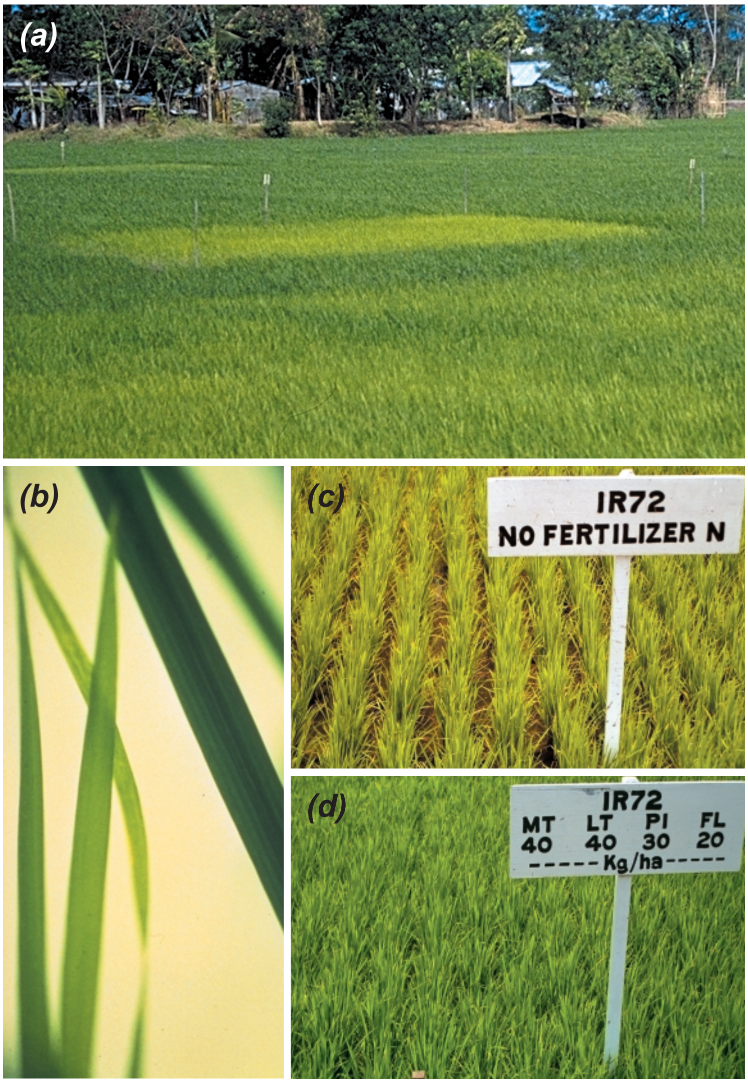
### In this chapter

# 3.1 Nitrogen Deficiency

## *Function and mobility of N*

Nitrogen is an essential constituent of amino acids, nucleic acids, nucleotides, and chlorophyll. It promotes rapid growth (increased plant height and number of tillers) and increased leaf size, spikelet number per panicle, percentage filled spikelets in each panicle, and grain protein content. Thus, N affects all parameters contributing to yield. Leaf N concentration is closely related to the rate of leaf photosynthesis and crop biomass production. When sufficient N is applied to the crop, the demand for other macronutrients such as P and K is increased.

$NO_3$-N and $NH_4$-N are the major sources available for uptake. Most absorbed $NH_4$-N is incorporated into organic compounds in the roots, whereas $NO_3$-N is more mobile in the xylem and is also stored in the vacuoles of different plant parts. $NO_3$-N may also contribute to maintaining cation-anion balance and osmo-regulation. To fulfill essential




***Nitrogen deficiency symptoms in rice***

*(a) In the omission plot where N has not been applied, leaves are yellowish green. (b) In N-deficient plants, leaves are smaller. (c) Tillering is reduced where N is deficient. (d) Greater tillering where N fertilizer has been applied.*

*Table 6. Optimal ranges and critical levels of N in plant tissue.*

| Growth stage | Plant part | Optimum (%) | Critical level for deficiency (%) |
|---|---|---|---|
| Tillering to panicle initiation | Y leaf | 2.9–4.2 | <2.5 |
| Flowering | Flag leaf | 2.2–3.0 | <2.0 |
| Maturity | Straw | 0.6–0.8 | |

functions as a plant nutrient, $NO_3$-N must be reduced to ammonia through the action of nitrate and nitrite reductase. N is required throughout the growth period, but the greatest requirement is between the early to midtillering and panicle initiation stages. Sufficient N supply during ripening is necessary to delay leaf senescence, maintain photosynthesis during grain filling, and increase the protein content in the grain. N is mobile within the plant and, because N is translocated from old senescent leaves to younger leaves, deficiency symptoms tend to occur initially in older leaves.

Compared with conventional (inbred) rice varieties, hybrid rice has important specific characteristics:

- Greater potential to absorb and use N from the soil because of a more vigorous root system (many superficial roots, greater root oxidation power).
- Higher efficiency of N translocation from source (stem, leaf) to sink (grain).
- N uptake peaks at tillering and grain filling stages.
- Greater $NO_3^-$ uptake and use during reproductive growth. Larger yield response to topdressed $NO_3$-N because of the large number of superficial roots.

## *N deficiency symptoms and effects on growth*

### Stunted, yellowish plants. Older leaves or whole plants are yellowish green.

N deficiency is the most commonly detected nutrient deficiency symptom in rice. Old leaves and sometimes all leaves become light green and chlorotic at the tip. Leaves die under severe N stress. Except for young leaves, which are greener, leaves are narrow, short, erect, and lemon-yellowish green. The entire field may appear yellowish. N deficiency often occurs at critical growth stages such as tillering and panicle initiation when the demand for N is large. N deficiency results in reduced tillering, small leaves, and short plants. Grain number is reduced. The visual symptoms of N deficiency can be confused with those of S deficiency (Section 3.5), but S deficiency is less common and tends to first affect younger leaves or all leaves on the plant. Slight N deficiency can be confused with Fe deficiency (Section 3.9), but the latter affects the *emerging* leaf first.

To reach maximum potential yield, leaf N must be maintained at or above 1.4 g $m^{-2}$ leaf area, which is equivalent to a chlorophyll meter reading (SPAD) of 35. A SPAD reading of 35 for the uppermost, fully expanded leaf is used as a threshold for N deficiency (i.e., the need to apply N) in transplanted high-yielding indica rice. A SPAD threshold of 32–33 should be used in direct-seeded rice where tillering is greater.

Note that SPAD values are poorly correlated with leaf N *content* expressed on a leaf dry weight basis (% N), but *closely correlated* with leaf N content expressed on a leaf area basis (g N $m^{-2}$).

In direct-seeded rice in southern Australia, fast tissue N-testing in the shoot at panicle initiation is commonly practiced to determine the requirement for N topdressing at the panicle initiation stage. N rates are adjusted as a function of tiller density and N content in the shoot. For example, topdressed N is not recommended at the panicle initiation stage in the following situations:

- 800–1,000 shoots $m^{-2}$ and shoot N at PI stage >2%.
- 1,000–1,200 shoots $m^{-2}$ and shoot N at PI stage >1.75%.

## Soil

Crop-based estimates provide the most reliable estimates of the indigenous N supply in intensive rice systems (Section 2.4). In irrigated lowland rice systems, most of the commonly used soil tests cannot be relied upon to predict soil N supply under field conditions, and therefore reliable, general critical levels or ranges cannot be given. Soil organic C or total soil N content are not reliable indicators of soil N supply in irrigated rice systems, but are more useful in upland rice systems.

Soil N supply can be measured by incubating soil under anaerobic conditions (2 weeks at 30ºC) and the results used to predict soil N supply and thus crop requirements. This method should be used with caution, because it may underestimate the true soil N-supplying capacity, and adequate field calibration is not yet available. It is also not practical as a part of routine soil analysis.

## Causes of N deficiency

N deficiency can be caused by one or more of the following:

- Low soil N-supplying power.
- Insufficient application of mineral N fertilizer.
- Low N fertilizer use efficiency (losses from volatilization, denitrification, incorrect timing and placement, leaching, and runoff).
- Permanently submerged conditions that reduce indigenous soil N supply (i.e., in triple cropping systems).
- N loss due to heavy rainfall (leaching and seepage).
- Temporary drying out of the soil during the growing period.
- Poor biological $N_2$ fixation because of severe P deficiency.

## Occurrence of N deficiency

N deficiency is common in all rice-growing soils where modern varieties are grown without sufficient mineral N fertilizer. Significant yield responses to N applied in mineral and/or organic forms are obtained in nearly all lowland rice soils where irrigation and other nutrients and pests are not limiting. N deficiency may also occur where a large amount of N fertilizer has been applied but at the wrong time or in the wrong way. Soils particularly prone to N deficiency include the following types:

- Soils with very low soil organic matter content (e.g., <0.5% organic C, coarse-textured acid soils).
- Soils with particular constraints to indigenous N supply (e.g., acid sulfate soils, saline soils, P-deficient soils, poorly drained wetland soils where the amount of N mineralization or biological $N_2$ fixation is small).
- Alkaline and calcareous soils with low soil organic matter status and a high potential for $NH_3$ volatilization losses.

## Effect of submergence on availability and uptake of N

The availability of N is greater in flooded soil than in aerated soil, but various unique features of flooded soils complicate N management. After submergence, the $O_2$ in the soil is rapidly depleted by soil micro-organisms, because the rate of $O_2$ diffusion is about 10,000 times slower in water-filled than in air-filled soil pores. As a result, the soil redox potential, an indicator of soil reduction, rapidly decreases within 3–5 weeks of submergence to a new steady-state level. The rate of decrease is determined by the amount of readily decomposable organic matter and the availability of $O_2$, $NO_3$-N, Mn-oxides and hydroxides, Fe-oxides and hydroxides, and $SO_4^{2-}$, which are used as electron acceptors in microbial decomposition.

Within a few days of flooding, nitrate is reduced and lost as $N_2$ and $N_2O$, while $NH_4^+$ tends to accumulate as a result of N mineralization. Within a few weeks of flooding, four zones develop and contribute to the N supply:

- A floodwater layer of varying depth (1–15 cm) with a living flora consisting of bacteria and algae that contribute to biological $N_2$ fixation (Section 5.1).
- A thin, superficial oxidized layer (0.1–1 cm) that lies immediately beneath the floodwater.
- A thick, reduced soil layer (10–20 cm) that lies between the oxidized surface layer and the plow sole.
- A narrow oxidized rhizosphere layer (0.1–0.5 cm) that lies within the reduced soil. Healthy rice plants maintain oxidized conditions in the rhizosphere by excreting $O_2$ transported from shoots to roots via aerenchyma.

$NH_4^+$ is nitrified to $NO_3^-$ in the thin oxidized surface layer and the rice rhizosphere. Nitrate is highly mobile, however, and may leach or diffuse into the reduced soil layer, where it is quickly lost due to denitrification (as gaseous $N_2$ and $N_2O$) and leaching (in coarse-textured soils). Because of the mineralization of soil organic matter and crop residues, soluble and exchangeable $NH_4^+$ accumulate in the reduced soil layer during the early growth period when crop N demand is small. Following diffusion into the *aerobic* surface soil layer, $NH_4$-N may be nitrified, diffuse back into the *reduced* soil layer, and be denitrified and lost. Although $NH_4^+$ is the predominant form of mineral N in flooded soils, rice takes up both $NH_4^+$ and $NO_3^-$ with equal efficiency. Some of the $NH_4^+$ diffusing towards rice roots from the bulk soil is probably oxidized to $NO_3^-$ in the rhizosphere of rice and absorbed by roots in the $NO_3$-N form.

Transformations of N differ according to whether the fertilizer N is incorporated into the soil (basal N) or topdressed into standing water.

If $NH_4$-N fertilizers are incorporated into the reduced soil layer before or after submergence, $NH_4^+$ is adsorbed on soil colloids, temporarily immobilized by soil microbes, or bound abiotically to components of soil organic matter such as phenol compounds. Losses from percolation are usually small, except in very coarse-textured soils.

Topdressed urea is rapidly hydrolyzed (within 2–4 days), and is susceptible to loss by $NH_3$ volatilization due to diurnal changes in the floodwater pH as a result of biological activity. Topdressed N losses are related to floodwater characteristics (e.g., floodwater depth, pH, temperature, and $NH_4^+$ concentration) in addition to wind speed and rice plant growth stage. After the midtillering phase, when a dense root system with many superficial roots has formed, plant uptake rates of N broadcast into standing water may be large ($\leq$10 kg ha$^{-1}$ per day) such that losses from $NH_3$ volatilization are small.

Irrigated lowland rice has a very dense, fibrous root system with >90% of roots present within the upper 20 cm of soil. Rice roots acquire N efficiently from the reduced layer and from topdressed N applied during later growth stages. Fertilizer applied into the reduced layer, however, is present in the soil longer than topdressed N. The root system of rainfed lowland and upland rice ramifies through the soil to a greater depth than that of irrigated rice.

## Crop N uptake and removal

Internal N use efficiency in rice is affected by the N supply and overall plant nutrient status. In a situation with balanced nutrition and *optimum* growth conditions, the optimal internal efficiency in modern rice varieties is 68 kg grain kg$^{-1}$ plant N uptake, equivalent to the removal of 14.7 kg N t$^{-1}$ at yield levels of 70–80% of maximum yield (Section 2.5).

In irrigated rice farms in Asia, the *observed* average N removal is ~17.5 kg N t$^{-1}$ grain yield (Table 7). Therefore, a rice crop yielding 6 t ha$^{-1}$ takes up ~105 kg N ha$^{-1}$, of which 40% remains in the straw at maturity. If the grain *only* is removed and the straw is returned to

*Table 7. N uptake and N content of modern rice varieties.*

| Plant part | Typical observed range [a] | Observed average [b] |
|---|---|---|
| | kg N uptake $t^{-1}$ grain yield | |
| Grain + straw | 15–20 | 17.5 |
| Grain | 9–12 | 10.5 |
| Straw | 6–8 | 7.0 |
| | % N content | |
| Grain | 0.93–1.20 | 1.06 |
| Straw | 0.51–0.76 | 0.63 |
| Unfilled spikelets | 0.76–1.02 | 0.89 |

[a] *25–75% interquartile range of farmers' fields and field experiments in Asia (+N treatments, n = 1,300).*

[b] *Median of farmers' fields and field experiments in Asia (+N treatments, n = 1,300).*

the field, N removal is ~10.5 kg N $t^{-1}$ grain yield. Almost all the N contained in the straw is lost upon burning.

These data may not represent optimal internal N use efficiency and it may be possible to further improve internal N use efficiency by adding sufficient amounts of P and K where these nutrients are deficient (Section 2.5).

## General N management

Treatment of N deficiency is easy and response to N fertilizer is rapid. Apply N fertilizer and follow the guidelines given below. The response may already be evident after 2–3 days (greening, improved vegetative growth) but this depends on the rice variety, soil type, weather conditions, N fertilizer used, amount applied, and time and method of application.

Dynamic soil-based and plant-based management is required to optimize N use efficiency for each season. The adjustment of the quantity of N applied in relation to variation in indigenous N supply is as important as the timing, placement, and source of applied N. Nitrogen management must focus on improving the fit between N supply and demand within a cropping season. In contrast to P and K fertilizers, the residual effect of N fertilizer is small, but long-term management of indigenous N sources must also be considered.

General measures to improve N use efficiency are as follows:

- Varieties: Do not apply large amounts of N to less responsive varieties, e.g., traditional (tall) varieties with low harvest index, grown in rainfed lowland and upland environments. Conventional modern rice varieties do not differ much in their potential nutrient recovery efficiency and internal nutrient use efficiency. Hybrid rice absorbs mineral N (particularly $NO_3^-$ during later growth stages) more efficiently than inbred rice varieties such that a late N application supplied in nitrate form may lead to a significant yield increase.
- Crop establishment: Choose a suitable plant spacing for each cultivar. Crops with suboptimal plant densities do not use fertilizer N efficiently. Adjust the number of splits and timing of N applications according to the crop establishment method (see below). Transplanted and direct-seeded rice require different N management strategies.
- Water management: Maintain proper water control, i.e., keep the field flooded to prevent denitrification, but avoid N losses due to water runoff over bunds immediately following fertilizer application. Fluctuating moisture conditions cause higher N losses due to

nitrification-denitrification. Fields can be kept moist but without standing water during early vegetative growth (e.g., during emergence and early tillering in direct-seeded rice before N has been applied). Rice, however, requires flooded conditions for optimum growth, nutrient uptake, and yield, particularly during reproductive growth.

- Crop management: Optimal response to N fertilizer depends on proper overall crop management. Establish a dense, healthy rice crop stand by using high-quality seed of a high-yielding variety, with multiple pest resistance and a suitable plant density. Control weeds that compete with rice for N. Control insects and diseases (damage reduces canopy efficiency and thus rice productivity). At the end of the rice season, losses of residual soil $NO_3$-N can be reduced if a dry-season crop is planted to recover residual N or if weeds are allowed to develop and then are incorporated into the soil in the subsequent cropping cycle.
- Soil management: Correct deficiencies of other nutrients (P, K, Zn) and correct for other soil problems (e.g., shallow rooting depth, toxicities). Response to applied N will be small on acid, low-fertility rainfed lowland and upland soils unless all existing soil fertility problems (acidity, Al toxicity, deficiencies of P, Mg, K, and other nutrients) have been corrected. Apply soil improvement materials to increase CEC (capacity to adsorb $NH_4^+$) on low-CEC soils. If cost-effective sources are available, zeolite (CEC 200–300 $cmol_c\ kg^{-1}$) or vermiculite (CEC 100–200 $cmol_c\ kg^{-1}$) can be used to increase N use efficiency on low-CEC soils (acid Ultisols, Oxisols, degraded paddy soils). These materials can be applied directly to the soil or mixed with N fertilizer (e.g., 20% of the total N application rate can be replaced with zeolite).
- Organic matter management: Over the long term, maintain or increase the supply of N from indigenous sources through proper organic matter management:
  - Apply available organic materials (farmyard manure, crop residues, compost) on soils containing a small amount of organic matter, particularly in rainfed lowland rice and intensive irrigated rice systems where rice is rotated with other upland crops such as wheat or maize.
  - In irrigated rice-rice systems, carry out dry, shallow tillage (5–10 cm) within 2 weeks of harvest. Early tillage enhances soil oxidation and crop residue decomposition during the fallow period and increases N availability up to the vegetative growth phase of the succeeding rice crop.
  - Increase the indigenous N-supplying power of permanently submerged soils by periodic drainage and drying. Examples are a midseason drainage of 5–7 days at the late tillering stage (~35 DAT) or occasional thorough aeration of the soil by substituting an upland crop for one rice crop, or omitting one rice crop.
- Fertilizer management: Application of N fertilizer is standard practice in most rice systems. To achieve yields of 5–7 t $ha^{-1}$, fertilizer N rates typically range from 80 to 150 kg $ha^{-1}$. Factors affecting the amount and timing of N applications in rice include:
  - variety grown,
  - crop establishment method,
  - soil N-supplying capacity (indigenous N supply), including residual effects of preceding crops or fallow periods,
  - water management,
  - type of N fertilizer used,
  - method of application, and
  - soil physical and chemical properties affecting fertilizer N transformations.

Excessive N or unbalanced fertilizer application (large amounts of N in combination with small amounts of P, K, or other nutrients) may reduce yield because of one or more of the following:

- Mutual leaf shading caused by excessive vegetative growth. Increased number of unproductive tillers that shade productive tillers and reduce grain production.
- Lodging caused by the production of long, weak stems.
- Increased number of unfilled grains.
- Reduced milling recovery and poor grain quality.
- Increased incidence of diseases such as bacterial leaf blight (caused by *Xanthomonas oryzae*), sheath blight (caused by *Rhizoctonia solani*), sheath rot (caused by *Sarocladium oryzae*), stem rot (caused by *Helminthosporium sigmoideum*), and blast (caused by *Pyricularia oryzae*), because of greater leaf growth and an excessively dense crop stand.
- Increased incidence of insect pests, particularly leaf folders (e.g., *Cnaphalocrocis medinalis*).

Some general recommendations can be made for N fertilizer use in rice:

- Apply about 15–20 kg N $t^{-1}$ grain yield target. The N fertilizer requirement is smaller in rainy-season crops (less sunshine, smaller potential yield) and larger in dry-season crops (more sunshine, greater potential yield) where larger N application rates result in more tillers and leaf area, and ultimately a larger grain yield.
- Divide N fertilizer recommendations larger than 60 kg N $ha^{-1}$ into 2–3 (wet-season crop) or 3–4 (dry-season crop) split applications. Use more splits, especially with long-duration varieties and in the dry season when crop yield potential is greater.
- Identify the need for a basal N application depending on soil N release dynamics, variety, and crop establishment method. Apply more basal N in these situations:
  - Soils with low INS (<40 kg N $ha^{-1}$).
  - Where the plant spacing is wide (<20 hills $m^{-2}$) to enhance tillering.
  - In areas with low air and water temperature at transplanting or sowing (e.g., irrigated rice fields at high altitudes).

  Soils with high INS (>50 kg N $ha^{-1}$) often do not require basal N incorporated into the soil. Hybrid rice always requires basal N. Avoid large basal N fertilizer applications (i.e., >50 kg N $ha^{-1}$) in TPR where growth is slow during the first 3 weeks after transplanting. Incorporate basal N into the soil before planting or sowing. Use $NH_4$-N and not $NO_3$-N as a basal N source.
- Monitor plant N status to optimize timing and amount of split applications in relation to crop demand and soil N supply. Use a chlorophyll meter (SPAD) or leaf color chart (LCC) to guide N management (Section 5.6). N fertilizer should be applied when the crop has the greatest need for N and when the rate of uptake is large. The highest recovery efficiency of applied N is achieved during late tillering to heading. Use $NH_4$ fertilizers as an N source for topdressed N applications.
- Apply a late N application (at flowering) to delay leaf senescence and enhance grain filling, but only to healthy crops with good yield potential. Source-limited varieties and hybrid rice usually require an application of N at flowering. To reduce the risk of lodging and pests, do not apply excessive amounts of N fertilizer between panicle initiation and flowering, particularly in the wet season.
- In planted fields, lower or remove the floodwater before applying topdressed N and then re-irrigate to enhance movement of N into the soil. Do not apply topdressed N when heavy rainfall is expected. Do not apply urea onto standing water under windy conditions

before canopy closure or at midday when the water temperature is highest.

- Use other means to increase N use efficiency if they are economically viable. Examples include:
  - N fertilizer placement in the reduced soil layer about 8–10 cm below the soil surface (deep placement of urea supergranules, tablets, briquettes, mudballs), and
  - slow-release N fertilizer (S-coated urea) or urea supergranules incorporated as a basal dressing before planting.

## *Site-specific N management in irrigated rice*

Key steps for calculating site-specific N fertilizer recommendations are as follows:

1 Estimate crop N demand for a target grain yield.

2 Estimate potential indigenous N supply.

3 Estimate recovery efficiency of applied N fertilizer.

4 Calculate N fertilizer rate as a function of Steps 1–3.

5 Decide about splitting and timing of N applications and N fertilizer source.

6 Estimate N fertilizer rate using multiple recovery efficiencies.

Refer to Boxes 1–3 at the end of this section for step-by-step instructions and worked examples.

## *NOTES:*

- Grain yield refers to filled grains adjusted to 14% moisture content.
- The approach to site-specific N management in irrigated rice described above assumes balanced fertilizer use, proper crop management, and that there are no other agronomic constraints to grain yield (i.e., modern rice variety with a harvest index of ~0.5, good-quality seed used, proper crop establishment, no water stress, little or no pest damage).

  Varieties grown in rainfed lowland and upland ecosystems often have a lower harvest index (0.3–0.4) and may suffer from water stress, which decreases internal N use efficiency and increases the N demand for a given yield level. Under suboptimal conditions, the internal efficiency of N use will be reduced, i.e., the response curve shifts downward and less grain yield is produced for a given amount of N uptake.
- By definition, INS is the *potential* supply of N from indigenous sources. It can only be measured accurately in a season with favorable climate and good crop management, assuming that no other factors limit growth. In a tropical climate, the dry-season crop is the best crop for measuring INS. As many factors affect soil N mineralization and grain yield formation, estimates of INS obtained from grain yield measured in 0 N plots may vary significantly among seasons. N uptake measured in 0 N plots is less variable than grain yield and is the preferred index of INS. Grain yield in 0 N plots tends to be smaller in broadcast wet-seeded rice than in transplanted rice grown on the same soil.
- Measuring grain yield in a small plot with no fertilizer application (-F plot) instead of in a proper N omission plot (with P, K, and other nutrients applied) is often an equally good index of INS in irrigated lowland rice, because N is usually the major factor limiting growth. On average, grain yields in -F plots are only ~0.3 t ha$^{-1}$ smaller than in a proper N omission plot and the difference in N uptake is negligible.
- If crop growth during the season is severely reduced by non-nutritional factors so that the yield target is unlikely to be achieved, reduce the amount of N applied based on observed crop status.

*Table 8. N fertilizer sources for rice.*

| Name | Formula | Content | Comments |
|---|---|---|---|
| Ammonium nitrate | $NH_4NO_3$ | 33–34% N | Acidifying, apply to upland rice only |
| Ammonium chloride | $NH_4Cl$ | 28% N | Acidifying |
| Ammonium sulfate | $(NH_4)_2SO_4$ | 21% N, 24% S | Acidifying |
| Ammonium bicarbonate | $NH_4HCO_3$ | 17% N | Non-acidifying, low-quality N |
| Urea | $CO(NH_2)_2$ | 46% N | Acidifying |
| Monoammonium phosphate (MAP) | $NH_4H_2PO_4$ | 11% N, 22% P | Soluble, quick-acting, acidifying |
| Diammonium phosphate (DAP) | $(NH_4)_2HPO_4$ | 18–21% N, 20% P | Soluble, quick-acting, acidifying |
| Urea phosphate | $CO(NH_2)_2 + H_3PO_4$ | 18% N, 20% P | Soluble, quick-acting |

- If crop growth during the season is better than expected and the yield target is likely to be surpassed, increase the amount of N applied based on observed crop status.
- Residual effects of fertilizer N in rice are small. Over periods of 3–5 years INS is unlikely to change significantly. Therefore, a reliable estimate of INS obtained once can be used for several years provided that no significant change in the cropping system and crop management practices occurs. It is advisable to reestimate INS periodically (e.g., after 4–5 years) using 0 N plots.

## *N fertilizer sources*

Liquid fertilizers such as urea ammonium nitrate solution (UAN, 28% N) are used in some mechanized rice-growing areas. Averaged over the whole growth period, the recovery efficiency of N from UAN is smaller (~50%) than for granular urea (~70%). Provided a dense superficial root system has formed, however, rice can make efficient use of $NO_3$-N applied at the panicle initiation stage or later.

Ammonia volatilization from different N fertilizer sources (Table 8) increases in the order ammonium sulfate < urea < ammonium bicarbonate.

Various special fertilizer products have become an important part of N management strategies in rice, particularly in rainfed and irrigated lowland systems. At present, however, their use is restricted by cost or the additional labor required to place these materials in the reduced soil layer. So far, controlled-release fertilizer use has only increased in Japan. Examples include:

- urea supergranules, briquettes, tablets,
- urea-formaldehyde (UF, 38% N),
- S-coated urea (SCU, 30–40% N, 6–30% S),
- polymer-coated urea (40–44% N, e.g., Osmocote, Nutricote, Polyon), and
- neem-coated urea (locally produced in India but not used widely).

SCU costs twice as much as conventional urea, whereas UF or polymer-coated materials usually cost 3–5 times as much. Their use is not economical for rice farmers in South and Southeast Asia at current prices, although these materials may result in reduced N requirement and yield increases of ~10%. This may change, however, when new technologies allow less costly production of coated materials. Nitrification and urease inhibitors have been investigated thoroughly, but increases in N efficiency achieved are usually too small to justify their use in rice farming.

*Box 1. Key steps for calculating site-specific N fertilizer recommendations.*

## Step 1. Estimate crop N demand (UN)

Define maximum yield ($Y_{max}$) based on site-specific climatic conditions.

Use Figure 7 to estimate the amount of N required to achieve the defined target grain yield for the selected maximum yield ($Y_{max}$) (Section 2.5).

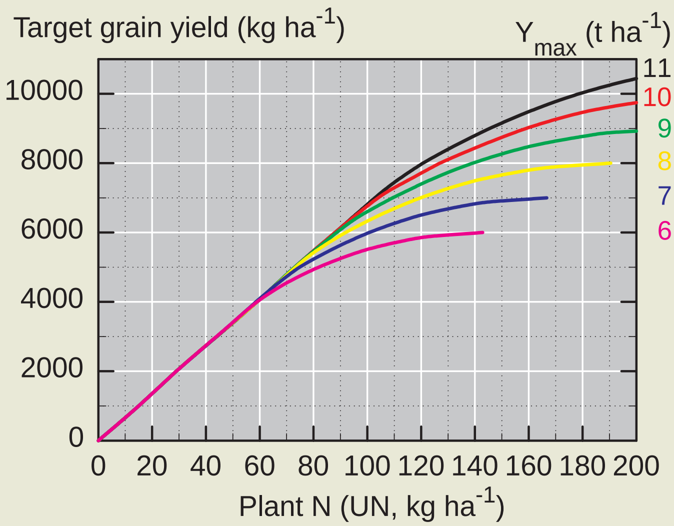



*Figure 7. Relationship between maximum yield ($Y_{max}$), target grain yield, and total N uptake (UN).*

## Step 2. Estimate potential indigenous N supply (INS)

If grain yield (t ha$^{-1}$) in an N omission plot was measured, estimate INS (Section 2.4):

*if GY(NPK) ≤ GY(0 N), then INS (kg N ha$^{-1}$) = GY(0 N) x 15;*

*if GY(NPK) > GY(0 N), then INS (kg N ha$^{-1}$) = GY(0 N) x 13.*

Otherwise, if grain yield was measured in an NPK plot only and a good estimate of $RE_N$ is available, use Equation N1:

$$INS\ (kg\ N\ ha^{-1}) \approx (GY \times 17) - (RE_N \times FN) \qquad (N1)$$

where GY is the grain yield in t ha$^{-1}$ (14% moisture content); $RE_N$ is the apparent recovery efficiency of applied N (~0.3–0.5 kg N kg$^{-1}$ N applied, see below); and FN is the amount of fertilizer N added (kg ha$^{-1}$).

The INS in most irrigated lowland rice soils ranges from 15 to >100 kg N ha$^{-1}$ crop$^{-1}$ and is most commonly around 40–70 kg N ha$^{-1}$ (average INS is 60 kg N ha$^{-1}$). Grain yields with no N applied are therefore mostly in the range of 3–5 t ha$^{-1}$, except on poorer soils and in rainfed or upland rice (<3 t ha$^{-1}$).

## Step 3. Estimate recovery efficiency of applied N fertilizer ($RE_N$)

$RE_N$ can be estimated for a particular cropping system and N application method by conducting an experiment with different N fertilizer rates where crop growth is not constrained by the supply of other nutrients (Section 5.5). $RE_N$ can then be calculated by difference using Equation N2:

*Box 1. (...continued).*

$$RE_N \text{ (kg kg}^{-1}) = (UN_2 - UN_1)/(FN_2 - FN_1) \qquad \text{(N2)}$$

where $RE_N$ is the recovery efficiency of N (kg of N taken up per kg of N applied); UN is the total N uptake with grain and straw (kg ha$^{-1}$); and FN is the amount of fertilizer N added (kg ha$^{-1}$) in two different N treatments (i.e., Treatment 2 receives a larger N rate than Treatment 1).

Ideally, a zero N plot is used as the reference (Treatment 1).

A reasonable estimate of $RE_N$ for tropical and subtropical lowland rice soils is 0.3–0.5 kg kg$^{-1}$, with greater efficiencies (≥0.4) expected when N is applied in 2–4 split applications and general crop growth is good and not limited by other factors. Efficiency is poor (<0.3) where large amounts of N are incorporated basally in soils with low CEC or high pH or applied during very early growth, or when other factors (climate, pests, nutrients, water) limit N uptake efficiency. With good crop management using plant-based N management strategies that use tools such as a chlorophyll meter or leaf color chart (Section 5.6), recovery efficiencies of 0.5–0.7 kg kg$^{-1}$ can be achieved in farmers' fields.

- If information on the average $RE_N$ for a specific crop management and N fertilization schedule is available from previous experiments (Equation N2), proceed directly to Steps 4 and 5. Step 6 is irrelevant in this case.
- If this information is not available, proceed directly to Steps 5 and 6.

## Step 4. Calculate N fertilizer rate (FN) using one recovery efficiency

Using the information obtained from Steps 1–3, we can now calculate the amount of fertilizer N required (FN) to achieve our yield target:

$$FN \text{ (kg N ha}^{-1}) = (UN - INS)/RE_N \qquad \text{(N3)}$$

where UN is the total N uptake with grain and straw (kg ha$^{-1}$); INS is the potential indigenous N supply (kg N ha$^{-1}$); and $RE_N$ is the recovery efficiency of N taken up (kg per kg of N applied).

## Step 5. Splitting and timing of N applications

A range of N application regimes are practiced. The major factors determining the choice of N application splits and timing are as follows:

- Cropping season (climate).
- Cropping system (rice monoculture, rice-upland crop system, rice-legumes).
- Variety (conventional modern variety, hybrid, high grain quality variety).
- Crop establishment method (transplanting, wet seeding, dry seeding).
- Water management (continuous flooding, intermittent irrigation).
- Soil properties (time curve of soil N release, supply of other nutrients, CEC, pH).
- Pest management (disease and insect control, rat damage).
- Socioeconomic factors (labor availability and cost, prices of rice and fertilizer, available fertilizer sources and application technology).

*Box 1. (...continued).*

The guidelines given below cover situations that are common in irrigated rice systems where N application rates are large. Approximate ranges for application dates (days after transplanting/DAT or sowing/DAS) are given, but the actual date depends on the variety (crop duration) and plant N status in the field. If possible, use tools such as a leaf color chart (Section 5.6) to arrive at the best application date and fit between N supply and crop N demand. This is because the conditions for N uptake depend largely on canopy development as affected by the factors listed earlier.

**Definitions**

TP – basal, incorporated before planting; topdressed applications. ET – early tillering, MT – midtillering, LT – late tillering, PI – panicle initiation, H – heading, FF – first flowering, CE – crop emergence. Actual days after transplanting (DAT) may vary depending on the growth duration of a variety. Actual days after sowing (DAS) may vary depending on the growth duration of a variety and the water management practice.

**1. Transplanted rice (inbred variety)**

Transplanted, 20–40 hills $m^{-2}$, high-yielding conventional variety, continuous flooding.

Transplanted rice has slower leaf area development, dry matter accumulation, and N uptake during early growth, but high growth rates and N uptake after midtillering to grain filling.

- Dry season: high potential yield ($Y_{max}$ ~10 t $ha^{-1}$), yield target 7–8 t $ha^{-1}$
  - FN 100–150 kg N $ha^{-1}$
    - 25% at ET (14–20 DAT, 25–35 kg N $ha^{-1}$)
    - 30% at MT–LT (30–35 DAT, 30–45 kg N $ha^{-1}$)
    - 45% at PI (40–50 DAT, 45–70 kg N $ha^{-1}$)
  - If INS <45 kg N $ha^{-1}$ and GY (0 N) <3 t $ha^{-1}$, apply an additional amount of 20 kg N $ha^{-1}$ as a basal application before TP.
  - If at H–FF (55–65 DAT) crop stand is dense, plants are N-deficient, weather conditions are very favorable, and no lodging or pests are expected, apply an additional amount of 15–20 kg N $ha^{-1}$.
- Wet season: low potential yield ($Y_{max}$ ~7 t $ha^{-1}$), yield target 5–6 t $ha^{-1}$
  - FN 80–100 kg N $ha^{-1}$
    - 25% at ET (14–20 DAT, 20–25 kg N $ha^{-1}$)
    - 30% at MT–LT (30–35 DAT, 25–30 kg N $ha^{-1}$)
    - 45% at PI (40–50 DAT, 35–45 kg N $ha^{-1}$)

**2. Transplanted rice (hybrid)**

Transplanted, 20–30 hills $m^{-2}$, hybrid rice, continuous flooding or intermittent irrigation, favorable climatic season with high potential yield, e.g., dry season.

Transplanted hybrid rice requires more N during early crop growth to enhance tillering, but also responds well to late N application because it is a source-limited panicle-weight-type crop.

- Dry season: high potential yield ($Y_{max}$ ~10 t $ha^{-1}$), yield target 7.5–8.5 t $ha^{-1}$
  - FN 120–160 kg N $ha^{-1}$

*Box 1. (...continued).*

- 35% before TP (40–55 kg N $ha^{-1}$)
- 20% at MT (15–20 DAT, 25–30 kg N $ha^{-1}$)
- 30% at LT–PI (35–45 DAT, 35–50 kg N $ha^{-1}$)
- 15% at H–FF (50–60 DAT, 20–25 kg N $ha^{-1}$)

### 3. Wet-seeded rice

100–150 kg seed $ha^{-1}$, broadcast, high-yielding conventional variety, continuous flooding after crop emergence.

Broadcast wet-seeded rice has more rapid leaf area development, dry matter accumulation, and N uptake during early growth, but slower growth rates and N uptake after panicle initiation, particularly during grain filling. Direct-seeded rice needs little late applied N because it is a panicle-number-type crop and source is not limiting.

- Dry season: high potential yield ($Y_{max}$ ~10 t $ha^{-1}$), yield target 7–8 t $ha^{-1}$
  - FN 100–150 kg N $ha^{-1}$
    - 20% at CE–ET (10–20 DAS, 20–30 kg N $ha^{-1}$)
    - 35% at MT (25–35 DAS, 35–55 kg N $ha^{-1}$)
    - 45% at PI (40–50 DAS, 45–70 kg N $ha^{-1}$)
  - If at H–FF (55–65 DAT) plants are very N-deficient, apply an additional amount of 15 kg N $ha^{-1}$.
- Wet season: low potential yield ($Y_{max}$ ~7 t $ha^{-1}$), yield target 5–6 t $ha^{-1}$
  - FN 80–100 kg N $ha^{-1}$
    - 20% at CE–ET (10–20 DAS, 15–20 kg N $ha^{-1}$)
    - 35% at MT (25–35 DAS, 30–35 kg N $ha^{-1}$)
    - 45% at PI (40–50 DAS, 35–45 kg N $ha^{-1}$)

### 4. Dry-seeded rice, temperate climate

100–150 kg seed $ha^{-1}$, broadcast or drilled in rows, high-yielding conventional variety, continuous flooding after crop emergence (4–6 weeks after sowing, delayed-flood control system).

A large amount of pre-flood N is required for increasing N uptake and dry matter production as well as improving the use efficiency of topdressed N applied at PI, e.g., in Australia and USA (California, Arkansas, Lousiana).

- Favorable climate, long growth duration, high potential yield ($Y_{max}$ ~10–15 t $ha^{-1}$)
  - FN 120–200 kg N $ha^{-1}$
    - Single split: 100% as a basal pre-flood application (i.e., at 4–5-leaf stage onto dry soil immediately prior to flooding). Apply additional N at PI stage depending on plant N status, or
    - Two-split: 50–80% as a basal pre-flood application (i.e., at 4–5-leaf stage onto dry soil immediately prior to flooding) and 20–50% at PI to panicle differentiation stage (PI + 10 days), or

*Box 1. (...continued).*

- Three-split: 50–60% as a basal pre-flood application (i.e., at 4–5-leaf stage onto dry soil immediately prior to flooding), 20–25% at MT, and 20–25% at PI to panicle differentiation stage (PI + 10 days).

## Step 6. Estimate N fertilizer rate (FN) using multiple recovery efficiencies

Where information on the recovery efficiency of fertilizer N ($RE_N$) is *not* available (Step 3), Figure 8 can be used to obtain an estimate of the $RE_N$ for each fertilizer N application when the number of splits has been decided (Step 5).

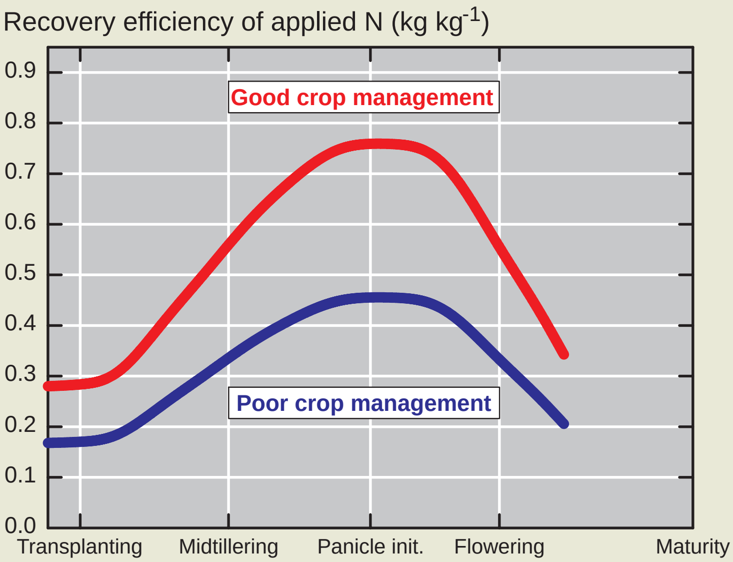



*Figure 8. Approximate recovery efficiency of topdressed N fertilizer for rice at different growth stages.*

*The red curve is for a healthy, dense crop yield stand with no other factors limiting N uptake. The blue curve shows a lower recovery efficiency where crop growth is poor due to unfavorable climate or poor crop management (including unbalanced nutrition, water stress, or pest damage).*

Using the crop nutrient demand (UN, kg ha$^{-1}$) and the indigenous N supply (INS, kg ha$^{-1}$) as estimated in Steps 1 and 2, calculate the net amount of N that has to be supplied by fertilizer (FNnet) to meet the crop nutrient demand for the specified yield target:

$$FNnet\ (kg\ ha^{-1}) = UN\ (kg\ ha^{-1}) - INS\ (kg\ ha^{-1}) \qquad (N4)$$

where UN is the total N uptake with grain and straw (kg ha$^{-1}$) and INS is the potential indigenous N supply (kg N ha$^{-1}$).

1 Estimate the net amount of N that has to be supplied for each split application:

$$FNnet_1 = FNnet \times FNsplit_1/100 \qquad (N5)$$

$$FNnet_2 = FNnet \times FNsplit_2/100 \qquad (N6)$$

$$\ldots$$

$$FNnet_n = FNnet \times FNsplit_n/100 \qquad (N7)$$

where $FNnet_1$, $FNnet_2$, …, $FNnet_n$ are the net amounts of fertilizer N applied in n split applications of N (kg ha$^{-1}$); and $FNsplit_1$, $FNsplit_2$, …, $FNsplit_n$ are the fertilizer N splits in % of total amount of N to be applied (from Step 5).

*Box 1. (...continued, last).*

2 Use Figure 8 to estimate the recovery efficiencies of fertilizer N depending on the growth stage at which the split applications are to be applied. Then calculate the amount of fertilizer N that needs to be applied with each split to achieve the required net fertilizer N supply:

$$FN_1 = FNnet_1/RE_{N1} \qquad (N8)$$

$$FN_2 = FNnet_2/RE_{N2} \qquad (N9)$$

$$FN_n = FNnet_n/RE_{Nn} \qquad (N10)$$

where $FN_1$, $FN_2$, …, $FN_n$ are the amounts of fertilizer N (kg $ha^{-1}$) to be applied in n split applications; and $RE_{N1}$, $RE_{N2}$, …, $RE_{Nn}$ are the recovery efficiencies in kg $kg^{-1}$ as estimated using Figure 8.

3 Calculate the total amount of fertilizer N (FN, kg $ha^{-1}$) to be applied:

$$FN = FN_1 + FN_2 + \ldots + FN_n \qquad (N11)$$

The overall average recovery efficiency of applied fertilizer N can be estimated using:

$$RE_N\ (kg\ kg^{-1}) = (FN_1\ x\ RE_{N1} + FN_2\ x\ RE_{N2} + \ \ldots + FN_n\ x\ RE_{Nn})/FN \qquad (N12)$$

where $FN_1$, $FN_2$, …, $FN_n$ are the actual amounts of fertilizer N (kg $ha^{-1}$) applied in n split applications; and $RE_{N1}$, $RE_{N2}$, …, $RE_{Nn}$ are the recovery efficiencies of the different split applications.

*Box 2. Example 1 – Calculating site-specific N fertilizer recommendations using one average recovery efficiency for applied N.*

*Assumptions:* Fertile irrigated lowland soil in tropical Asia with a grain yield of 3.5 t $ha^{-1}$ when no fertilizer is applied. Variety IR72 is used and transplanting is practiced.

## Step 1. Estimate crop N demand (UN)

- Dry season: target grain yield 7 t $ha^{-1}$ (maximum yield ($Y_{max}$) for this season: 10 t $ha^{-1}$):

  *UN ≈ 105 kg N $ha^{-1}$* *(from Figure 7)*

- Wet season: target grain yield 5 t $ha^{-1}$ (maximum yield ($Y_{max}$) for this season: 7 t $ha^{-1}$):

  *UN ≈ 78 kg N $ha^{-1}$* *(from Figure 7)*

## Step 2. Estimate potential indigenous N supply (INS)

In a previous favorable dry-season crop, grain yield in a small, 0 N plot was 3.5 t $ha^{-1}$, and smaller than the yield in a neighboring NPK plot:

*INS ≈ 3.5 x 13 = 46 kg N $ha^{-1}$* *(from Figure 4)*

## Step 3. Estimate recovery efficiency of applied N fertilizer ($RE_N$)

The soil has a medium-heavy texture (clay loam) with good $NH_4^+$ adsorption. P and K management could be improved through a site-specific fertilizer management approach (Sections 3.2 and 3.3). A leaf color chart (Section 5.6) is used to optimize the timing of split N applications. High recovery efficiency of applied N is achieved in experiments where these measures have been adopted:

*$RE_N$ ≈ 0.50 kg $kg^{-1}$ applied in the dry season* *(from Equation N1)*

*$RE_N$ ≈ 0.45 kg $kg^{-1}$ applied in the wet season* *(from Equation N2)*

## Step 4. Calculate N fertilizer rate (FN)

- Dry season: target grain yield 7 t $ha^{-1}$

  *FN = (105 – 46)/0.50 = 118 kg N $ha^{-1}$* *(from Equation N3)*

- Wet season: target grain yield 5 t $ha^{-1}$

  *FN = (78 – 46)/0.45 = 71 kg N $ha^{-1}$* *(from Equation N3)*

## Step 5. Splitting and timing of N applications

| | Dry season | Wet season |
|---|---|---|
| Basal, incorporated | 23 kg N $ha^{-1}$ (20%) | – |
| Midtillering, 20 DAT | 30 kg N $ha^{-1}$ (25%) | 28 kg N $ha^{-1}$ (40%) |
| Panicle initiation, 40 DAT | 47 kg N $ha^{-1}$ (40%) | 43 kg N $ha^{-1}$ (60%) |
| First flowering, 65 DAT | 18 kg N $ha^{-1}$ (15%) | – |

Actual application rates (±10–20% of predicted FN) and dates may vary, depending on plant N status at different growth stages.

*Box 3. Example 2 – Calculating site-specific N fertilizer recommendations using more than one recovery efficiency for applied N.*

*Assumptions:* We use the same conditions as in Example 1 for a dry-season crop. Steps 1 and 2 are the same as in Example 1. An average $RE_N$, however, is not known beforehand so we proceed to Step 5.

## Step 5. Splitting and timing of N applications

Based on crop management characteristics (transplanted rice, conventional high-yielding variety), we choose the following N application schedules (from Box 1):

- Dry season: no basal because INS >40 kg N $ha^{-1}$
    - $FNsplit_1$ = 30% at midtillering (MT)
    - $FNsplit_2$ = 50% at panicle initiation (PI)
    - $FNsplit_3$ = 20% at first flowering (FF)

1 Estimate N fertilizer rate (FN) using multiple recovery efficiencies.

| | |
|---|---|
| $FNnet = 105 - 46 = 59$ kg N $ha^{-1}$ | (from Equation N4) |
| $FNnet_1 = 59 \times 30/100 = 17.7$ kg N $ha^{-1}$ | (from Equation N5) |
| $FNnet_2 = 59 \times 50/100 = 29.5$ kg N $ha^{-1}$ | (from Equation N6) |
| $FNnet_3 = 59 \times 20/100 = 11.8$ kg N $ha^{-1}$ | (from Equation N7) |

2 Using Figure 8, we estimate recovery efficiencies of about 0.45, 0.65, and 0.58 kg $kg^{-1}$ (slightly below the achievable $RE_N$) for the three N applications, so that:

| | |
|---|---|
| $FN_1 = 17.7/0.45 = 39$ kg N $ha^{-1}$ at MT | (from Equation N8) |
| $FN_2 = 29.5/0.65 = 45$ kg N $ha^{-1}$ at PI | (from Equation N9) |
| $FN_3 = 11.8/0.58 = 20$ kg N $ha^{-1}$ at FF | (from Equation N10) |
| $FN = 39 + 45 + 20 = 104$ kg N $ha^{-1}$ | (from Equation N11) |

3 The overall predicted recovery efficiency of applied fertilizer N is

$$RE_N = (39 \times 0.45 + 45 \times 0.65 + 20 \times 0.58)/104 = 0.56 \text{ (kg kg}^{-1}\text{)}$$ (from Equation N12)

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# 3.2 Phosphorus Deficiency

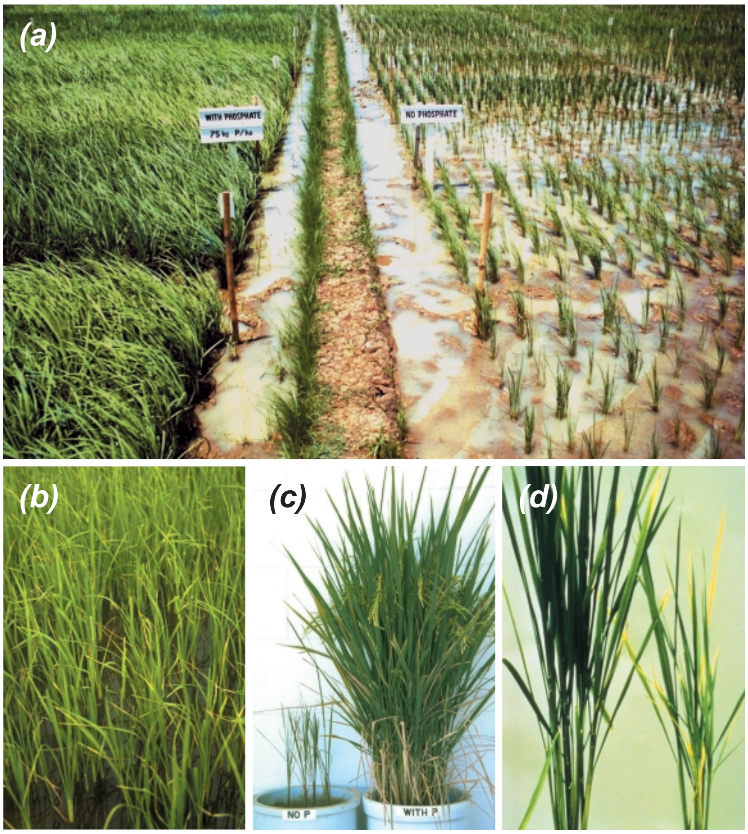
## *Function and mobility of P*

Phosphorus is an essential constituent of adenosine triphosphate (ATP), nucleotides, nucleic acids, and phospholipids. Its major functions are in energy storage and transfer and the maintenance of membrane integrity. P is mobile within the plant and promotes tillering, root development, early flowering, and ripening (especially where the temperature is low). It is particularly important in early growth stages. The addition of mineral P fertilizer is required when the rice plant's root system is not yet fully developed and the native soil P supply is small. P is remobilized within the plant during later growth stages if sufficient P has been absorbed during early growth.

## *P deficiency symptoms and effects on growth*

### Stunted dark green plants with erect leaves and reduced tillering.

P-deficient plants are stunted with greatly reduced tillering. Leaves are narrow, short, very erect, and 'dirty' dark green. Stems are thin and spindly and plant development is retarded. The number of leaves, panicles, and grains per panicle is also reduced. Young leaves appear to be healthy but older leaves turn brown and die. Red and purple colors may develop in leaves if the variety has a tendency to produce anthocyanin. Leaves appear pale green when P and N deficiency (Section 3.1) occur simultaneously. Moderate P deficiency is difficult to recognize in the field. P deficiency is often associated with other nutrient disorders




**_Phosphorus deficiency symptoms in rice_**

*(a) Tillering is reduced where P is deficient. (b) Even under less pronounced P deficiency, stems are thin and spindly, and plant development is retarded. (c), (d) Plants are stunted, small, and erect compared with normal plants.*

*Table 9. Optimal ranges and critical levels of P in plant tissue.*

| Growth stage | Plant part | Optimum (%) | Critical level for deficiency (%) |
|---|---|---|---|
| Tillering to panicle initiation | Y leaf | 0.20–0.40 | <0.10 |
| Flowering | Flag leaf | 0.20–0.30 | <0.18 |
| Maturity | Straw | 0.10–0.15 | <0.06 |



such as Fe toxicity at low pH (Section 4.1), Zn deficiency (Section 3.4), Fe deficiency (Section 3.9), and salinity (Section 4.6) in alkaline soils.

Other effects of P deficiency include:

- Delayed maturity (often by 1 week or more). When P deficiency is severe, plants may not flower at all.
- Large proportion of empty grains. When P deficiency is very severe, grain formation may not occur.
- Low 1,000-grain weight and poor grain quality.
- No response to mineral N fertilizer application.
- Low tolerance for cold water.
- Absence of algae in floodwater.
- Poor growth (small leaves, slow establishment) of green manure crops.

## *Plant*

During vegetative growth (before flowering), P supply is sufficient and a response to P is unlikely when P leaf concentration is 0.2–0.4%. Yields greater than 7 t $ha^{-1}$ require >0.06% P in the straw at harvest and >0.18% P in the flag leaf at flowering.

## *Soil*

Numerous soil P tests are in use and critical levels generally depend on soil type and targeted yield level. Olsen-P (0.5 M $NaHCO_3$ at pH 8.5) and, to a lesser extent, Bray-1 P (0.03 M $NH_4F$ + 0.025 M HCl) are used as a test for P in flooded rice soils. Critical levels for Olsen-P reported for rice range from 5 mg P $kg^{-1}$ in acid soils to >25 mg P $kg^{-1}$ in calcareous soils.

For lowland rice soils with little or no free $CaCO_3$, Olsen-P test results can be classified as follows:

- <5 mg P $kg^{-1}$ (low P status) → response to P fertilizer certain,
- 5–10 mg P $kg^{-1}$ (medium P status) → response to P fertilizer probable, and
- >10 mg P $kg^{-1}$ (high P status) → response to P fertilizer only at very high yield levels (>8 t $ha^{-1}$).

For lowland rice soils with little or no free $CaCO_3$, Bray-1 P test results can be classified as follows:

- <7 mg P $kg^{-1}$ (low P status) → response to P fertilizer certain,
- 7–20 mg P $kg^{-1}$ (medium P status) → response to P fertilizer probable, and
- >20 mg P $kg^{-1}$ (high P status) → response to P fertilizer only at very high yield levels (>8 t $ha^{-1}$).

Other critical soil levels for occurrence of P deficiency are as follows:

- Bray-2 P: <12–20 mg P $kg^{-1}$ acid soils, 0.03 M $NH_4F$ + 0.1 M HCl.
- Mehlich-1 P: <5–7 mg P $kg^{-1}$ upland rice, 0.05 M HCl + 0.0125 M $H_2SO_4$.
- Mehlich-3 P: <28 kg P $ha^{-1}$ lowland rice, Arkansas.

## *NOTES:*

✍ Olsen-P measured on a dried soil sample is a more versatile soil test for irrigated lowland rice soils because it can be used for a wider pH range and it measures the amount of P available through plant-induced P solubilization in the rhizosphere under anaerobic conditions.

- Acid extractions (e.g., Bray-1, Bray-2, Mehlich-1) are more suitable for measuring the amount of available P in acid rainfed lowland and upland soils.
- Various resin-P measurement techniques have been proposed. Generally, they predict P uptake by rice better than static soil tests. They are not yet used routinely, however, except in Brazil.
- In upland soils, immobilization of P occurs by diffusion to adsorption sites within soil aggregates so that conventional soil tests using dried, crushed soil samples may give misleading results.
- The Hedley procedure can be used for sequential fractionation of soil P pools.

## *Causes of P deficiency*

The common causes of P deficiency are as follows:

- Low indigenous soil P-supplying power.
- Insufficient application of mineral P fertilizer.
- Low efficiency of applied P fertilizer use due to high P-fixation capacity or erosion losses (in upland rice fields only).
- P immobilization in Ca phosphates due to excessive liming.
- Excessive use of N fertilizer with insufficient P application.
- Cultivar differences in susceptibility to P deficiency and response to P fertilizer.
- Crop establishment method (P deficiency is more likely in direct-seeded rice where plant density is high and root systems are shallow).

## *Occurrence of P deficiency*

P deficiency is widespread in all major rice ecosystems and is the major growth-limiting factor in acid upland soils where soil P-fixation capacity is often large. Soils particularly prone to P deficiency include the following types:

- Coarse-textured soils containing small amounts of organic matter and small P reserves (e.g., sandy soils in northeast Thailand, Cambodia).
- Highly weathered, clayey, acid upland soils with high P-fixation capacity (e.g., Ultisols and Oxisols in many countries).
- Degraded lowland soils (e.g., North Vietnam).
- Calcareous, saline, and sodic soils.
- Volcanic soils with high P-sorption capacity (e.g., Andisols in Japan and in parts of Sumatra and Java).
- Peat soils (Histosols).
- Acid sulfate soils in which large amounts of active Al and Fe result in the formation of insoluble P compounds at low pH.

## *Effect of submergence on P availability and uptake*

At first, flooding of dry soil causes an increase in the concentration of P in the soil solution because of the release of sorbed and co-precipitated P following the reduction of $Fe^{3+}$ compounds. Flooding also enhances diffusion, the main mechanism of P supply to roots. Processes involved include:

- reduction of $Fe^{3+}$ to more soluble $Fe^{2+}$ phosphates,
- desorption of P held by $Fe^{3+}$ oxides,
- release of occluded P,
- hydrolysis of Fe and Al phosphates,
- increased mineralization of organic P (short-term 'flush' effect), and
- increased solubility of Ca phosphates.

Two to four weeks after submergence, however, the initial flush of available P is followed by a decrease in availability due to the precipitation of $Fe^{2+}$-P compounds and the adsorption of P on clay particles and Al hydroxides. This decrease in P availability is more pronounced in soils containing large amounts of active or free Fe and Al (e.g., Oxisols, Ultisols, Andisols, Sulfaquents). A large proportion of P taken up by rice, however,

*Table 10. P uptake and P content of modern rice varieties.*

| Plant part | Typical observed range [a] | Observed average [b] |
|---|---|---|
| | kg P uptake $t^{-1}$ grain yield | |
| Grain + straw | 2.5–3.5 | 3.0 |
| Grain | 1.7–2.3 | 2.0 |
| Straw | 0.8–1.2 | 1.0 |
| | % P content | |
| Grain | 0.18–0.26 | 0.21 |
| Straw | 0.07–0.12 | 0.10 |
| Unfilled spikelets | 0.13–0.20 | 0.17 |

[a] *25–75% interquartile range of farmers' fields and field experiments in Asia (n = 1,300).*

[b] *Median of farmers' fields and field experiments in Asia (n = 1,300).*

is drawn from this acid-soluble P pool. The rice plant is able to use acid-soluble P under submerged conditions by acidifying the rhizosphere (due to the release of $H^+$ from rice roots to balance excess absorption of cations over anions, and $H^+$ generated by the oxidation of $Fe^{2+}$ by $O_2$ released by roots).

$Mn^{2+}$ and $Fe^{2+}$, formed under reducing conditions during the growing season under flooded conditions, are rapidly oxidized during fallow periods following drainage. Oxidation of $Fe^{2+}$ results in the precipitation of $Fe^{3+}$ hydrous oxides, which adsorb P. Therefore, upland crops grown after rice (e.g., wheat) may be affected by P deficiency, even though the P supply was adequate for the previous rice crop grown under irrigated conditions. Conversely, reflooding a thoroughly dried (oxidized) soil increases P availability to rice during early vegetative growth, due to the rapid liberation of P adsorbed on $Fe^{3+}$ hydrous oxides.

## Crop P uptake and removal

The internal efficiency of P use in rice depends on P supply and general plant nutritional status. With balanced nutrition and *optimum* growth conditions, an internal efficiency of 385 kg grain $kg^{-1}$ plant P uptake can be expected, equivalent to the removal of 2.6 kg P $t^{-1}$ at economic yields (i.e., 70–80% of the maximum yield) (Section 2.5).

In farmers' fields, however, the *measured* average internal efficiency is only ~340 kg grain $kg^{-1}$ P uptake; the *observed* average P removal in irrigated rice systems in Asia is 3 kg P $t^{-1}$ grain yield (Table 10). Therefore, a rice crop yielding 6 t $ha^{-1}$ takes up ~18 kg P $ha^{-1}$ (compared with only 15.6 kg P $ha^{-1}$ under optimum growth conditions), of which >30% remains in the straw at maturity.

If the grain *only* is removed and straw is returned to the field, P removal is ~2 kg P $t^{-1}$ grain. About 20–25% of the P contained in straw is lost on burning.

## General P management

P management should be considered as a *long-term* investment in soil fertility, and it is more effective to prevent P deficiency than to treat P deficiency symptoms (in contrast to N deficiency, for which treatment and prevention are equally important). P requires a *long-term management strategy* because P is not easily lost or added to the root zone by the biological and chemical processes that affect N supply. P fertilizer application provides a residual after-effect that can persist for several years. Management must emphasize the buildup and maintenance of adequate soil-available P levels to ensure that P supply does not limit crop growth and N use efficiency.

General measures to prevent P deficiency and improve P use efficiency are as follows:

- Varieties: Select rice cultivars that use P efficiently, particularly on acid upland soils. P-efficient rice cultivars have either greater P acquisition (increased external efficiency because of better root morphology or increased excretion of organic acids or $O_2$) or higher internal efficiency of P use (larger grain yield when P uptake is small). Examples are IR20, IR26, IR64, and IR74.
- Soil management: In rice-rice systems, carry out dry, shallow tillage (10 cm) <2 weeks after harvest. Early tillage enhances soil oxidation and crop residue decomposition during the fallow period, and increases P availability during vegetative growth of the succeeding rice crop. This practice is not recommended for rice-upland crop systems because early tillage after harvesting the rice crop may *decrease* the availability of P in the succeeding upland crop (e.g., wheat). On acid, low-fertility rainfed lowland and upland soils, all existing soil fertility problems (acidity, Al toxicity, deficiencies of Mg, K, and other nutrients) must be corrected before a response to P is obtained.
- Phosphobacteria application: In field trials with irrigated rice in southern India, an increase in P availability was found after the application of phosphobacteria to the soil, as a seed coating, or as a seedling dip.
- Crop management: Establish a healthy plant population by using high-quality seed of a high-yielding variety with multiple pest resistance planted at the correct density with proper water and pest management.
- Straw management: Incorporate rice straw. Although the total amount of P contained in the straw is small (1 kg P $t^{-1}$ straw), it will contribute to maintaining a positive P balance in the long term.
- Fertilizer management: Apply optimum doses of N and K and correct micronutrient deficiencies. Replenish P removed in crop products by applying P fertilizers, farmyard manure, or other materials (night soil, compost). If P-deficiency symptoms are already evident, there may be no response to P applied to the current crop. Factors affecting P application rates and response to P fertilizer include:
  - type of P fertilizer used,
  - timing and method of application,
  - soil P-supplying capacity (indigenous P supply),
  - soil physical and chemical properties that affect applied P,
  - supply of other nutrients (e.g., N, K),
  - water management, temperature, and availability,
  - variety grown, and
  - cropping system and cropping history.

Application of P fertilizer is standard practice in most irrigated rice systems. To maintain yields of 5–7 t $ha^{-1}$ and replenish P removed with grain and straw, fertilizer P rates should be in the range of 15–30 kg P $ha^{-1}$. It is necessary, however, to correct deficiencies of other nutrients (N, K, Zn), correct other soil problems (shallow rooting depth, toxicities), and ensure proper overall crop management before a response to P fertilizer can be expected.

Some general recommendations can be made for P fertilizer use in rice:

- If most of the straw is retained in the field (e.g., after combine harvest or harvest of panicles only) and the P input from manure is small, apply at least 2 kg P $ha^{-1}$ per ton grain harvested (e.g., 10 kg P for a yield of 5 t $ha^{-1}$) to replenish P removed with harvested grain.
- If most of the straw is removed from the field and P input from other sources (manure, water, sediments) is small, apply at least 3 kg P $ha^{-1}$ per ton grain harvested (e.g., 15 kg P for a yield of 5 t $ha^{-1}$) to replenish P removed with grain.
- Large amounts of P fertilizer are required to recapitalize soil stocks where soil P has been severely depleted because of

long-term P removal (e.g., degraded paddy soils). Large ameliorative applications of 200–500 kg P $ha^{-1}$ are required where acid soils are brought into production in newly developed irrigated rice fields.

- In upland rice systems on strongly P-sorbing soils, large initial P applications or repeated smaller P applications may be required. The adsorption of added P decreases as the quantity of P already adsorbed increases. Therefore, crop response to P increases with repeated small additions of P. In acid upland soils in the humid tropics (Ultisols, Oxisols), when the Mehlich-1 P is <10 mg $kg^{-1}$, about 20 kg P $ha^{-1}$ is required to increase the amount of Mehlich-1 soil P by 1 mg P $kg^{-1}$. When the Mehlich-1 P is >10 mg $kg^{-1}$, only 10–15 kg P $ha^{-1}$ is required to increase Mehlich-1 soil P by 1 mg P $kg^{-1}$. In upland rice systems, P fixation can be avoided by applying P fertilizer in a band beneath the seed. Root proliferation in and close to the band increases with increased soluble-P concentration near the root surface.
- P applied to either rice or wheat has a residual effect on the succeeding crop, but direct application to each crop is more efficient.
- Rock phosphate should be broadcast and incorporated *before* flooding, when soil pH is low, to allow reactions between the soil and fertilizer that release P for plant uptake.

In some soils, excessive application of soluble-P sources may, under conditions of poor aeration, induce Zn deficiency.

## *Site-specific P management in irrigated rice*

Key steps for calculating site-specific P fertilizer recommendations are as follows:

1. Estimate crop P demand for a target grain yield.
2. Estimate potential indigenous P supply.
3. Estimate recovery efficiency of applied P fertilizer.
4. Calculate P fertilizer rate as a function of Steps 1–3.
5. Decide about splitting and timing of P applications.

Refer to Boxes 4 and 5 at the end of this section for step-by-step instructions and a worked example.

### *NOTES:*

- Grain yield refers to filled grains adjusted to 14% moisture content. All calculations are based on elemental P. To convert P to $P_2O_5$, multiply the amount of fertilizer P applied by 2.291.
- The approach to site-specific P management in irrigated rice described above assumes balanced fertilizer use, proper crop management, and that there are no other agronomic constraints on grain yield (i.e., modern rice variety with a harvest index of about 0.5, good seed quality and crop establishment, no water stress, little or no pest damage).

  Varieties grown in rainfed lowland and upland ecosystems often have a smaller harvest index (0.3–0.4) and may suffer from water stress, which results in decreased internal P use efficiency and increases the P requirement to achieve a particular yield.
- By definition, IPS is the *potential* supply of P from indigenous sources and can only be measured accurately in a season with favorable climate and proper crop management on the assumption that no other factors limit growth. In a tropical climate, it is best to measure IPS in a dry-season crop.
- If IPS is very large and P removal with grain and straw at the target yield level is equal to IPS, a maintenance fertilizer-P dose equivalent to IPS is sufficient to sustain current yields.

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*Table 11. P fertilizer sources for rice.*

| Name | Formula | Content | Comments |
|---|---|---|---|
| Single superphosphate | $Ca(H_2PO_4)_2 \cdot H_2O$ + $CaSO_4 \cdot 2\,H_2O$ | 7–9% P, 13–20% Ca, 12% S | Soluble, neutral (16–21% $P_2O_5$) |
| Triple superphosphate | $Ca(H_2PO_4)_2 \cdot H_2O$ | 18–22% P, 9–14% Ca, 1.4% S | Soluble, neutral (41–50% $P_2O_5$) |
| Monoammonium phosphate (MAP) | $NH_4H_2PO_4$ | 22% P, 11% N | Soluble, acidifying (51% $P_2O_5$) |
| Diammonium phosphate (DAP) | $(NH_4)_2HPO_4$ | 20–23% P, 18–21% N (most common 20% P) | Soluble, acidifying (46–53% $P_2O_5$) |
| Urea phosphate (UP) | $CO(NH_2)_2$ + $H_3PO_4$ | 20% P, 18% N | Soluble (46% $P_2O_5$) |
| Partly acidulated rock phosphate | $Ca_3(PO_4)_2$ | 10–11% P | >1/3 water-soluble (23–26% $P_2O_5$) |
| Rock phosphate, finely powdered | $Ca_3(PO_4)_2$ | 11–17% P, 33–36% Ca | Very slow acting (25–39% $P_2O_5$) |

- If IPS is medium to high (>15 kg P $ha^{-1}$) and the actual yield achieved is close to the chosen yield target, the approach described above will result in balanced nutrition and a balanced P budget.
- In soils with low IPS (<12 kg P $ha^{-1}$), the fertilizer recommendation for a high yield target may become unrealistically large. In this situation, it is recommended that IPS be built up over time (several crops with moderate to large amounts of P fertilizer applied) before very large yields can be achieved.
- If the actual amount of fertilizer P applied (estimated from Equation P3 in Box 4) is large but the yield target is not achieved (e.g., crop growth is seriously reduced during the season due to adverse growing conditions), some excess P will remain in the soil (i.e., positive P balance). Conversely, actual yield and P uptake may exceed the target because climate was favorable or a particularly high quality of crop management was achieved (i.e., negative P balance). Therefore, to calculate the P recommendation for the succeeding rice crop, the estimate of IPS should be adjusted upward if the previous crop P balance was positive, or downward if the previous crop P balance was negative. A rough estimate of an adjusted IPS can be obtained using the following equation:

$$IPS^*\ (kg\ P\ ha^{-1}) \approx IPS + [(FP_a + CRP_a - UP_a) \times RE_{Pr}] \quad (P4)$$

where IPS* is the IPS predicted for the succeeding rice crop (i.e., adjusted for the actual P balance); IPS is the initial estimate of IPS (kg P $ha^{-1}$); $FP_a$ is the amount of fertilizer P applied (kg $ha^{-1}$); $CRP_a$ is the amount of P remaining in the field with crop residues (estimate from Equation P1 and adjust for straw management practice, kg P $ha^{-1}$); $UP_a$ is the actual P uptake (estimate from Figure 9 using the actual grain yield measured, kg P $ha^{-1}$); and $RE_{Pr}$ is the recovery fraction of the residual P remaining in the field (kg $kg^{-1}$, ~0.2).

## P fertilizer sources

All commercially available P fertilizers are suitable for irrigated rice (Table 11), so the choice of fertilizer material should be based on:

- the cost per kilogram of $P_2O_5$,

- other nutrient content, and
- solubility or reactivity of the P fertilizer in the soil.

P fertilizers can also provide S. Care should be taken to ensure a sufficient supply of S from other sources when changing from S-containing (e.g., single superphosphate) to S-free P fertilizers (e.g., triple superphosphate). Note that the solution produced from the dissolution of superphosphate in soil has a pH approaching 1 whereas that from diammonium phosphate has a pH approaching 8.

Finely ground rock phosphate is an effective (and often the least costly) P fertilizer source for very acid rainfed lowland and upland soils (pH <4.5). In tropical environments, the effectiveness of rock phosphates depends on the extent to which the required P uptake rate of the crop plant can be maintained by the dissolution of rock phosphate P in the soil. Rock phosphate also contains Ca, which may help to alleviate subsoil acidity and Ca deficiency in highly weathered tropical soils (Section 3.8).



*Box 4. Key steps for calculating site-specific P fertilizer recommendations.*

**Step 1. Estimate crop P demand (UP)**

Define maximum yield ($Y_{max}$) based on site-specific climatic conditions.

Use Figure 9 to estimate the amount of P required to achieve the defined target grain yield for the selected maximum yield ($Y_{max}$) (Section 2.5).

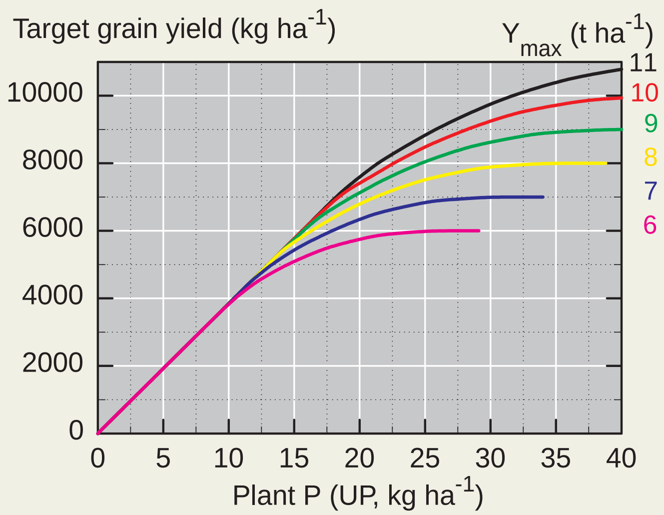


*Figure 9. Relationship between maximum yield ($Y_{max}$), target grain yield, and total P uptake (UP).*

*Box 4. (...continued, last).*

## Step 2. Estimate the potential indigenous P supply (IPS)

If grain yield (t $ha^{-1}$) in a P omission plot was measured, estimate IPS (Section 2.4):

*if* $GY(NPK) \leq GY(0\ P)$, *then* $IPS\ (kg\ P\ ha^{-1}) = GY(0\ P) \times 2.6$;

*if* $GY(NPK) > GY(0\ P)$, *then* $IPS\ (kg\ P\ ha^{-1}) = GY(0\ P) \times 2.3$.

Otherwise, if grain yield was measured in an NPK plot only, and a good estimate of $RE_P$ is available, use Equation P1:

$$IPS\ (kg\ P\ ha^{-1}) \approx (GY \times 3) - (RE_P \times FP) \quad (P1)$$

where GY is the grain yield in t $ha^{-1}$ (14% moisture content); $RE_P$ is the apparent first-crop recovery efficiency of applied P (about 0.2–0.3 kg $kg^{-1}$, see below); and FP is the amount of fertilizer P added (kg $ha^{-1}$).

The IPS in most irrigated lowland rice soils is 5–30 kg P $ha^{-1}$ per crop and is usually around 12–19 kg P $ha^{-1}$ (average: 15 kg P $ha^{-1}$), which is sufficient to sustain yields of 4–6 t $ha^{-1}$ in the short term.

## Step 3. Estimate recovery efficiency of applied P fertilizer ($RE_P$)

$RE_P$ can be estimated for a particular cropping system and P application method by conducting an experiment with different P rates where crop growth is not constrained by the supply of other nutrients (Section 5.5). $RE_P$ can then be calculated by difference using Equation P2:

$$RE_P\ (kg\ kg^{-1}) = (UP_2 - UP_1)/(FP_2 - FP_1) \quad (P2)$$

where $RE_P$ is the recovery efficiency of P (kg of P taken up per kg of P applied); UP is the total P uptake with grain and straw (kg $ha^{-1}$); and FP is the amount of fertilizer P added (kg $ha^{-1}$) in two different P treatments (i.e., Treatment 2 receives a larger P rate than Treatment 1).

Ideally, a zero P plot is used as the reference (Treatment 1).

A reasonable estimate of $RE_P$ for tropical and subtropical lowland rice soils is 0.2–0.3 kg $kg^{-1}$. Greater efficiencies (≥0.25) are obtained when P is topdressed and poorer efficiencies (<0.2) where a large amount of P is incorporated as a basal dressing into a soil with high P fixation potential or a soil with high IPS.

## Step 4. Calculate P fertilizer rate (FP)

Calculate the amount of fertilizer P required (FP) to achieve the yield target:

$$FP\ (kg\ P\ ha^{-1}) = (UP - IPS)/RE_P \quad (P3)$$

where UP is the total P uptake with grain and straw (kg $ha^{-1}$); IPS is the potential indigenous P supply (kg P $ha^{-1}$); and $RE_P$ is the recovery efficiency of P taken up (kg per kg of P applied).

## Step 5. Splitting and timing of P applications

P fertilizers are usually incorporated in the soil before planting as a basal dressing.

*Box 5. Example 3 – Calculating site-specific P fertilizer recommendations.*

*Assumptions:* A fertile irrigated lowland soil in tropical Asia with a grain yield of 3.5 t $ha^{-1}$ when no fertilizer is applied. The soil has only moderate P-fixation potential and transplanted rice is grown. Most of the straw remains in the field after harvest and is burned *in situ*.

## Step 1. Estimate crop P demand (UP)

- Dry season: target grain yield 7 t $ha^{-1}$ (maximum yield ($Y_{max}$) for this season: 10 t $ha^{-1}$)

  *UP ≈ 20 kg P $ha^{-1}$* *(from Figure 9)*

- Wet season: target grain yield 5 t $ha^{-1}$ (maximum yield ($Y_{max}$) for this season: 7 t $ha^{-1}$)

  *UP ≈ 15 kg P $ha^{-1}$* *(from Figure 9)*

## Step 2. Estimate indigenous P supply (IPS)

In a previous dry-season crop under favorable conditions, when the farmer applied 10 kg P $ha^{-1}$ and the full amount of N and K, his grain yield was 5.7 t $ha^{-1}$. We assume a recovery efficiency of applied P of 0.2 kg $kg^{-1}$ applied:

*IPS ≈ (5.7 x 3) – (0.2 x 10) = 15 kg P $ha^{-1}$* *(from Equation P1)*

## Step 3. Estimate recovered fraction of applied P ($RE_P$)

The soil is a moderately P-fixing medium-heavy textured clay-loam soil. We assume a first-season recovery efficiency for applied P fertilizer of 20%:

*$RE_P$ ≈ 0.20 kg $kg^{-1}$ applied (20% first-season recovery)*

## Step 4. Calculate P fertilizer rate (FP)

- Dry season: target grain yield 7 t $ha^{-1}$

  *FP = (20 – 15)/0.20 = 25 kg P $ha^{-1}$ = 57 kg $P_2O_5$ $ha^{-1}$* *(from Equation P3)*

  Total P removal is ~15 kg P $ha^{-1}$ because the farmer removes only the grain (= 7 t x 2 kg P $t^{-1}$ grain = 14 kg P $ha^{-1}$) and ~20% of the straw from his field (= 7 t straw x 0.2 x 1 kg P $t^{-1}$ straw = 1.4 kg P $ha^{-1}$). The recommended P rate results in a small positive P balance. This is acceptable because IPS is only moderate and should be built up to levels of 20–25 kg P $ha^{-1}$ per crop.

- Wet season: target grain yield 5 t $ha^{-1}$

  *FP = (15 – 15)/0.20 = 0 kg P $ha^{-1}$* *(from Equation P3)*

  Because of smaller yield potential, it is usually not necessary to apply larger rates of P to the wet-season crop. To maintain IPS and compensate for the poor exploitation of indigenous P sources under wet-season conditions, however, the farmer should at least replenish the amount of P contained in grain and straw removed from the field (estimate from Table 10). Because the farmer removes only the grain (= 5 t x 2 kg P $t^{-1}$ grain = 10 kg P $ha^{-1}$) and ~20% of the straw from his field (= 5 t straw x 0.2 x 1 kg P $t^{-1}$ straw = 1 kg P $ha^{-1}$), the total removal is ~11 kg P $ha^{-1}$. Therefore, an application of 15 kg P $ha^{-1}$ is recommended for the gradual buildup of IPS.

## Step 5. Splitting and timing of P applications

- Dry and wet season: apply all P as a basal dressing by incorporating the P fertilizer into the soil before planting.

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# 3.3 Potassium Deficiency

### Function and mobility of K

Potassium has essential functions in osmoregulation, enzyme activation, regulation of cellular pH, cellular cation-anion balance, regulation of transpiration by stomata, and the transport of assimilates (the products of photosynthesis). K provides strength to plant cell walls and is involved in the lignification of sclerenchyma tissues. On the whole-plant level, K increases leaf area and leaf chlorophyll content, delays leaf senescence, and therefore contributes to greater canopy photosynthesis and crop growth. Unlike N and P, K does not have a pronounced effect on tillering. K increases the number of spikelets per panicle, percentage of filled grains, and 1,000-grain weight.

K deficiency results in an accumulation of labile low-molecular-weight sugars, amino acids, and amines that are suitable food sources for leaf disease pathogens. K improves the rice plant's tolerance of adverse climatic conditions, lodging, insect pests, and diseases. Deficiency symptoms tend to occur in older leaves first, because K is very mobile within the plant and is retranslocated to young leaves from old senescing leaves. Often, yield response to K fertilizer is only observed when the supply of other nutrients, especially N and P, is sufficient.

### K deficiency symptoms and effects on growth

**Dark green plants with yellowish brown leaf margins or dark brown necrotic spots first appear on the tips of older leaves.**

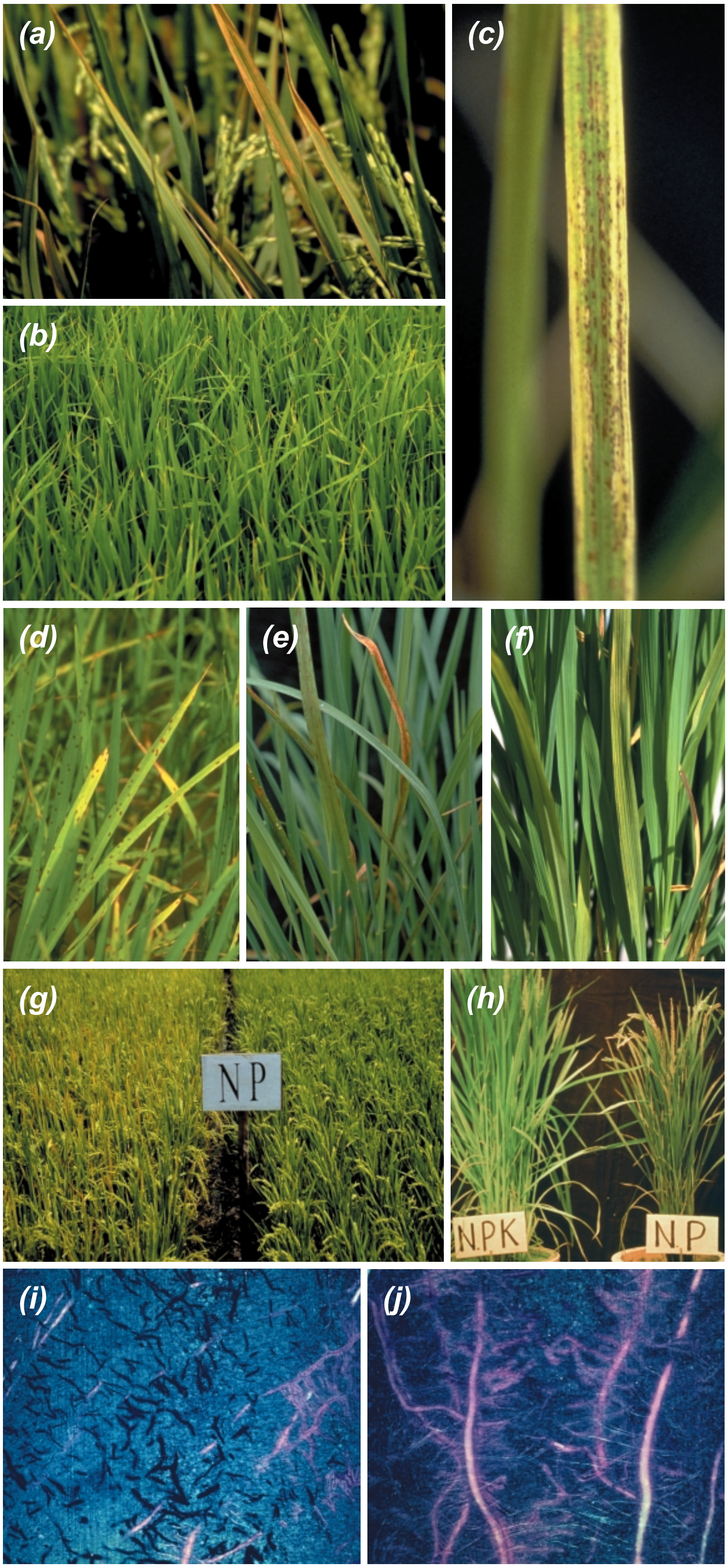
Under severe K deficiency, leaf tips are yellowish brown. Symptoms appear first on older leaves, then along the leaf edge, and finally on the leaf base. Upper leaves are short, droopy, and 'dirty' dark green. Older leaves change from yellow to brown and, if the deficiency is not corrected, discoloration gradually appears on younger leaves. Leaf tips and margins may dry up. Yellow stripes may appear along leaf interveins, and lower leaves become droopy. Leaf symptoms of K deficiency (particularly the appearance of yellowish brown leaf margins) are similar to those of tungro virus disease. Unlike K deficiency, however, tungro occurs as patches within a field, affecting single hills rather than the whole field.

When K deficiency is severe, rusty brown spots appear on the tips of older leaves and later spread over the whole leaf, which then turns brown and becomes dessicated. Irregular necrotic spots may also occur on panicles.

K deficiency is often not detected because its symptoms are not as easy to recognize as those of P and N deficiency, and symptoms tend to appear during later growth stages. Leaf symptoms are usually more apparent in hybrid rice varieties than in inbred modern varieties, because of their greater K demand and narrower optimal N:K ratio.

Other symptoms and effects on growth are as follows:

- Stunted plants (smaller leaves, short and thin stems). Tillering is reduced only under very severe deficiency.
- Greater incidence of lodging.
- Early leaf senescence, leaf wilting, and leaf rolling, particularly under conditions of high temperature and low humidity.
- Large percentage of sterile or unfilled spikelets caused by poor pollen viability and retarded carbohydrate translocation. Reduced 1,000-grain weight.
- Unhealthy root system (many black roots, low root length density), causing a reduction in the uptake of other nutrients. Reduced cytokinin production in roots.
- Poor root oxidation power, causing decreased resistance to toxic substances




### *Potassium deficiency symptoms in rice*

*(a), (b), (c) Leaf margins become yellowish brown. (d), (e) Dark brown spots appear on the leaf surface. (f) Leaf bronzing is also a characteristic of K deficiency. (g) K deficiency symptoms are more likely to occur in hybrid rice (on the left) than in modern inbred varieties (on the right). (h) Rice yields are often constrained by unbalanced fertilization where the response to N and P is constrained by insufficient K. (i) K-deficient rice plant roots may be covered with black iron sulfide. (j) In comparison, healthy rice roots are covered with red-brown iron oxide.*

*Table 12. Optimal ranges and critical levels of K in plant tissue.*

| Growth stage | Plant part | Optimum (%) | Critical level for deficiency (%) |
|---|---|---|---|
| Tillering to panicle initiation | Y leaf | 1.8–2.6 | <1.5 |
| Flowering | Flag leaf | 1.4–2.0 | <1.2 |
| Maturity | Straw | 1.5–2.0 | <1.2 |

produced under anaerobic soil conditions, e.g., Fe toxicity caused by K deficiency (Section 4.1).

- Increased incidence of diseases, in particular, brown leaf spot (caused by *Helminthosporium oryzae*), cercospora leaf spot (caused by *Cercospora* spp.), bacterial leaf blight (caused by *Xanthomonas oryzae*), sheath blight (caused by *Rhizoctonia solani*), sheath rot (caused by *Sarocladium oryzae*), stem rot (caused by *Helminthosporium sigmoideum*), and blast (caused by *Pyricularia oryzae*) where excessive N fertilizer and insufficient K fertilizer have been used.

## Plant

During vegetative growth up to flowering, the K supply is usually sufficient, and a response to additional K is unlikely when the leaf concentration is between 1.8% and 2.6%. To produce the maximum number of spikelets per panicle, the K content of mature leaves should be >2% at the booting stage.

The critical level for K in straw at harvest is between 1.0% and 1.5%, but yields >7 t $ha^{-1}$ require >1.2% K in the straw at harvest and >1.2% K in the flag leaf at flowering.

For optimum growth, the N:K ratio in straw should be between 1:1 and 1:1.4.

## Soil

The 1N $NH_4OAc$-extractable K in lowland rice soils ranges from 0.05 to 2 $cmol_c$ $kg^{-1}$ (x 391 = mg $kg^{-1}$). A critical concentration of 0.2 $cmol_c$ K $kg^{-1}$ soil is often used. Depending on soil texture, clay mineralogy, and K input from natural sources, however, critical levels of $NH_4OAc$-extractable K can vary from 0.1 to 0.4 $cmol_c$ K $kg^{-1}$. The amount of tightly bound or 'fixed' K increases with clay content so that critical levels are larger in soils containing large amounts of 2:1 clay minerals. Critical ranges with general applicability are as follows:

- Exchangeable K <0.15 $cmol_c$ $kg^{-1}$ → low K status, response to K fertilizer certain,
- Exchangeable K 0.15–0.45 $cmol_c$ $kg^{-1}$ → medium K status, response to K fertilizer probable, and
- Exchangeable K >0.45 $cmol_c$ $kg^{-1}$ → high K status, response to K fertilizer only at very high yield levels (>8 t $ha^{-1}$).

On lowland rice soils with high K 'fixation' and release of nonexchangeable K (e.g., vermiculitic soils), 1N $NH_4OAc$-extractable K is often small (<0.2 $cmol_c$ $kg^{-1}$) and not a reliable soil test for assessing K supply.

K saturation (% of total CEC) is often a better indicator of soil K supply than the absolute amount of K extracted with 1N $NH_4OAc$, because it takes into account the relationship between K and other exchangeable cations (Ca, Mg, Fe). The proposed ranges are as follows:

- K saturation <1.5% → low K status, response to K fertilizer certain,
- K saturation 1.5–2.5% → medium K status, response to K fertilizer probable, and
- K saturation >2.5% → high K status, response to K fertilizer unlikely.

Other critical soil levels where K deficiency is likely to occur are as follows:

- 0.05 $cmol_c$ K $kg^{-1}$: Electro-ultrafiltration (EUF) K, 0–10 minutes,
- 0.12 $cmol_c$ K $kg^{-1}$: EUF-K, 0–35 minutes,

- 0.25 $cmol_c$ K $kg^{-1}$: 1N $HNO_3$ (slow-release K) 196 kg K $ha^{-1}$ Mehlich III, Arkansas

A (Ca + Mg):K ratio >100 (all measured as exchangeable cations) may indicate low soil K availability for rice.

## Causes of K deficiency

The common causes of K deficiency are as follows:

- Low soil K-supplying capacity.
- Insufficient application of mineral K fertilizer.
- Complete removal of straw.
- Small inputs of K in irrigation water.
- Low recovery efficiency of applied K fertilizer due to high K-fixation capacity or leaching losses.
- Presence of excessive amounts of reduced substances in poorly drained soils (e.g., $H_2S$, organic acids, $Fe^{2+}$), resulting in retarded root growth and K uptake.
- Wide Na:K, Mg:K, or Ca:K ratios in soil, and sodic/saline conditions. Excess Mg in soils derived from ultrabasic rocks. Large bicarbonate concentration in irrigation water.

## Occurrence of K deficiency

K deficiency in rice is more common under the following crop management practices:

- Excessive use of N or N + P fertilizers with insufficient K application.
- In direct-sown rice during early growth stages, when the plant population is large and root system is shallow.
- Cultivars differ in susceptibility to K deficiency and response to K fertilizer. The K requirement of hybrid rice is greater than that of inbred modern rice varieties because hybrid rice requires a narrower N:K ratio in the plant. Additional K is required to sustain the vigorous root system, increase the formation of superficial roots, and improve grain filling in hybrid rice.

Soils particularly prone to K deficiency include the following types:

- Soils inherently low in K:
  - Coarse-textured soils with low CEC and small K reserves (e.g., sandy soils in northeast Thailand, and Cambodia).
  - Highly weathered acid soils with low CEC and low K reserves, e.g., acid upland soils (Ultisols or Oxisols) and degraded lowland soils (e.g., in North Vietnam, northeast Thailand, Cambodia, and Lao PDR).
- Soils on which K uptake is inhibited:
  - Lowland clay soils with high K fixation due to the presence of large amounts of 2:1 layer clay minerals (e.g., illitic clay soils in India, and vermiculitic clay soils in the Philippines).
  - Soils with a large K content but very wide (Ca + Mg):K ratio (e.g., some calcareous soils or soils derived from ultrabasic rocks). Wide (Ca + Mg):K ratios result in stronger K adsorption to cation exchange sites, and reduce the concentration of K in the soil solution.
  - Leached, 'old' acid sulfate soils with a small base cation content. K deficiency may occur on acid sulfate soils even when the soil K content is large (e.g., in Thailand and South Vietnam).
  - Poorly drained and strongly reducing soils where K uptake is inhibited by the presence of $H_2S$, organic acids, and an excessive concentration of $Fe^{2+}$.
  - Organic soils (Histosols) with small K reserves (e.g., in Kalimantan, Indonesia).

*Table 13. K uptake and K content of modern rice varieties.*

| Plant part | Typical observed range [a] | Observed average [b] |
|---|---|---|
| | kg K uptake $t^{-1}$ grain yield | |
| Grain + straw | 14–20 | 17.0 |
| Grain | 2–3 | 2.5 |
| Straw | 12–17 | 14.5 |
| | % K content | |
| Grain | 0.22–0.31 | 0.27 |
| Straw | 1.17–1.68 | 1.39 |
| Unfilled spikelets | 0.61–1.20 | 1.07 |

[a] *25–75% interquartile range of farmers' fields and field experiments in Asia (n = 1,300).*

[b] *Median of farmers' fields and field experiments in Asia (n = 1,300).*

## Effect of submergence on K availability and uptake

Under anaerobic conditions following submergence, exchangeable K is displaced from cation exchange sites into the soil solution due to competition for exchange sites from $Mn^{2+}$ and $Fe^{2+}$. This results in increased solution-K concentration and enhanced K diffusion to rice roots, particularly on soils with a small K-fixation potential (e.g., soils containing predominantly 1:1 layer kaolinitic clay minerals). A larger concentration of K in the soil solution, however, may increase K losses due to leaching in coarse-textured soils or soils with a high percolation rate (>10 mm per day).

Flooding of dry lowland rice soils containing vermiculite, illite, or other K-fixing minerals (2:1 layer clay minerals) may increase K fixation and reduce the solution concentration, so that rice depends on nonexchangeable reserves for K uptake. Rice roots release $H^+$ (to balance the excess of cation over anion intake) and $O_2$ (to oxidize $Fe^{2+}$), however, and both these processes cause acidification in the rhizosphere, thus increasing the release of nonexchangeable K (because $K^+$ is displaced from interlayer positions by $H^+$ ions).

## Crop K uptake and removal

The internal K use efficiency of rice depends on the K supply and overall plant nutritional status. Under balanced nutrition and optimum growth conditions, an internal efficiency of 69 kg grain $kg^{-1}$ plant K uptake can be expected, i.e., equivalent to a removal of 14.5 kg K $t^{-1}$ at economic yield levels (70–80% of maximum yield) (Section 2.5).

In farmers' fields, however, the *measured* average internal K use efficiency is only 60 kg grain $kg^{-1}$ K taken up. The *observed* average K removal in irrigated rice systems in Asia is 17 kg K $t^{-1}$ grain yield (Table 13). Therefore, a rice crop yielding 6 t $ha^{-1}$ takes up ~100 kg K $ha^{-1}$ (compared with only 87 kg K $ha^{-1}$ under optimum growth conditions) of which >80% remains in the straw at maturity.

If the grain *only* is removed and straw is returned to the field, K removal is ~2.5 kg K $t^{-1}$ of grain yield. Burning the straw causes no K losses to the atmosphere, but K may be leached from the ash if the straw is burned in large heaps or piles following threshing (e.g., as practiced in the Philippines and Indonesia).

## General K management

K management should be considered part of *long-term* soil fertility management, because K is not easily lost from or added to the root zone by the short-term biological and chemical processes that affect the N supply. K management must ensure that N use efficiency is not constrained by K deficiency.

General measures to prevent K deficiency and improve K use efficiency are as follows:

- Natural inputs: Estimate K input from indigenous sources to assess site-specific K requirements. In most irrigated rice areas, K input from irrigation water ranges between 10 and 50 kg K $ha^{-1}$ per crop, which is insufficient to balance crop removal and leaching losses at current average yield levels of 5–6 t $ha^{-1}$. The K concentration in irrigation water tends to follow the order shallow-well water (5–20 mg K $L^{-1}$, near human settlements) > deep-well groundwater (3–10 mg K $L^{-1}$, up to 20 mg K $L^{-1}$ in volcanic layers) > surface water (1–5 mg $L^{-1}$, canal, river).

  K inputs in irrigation water can be calculated where the amount of irrigation water used per season is known, e.g., if the average K concentration in irrigation water is 3 mg K $L^{-1}$, 30 kg K $ha^{-1}$ is added in 1,000 mm of irrigation water. The K content of irrigation water can vary considerably from place to place and from year to year. Irrigation water with low K content will add to the depletion of soil K and induce severe K deficiency, whereas water rich in K may be sufficient to meet K requirements of high-yielding crops. If the site-specific K management approach described below is used, K input from irrigation and other natural sources is already included in the crop-based estimate of the indigenous K supply.
- Soil management: Increase K uptake by improving root health with soil management practices (e.g., deep tillage to improve percolation to at least 3–5 mm per day; avoid excessively reducing conditions in soil).
- Crop management: Establish an adequate population of healthy rice plants by using high-quality seed of a modern variety with multiple pest resistance, and optimum crop husbandry (water and pest management).
- Straw management: Incorporate rice straw. If burning is the only option for crop residue management, spread the straw evenly over the field (e.g., as it is left after combine harvesting) before burning. Ash from burnt straw heaps should also be spread over the field.
- Balanced fertilizer management: Apply optimum doses of N and P fertilizers and correct micronutrient deficiencies. Apply K fertilizers, farmyard manure, or other materials (rice husk, ash, night soil, compost) to replenish K removed in harvested crop products.

Some general fertilizer recommendations for K fertilizer use in rice are as follows:

- Correct deficiencies of other nutrients (N, P, Zn), correct other soil problems (restricted rooting depth, mineral toxicities), and ensure proper overall crop management to maximize the response to K fertilizer. To maintain yields of 5–7 t $ha^{-1}$ and replenish K removed with grain and straw, fertilizer K rates range between 20 and 100 kg K $ha^{-1}$. The required application rate depends on many factors: the soil's buffer capacity for K (large in vertisols and other soils containing lattice clays), soil texture, availability of other nutrients, variety, yield target, straw management, cropping intensity, and the amount of K in the irrigation water. On many lowland soils in Asia, a significant response to fertilizer K is only achieved where all other factors are properly managed and yields are >6 t $ha^{-1}$.
- If most of the straw remains in the field (e.g., after combine harvesting or harvest of panicles only) and K inputs from animal manure are small, apply 3 kg K $ha^{-1}$ per ton grain harvested (i.e., 15 kg K for 5 t $ha^{-1}$ yield) to replenish K removal.
- Where straw is removed from the field and the K input from other sources (animal manure, water, sediment) is small, apply at least 10 kg K $ha^{-1}$ per ton grain harvested (i.e., 50 kg K for 5 t $ha^{-1}$

yield) to replenish most of the K removed. To avoid long-term soil K depletion, and if budgets allow, attempt to replenish completely the K removed by applying 15 kg K $ha^{-1}$ per ton grain harvested.

- Hybrid rice always requires larger applications of K (50–100 kg K $ha^{-1}$ on most soils) than inbred modern varieties.

## *Site-specific K management in irrigated rice*

Key steps for calculating site-specific K fertilizer recommendations are as follows:

1 Estimate crop K demand for a target grain yield.

2 Estimate potential indigenous K supply.

3 Estimate recovery efficiency of applied K fertilizer.

4 Calculate K fertilizer rate as a function of steps 1–3.

5 Decide about splitting and timing of K applications.

Refer to Boxes 6 and 7 at the end of this section for step-by-step instructions and a worked example.

## *NOTES:*

- Grain yield refers to filled grains adjusted to 14% moisture content. All calculations are done using elemental K as the unit. To convert K to $K_2O$, multiply the amount of fertilizer K applied by 1.2.
- The approach to site-specific K management in irrigated rice described above assumes balanced fertilizer use, proper crop management, and that there are no other agronomic constraints to grain yield (i.e., modern rice variety with a harvest index of about 0.5, good seed quality and crop establishment, no water stress, little or no pest damage).

  Varieties grown in rainfed lowland and upland ecosystems often have a lower harvest index (0.3–0.4). Water stress may also occur, resulting in decreased internal K use efficiency and a larger K requirement to produce the same yield. If any of these factors are not managed properly, the internal efficiency of K will be reduced (i.e., less grain yield will be produced at a given rate of K uptake).
- By definition, IKS is the *potential* supply of K from indigenous sources. Thus, it can only be measured accurately in a season with favorable climate and good crop management, assuming that no other factors limit growth. In a tropical climate, it is best to measure IKS in a dry-season crop.
- If IKS is medium to high (>80 kg K $ha^{-1}$) and the actual yield achieved is close to the yield target, the approach described will result in balanced nutrition and a balanced K budget.
- In soils with very low IKS (<50 kg K $ha^{-1}$), the fertilizer recommendation for a high yield target may be too costly to implement in one season. In such cases, it is recommended to build up IKS over several cropping seasons by applying moderate to large amounts of K fertilizer until the target yield is reached.
- If the actual amount of fertilizer K applied is large, but crop growth during that season is reduced (due to non-nutritional factors) and the yield target is not reached, some excess K will remain in the soil (i.e., positive K balance). Conversely, actual yield and K uptake may exceed the target (because climate was more favorable or the quality of crop management was high) (i.e., negative K balance). Therefore, to calculate the K recommendation for the succeeding rice crop, the estimate of IKS should be adjusted *upwards* if the previous crop K balance was positive, or *downwards* if the previous crop K balance was negative. A coarse estimate of an adjusted IKS can be obtained with the following calculation:

$$IKS^* \ (kg\ K\ ha^{-1})$$
$$\approx IKS + [(FK_a + CRK_a - UK_a) \times RE_{K}] \quad (K4)$$

*Table 14. K fertilizer sources for rice.*

| Name | Formula | Content | Comments |
|---|---|---|---|
| Potassium chloride | KCl | 50% K | Muriate of potash (60% $K_2O$) |
| Potassium nitrate | $KNO_3$ | 37% K, 13% N | In compounds (44% $K_2O$) |
| Potassium sulfate | $K_2SO_4$ | 40–43% K, 18% S | In compounds (50% $K_2O$) |
| Langbeinite | $K_2SO_4 \cdot MgSO_4$ | 18% K, 11% Mg, 22% S | Quick-acting |
| Compound fertilizers | N + P + K | Variable | Common in rice |

where IKS* is the IKS predicted for the succeeding rice crop (i.e., adjusted for the actual K balance); IKS is the initial estimate of IKS (kg K $ha^{-1}$); $FK_a$ is the actual amount of fertilizer K applied (kg $ha^{-1}$); $CRK_a$ is the amount of K remaining in the field with crop residues (estimate from Equation K1 and adjust for straw management practice, kg K $ha^{-1}$); $UK_a$ is the actual K uptake (estimate from Equation K1 using the actual grain yield measured, kg K $ha^{-1}$); and $RE_{Kr}$ is the recovery fraction of the residual K remaining in the field (kg $kg^{-1}$, ~0.4).

## K fertilizer sources

Sodium can substitute for *some* nonspecific functions of K in the plant (e.g., turgor control), but *not* for specific functions such as enzyme activation. NaCl (common salt) can be used as a substitute for K fertilizer (Table 14) where

- K fertilizers are not available or are too costly,
- soils contain small amounts of available K, and
- yield levels are low to moderate (<5 t $ha^{-1}$).

Farmers in Cambodia often apply low-cost sea salt to their poor soils. During World War II, farmers in Japan partially replaced K fertilizer with NaCl when K fertilizer was not available.

POTASSIUM

*Box 6. Key steps for calculating site-specific K fertilizer recommendations.*

**Step 1. Estimate crop K demand (UK)**

Define maximum yield ($Y_{max}$) based on site-specific climatic conditions.

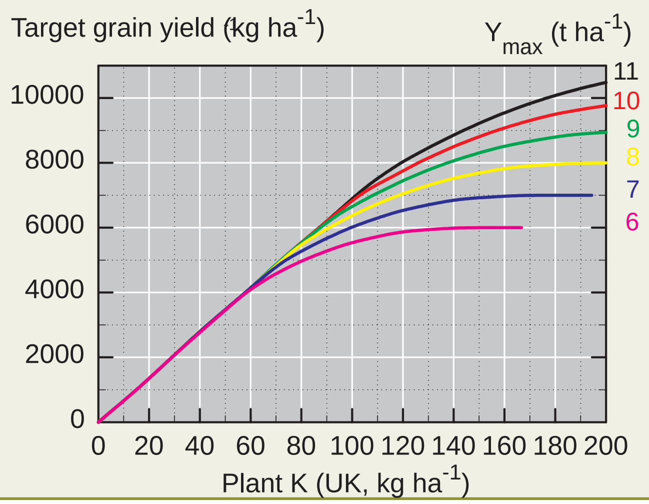



*Figure 10. Relationship between maximum yield ($Y_{max}$), target grain yield, and total K uptake (UK).*

*Box 6. (...continued).*

Use Figure 10 to estimate the amount of K required to achieve the defined target grain yield for the selected maximum yield ($Y_{max}$) (Section 2.5).

## Step 2. Estimate potential indigenous K supply (IKS)

If grain yield (t ha$^{-1}$) in a K omission plot was measured, estimate IKS (Section 2.4):

*if* $GY(NPK) \leq GY(0\ K)$, *then* $IKS\ (kg\ K\ ha^{-1}) = GY(0\ K) \times 15$;

*if* $GY(NPK) > GY(0\ K)$, *then* $IKS\ (kg\ K\ ha^{-1}) = GY(0\ K) \times 13$.

Otherwise, if grain yield was measured in an NPK plot only, and a good estimate of $RE_K$ is available, use Equation K1:

$$IKS\ (kg\ K\ ha^{-1}) \approx (GY \times 17) - (RE_K \times FK) \qquad (K1)$$

where GY is the grain yield in t ha$^{-1}$ (14% moisture content); $RE_K$ is the apparent first-crop recovery efficiency of applied K (~0.4–0.6 kg kg$^{-1}$, see below); and FK is the amount of fertilizer K added (kg ha$^{-1}$).

The IKS in most lowland rice soils ranges between 30 and 120 kg K ha$^{-1}$ per crop and is usually 60–90 kg K ha$^{-1}$ (average IKS is 80 kg K ha$^{-1}$). This is sufficient to sustain yields of 4–6 t ha$^{-1}$ over the short term, assuming a crop requirement of 15 kg K t$^{-1}$ grain yield if no K is applied.

## Step 3. Estimate recovery efficiency of applied K fertilizer ($RE_K$)

$RE_K$ can be estimated for a particular cropping system and K application method by conducting an experiment with different fertilizer K rates where crop growth is not constrained by the supply of other nutrients. $RE_K$ can then be calculated by the difference using Equation K2:

$$RE_K\ (kg\ kg^{-1}) = (UK_2 - UK_1)/(FK_2 - FK_1) \qquad (K2)$$

where $RE_K$ is the recovery fraction (kg of K taken up per kg of K applied); UK is the total K uptake with grain and straw (kg ha$^{-1}$); and FK is the amount of fertilizer K added (kg ha$^{-1}$) in two different K treatments (i.e., Treatment 2 receives a larger K rate than Treatment 1).

Ideally, a zero K plot is used as the reference (Treatment 1).

A reasonable estimate of $RE_K$ for lowland rice is 0.4–0.6 kg kg$^{-1}$, with greater efficiencies (≥0.5) when K application is topdressed or applied in two or more splits. Efficiency is poor (<0.5) where a large amount of K is incorporated as a basal application in soils with high K-fixation potential or in coarse-textured soils prone to leaching.

## Step 4. Calculate K fertilizer rate (FK)

Calculate the amount of fertilizer K required (FK) to achieve the yield target:

$$FK\ (kg\ K\ ha^{-1}) = (UK - IKS)/RE_K \qquad (K3)$$

where UK is the total K uptake with grain and straw (kg ha$^{-1}$); IKS is the potential indigenous K supply (kg K ha$^{-1}$); and $RE_K$ is the recovery efficiency of K taken up (kg per kg of K applied).

*Box 6. (...continued, last).*

## Step 5. Splitting and timing of K applications

K can be applied in 1–3 split applications. The first dose is applied at or shortly after planting, the second dose at the panicle initiation (PI) stage (40–50 DAT for short- to medium-duration varieties), and the third at first flowering (60–70 DAT). The number of splits required depends on soil K buffering characteristics, crop establishment method used, and the local importance of K for reducing pest and disease incidence.

General guidelines for splitting and timing the application of K fertilizers include the following:

- If the amount of K fertilizer required is small (FK <30 kg K $ha^{-1}$), all K can be supplied as a basal application.
- If the amount of K fertilizer required is medium to large (FK 30–100 kg K $ha^{-1}$), supply 50% K as a basal application or within 10 and 14 DAT and 50% at PI.
- If the amount of K fertilizer required is very large (FK >100 kg K $ha^{-1}$), supply 50% K as a basal application or within 10 and 14 DAT , 30% at PI, and 20% at flowering.
- In direct-seeded rice planted at a high plant density, the first K dose should be applied at about 10–15 DAS.
- In soils where other constraints limit K uptake or where leaching losses are likely, always split K into at least two doses. This includes high-CEC soils (high K fixation), coarse-textured soils, and problem soils (e.g., acid sulfate, alkaline, Fe-toxic, poorly drained, or P-deficient soils).
- Apply part of the K recommendation at flowering to support grain filling and increase resistance to lodging and diseases in dense canopies if the target yield is very high. Late K application can also be supplied as foliar sprays.

*Box 7. Example 4 – Calculating site-specific K fertilizer recommendations.*

*Assumptions:* A fertile irrigated lowland soil in tropical Asia with a grain yield of 3.5 t $ha^{-1}$ if no fertilizer is applied. The soil has only moderate K-fixation potential and transplanted rice is grown. Most of the straw remains in the field after harvest and is burned *in situ*.

## Step 1. Estimate crop K demand (UK)

- Dry season: target grain yield 7 t $ha^{-1}$ (maximum yield ($Y_{max}$) for this season: 10 t $ha^{-1}$)

  $UK \approx 105$ kg K $ha^{-1}$ *(from Figure 10)*

- Wet season: target grain yield 5 t $ha^{-1}$ (maximum yield ($Y_{max}$) for this season: 7 t $ha^{-1}$)

  $UK \approx 75$ kg K $ha^{-1}$ *(from Figure 10)*

## Step 2. Estimate indigenous K supply (IKS)

In a previous favorable dry-season crop, when the farmer applied 30 kg K $ha^{-1}$ and the full amount of N and P, his grain yield was 5.9 t $ha^{-1}$. We assume a recovery efficiency of applied K of 0.5 kg $kg^{-1}$ applied:

$$IKS \approx (5.9 \times 17) - (0.5 \times 30) = 85 \text{ kg K ha}^{-1} \quad \text{(from Equation K1)}$$

POTASSIUM

*Box 7. (...continued, last).*

### Step 3. Estimate recovery efficiency of applied K fertilizer ($RE_K$)

The soil has a medium-heavy texture (clay loam) with moderate K fixation so that losses will be small (much of the applied K not taken up by the crop will remain in the soil and benefit subsequent rice crops).

$RE_K \approx 0.5$ *kg kg$^{-1}$ applied (50% first-season recovery)*

### Step 4. Calculate K fertilizer rate (FK)

- Dry season: target grain yield 7 t ha$^{-1}$

  $FK = (105 - 85)/0.5 = 40$ kg K ha$^{-1}$ = 48 kg $K_2O$ ha$^{-1}$ *(from Equation K3)*

  The farmer removes only the grain (= 7 t x 2.5 kg K t$^{-1}$ grain = 18 kg K ha$^{-1}$) and ~20% of the straw from his field (= 7 t straw x 0.2 x 14.5 kg K t$^{-1}$ straw = 20 kg K ha$^{-1}$). Therefore, the total removal is ~38 kg K ha$^{-1}$ and the recommended K rate results in a zero K balance.

- Wet season: target grain yield 5 t ha$^{-1}$

  $FK = (75 - 87)/0.5 = -24$ kg K ha$^{-1}$ *(from Equation K3)*

  Because of the smaller yield potential and high IKS, no K would be required in the wet-season crop. To maintain IKS, however, the farmer should replenish the amount of K removed with grain and straw from the field (estimate from Equation K1). The farmer removes only the grain (= 5 t x 2.5 kg K t$^{-1}$ grain = 12.5 kg K ha$^{-1}$) and ~20% of the straw from his field (= 5 t straw x 0.2 x 13.5 kg K t$^{-1}$ straw = 13.5 kg K ha$^{-1}$). Therefore, total removal is ~26 kg K ha$^{-1}$ and a maintenance K application of ~25 kg K ha$^{-1}$ is sufficient.

### Step 5. Splitting and timing of K applications

- Dry season: supply 50% of FK basally (KCl incorporated before planting) and 50% as a KCl topdressing at panicle initiation.
- Wet season: supply all K as a basal application (KCl incorporated before planting).

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# 3.4 Zinc Deficiency

## *Function and mobility of Zn*

Zinc is essential for several biochemical processes in the rice plant, such as:

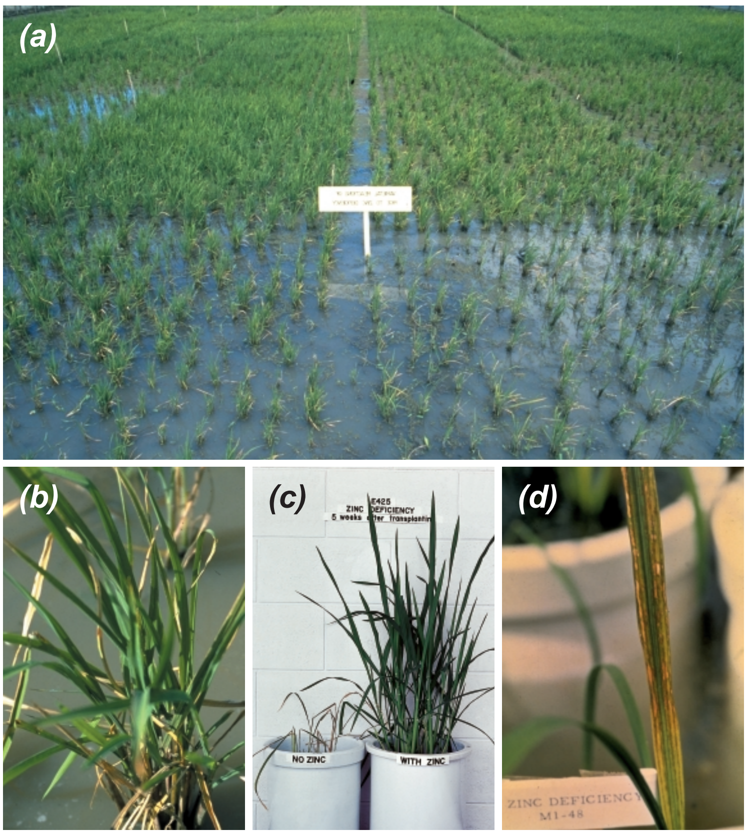
- cytochrome and nucleotide synthesis,
- auxin metabolism,
- chlorophyll production,
- enzyme activation, and
- the maintenance of membrane integrity.

Zn accumulates in roots but can be translocated from roots to developing plant parts. Because little *retranslocation* of Zn occurs within the leaf canopy, particularly in N-deficient plants, Zn deficiency symptoms are more common on young or middle-aged leaves.

## *Zn deficiency symptoms and effects on growth*

**Dusty brown spots on upper leaves of stunted plants appearing 2–4 weeks after transplanting.**

Symptoms appear between two to four weeks after transplanting, with uneven plant growth and patches of poorly established hills in the field, but the crop may recover without intervention. Under severe Zn deficiency, tillering decreases and may stop completely, and time to crop maturity may be increased. Zn deficiency can also increase spikelet sterility in rice. Midribs, particularly near the leaf base of younger leaves, become chlorotic. Leaves lose turgor and turn brown as brown blotches and streaks appear on lower leaves,




***Zinc deficiency symptoms in rice***

*(a) Uneven field growth, plant stunting (foreground). (b) Tillering is reduced. (c) Growth is severely affected by Zn deficiency (left). (d) Appearance of dusty brown spots on upper leaves.*

*Table 15. Optimal ranges and critical levels of Zn in plant tissue.*

| Growth stage | Plant part | Optimum (mg $kg^{-1}$) | Critical level for deficiency (mg $kg^{-1}$) |
|---|---|---|---|
| Tillering | Y leaf | 25–50 | <20 |
| Tillering | Whole shoot | 25–50 | <10 |

enlarge, and coalesce. A white line sometimes appears along the leaf midrib. Plant growth is stunted and leaf blade size is reduced.

In Japan, Zn deficiency is the cause of the 'Akagare Type II' disorder in rice.

Other effects on growth include the following:

- Symptoms may be more pronounced during early growth stages, because of Zn immobilization (due to increased bicarbonate concentration in the soil where strongly reducing conditions persist following flooding). If the deficiency is not severe, plants may recover after 4–6 weeks, but maturity is delayed and yield reduced.
- Symptoms may resemble Fe deficiency (Section 3.9), which also occurs on alkaline soils. On alkaline soils, Zn deficiency is often associated with S deficiency (Section 3.5).
- Symptoms may resemble Mn deficiency (Section 3.10) and Mg deficiency (Section 3.7).
- Leaf spots may resemble Fe toxicity in appearance but the latter occurs on high organic status soils with low pH.
- Symptoms may resemble grassy stunt and tungro virus diseases.

## Plant

Ranges of Zn deficiency in the whole shoot during vegetative growth (tillering) are as follows (Table 15):

- <10 mg $kg^{-1}$: Zn deficient
- 10–15 mg $kg^{-1}$: Zn deficiency very likely
- 15–20 mg $kg^{-1}$: Zn deficiency likely
- >20 mg $kg^{-1}$: Zn sufficient

The ratios of P:Zn and Fe:Zn in the shoot at tillering to the PI stage are good indicators of Zn status. Values should not exceed:

- P:Zn = 20–60:1 in shoots 6 weeks after planting, and
- Fe:Zn = 5–7:1 in shoots 6 weeks after planting

Leaf Zn concentration is a less reliable indicator of Zn deficiency, except in cases of extreme deficiency (leaf Zn <15 mg $kg^{-1}$).

## Soil

The critical soil levels for occurrence of Zn deficiency are as follows:

- 0.6 mg Zn $kg^{-1}$: 1N $NH_4$-acetate, pH 4.8
- 0.8 mg Zn $kg^{-1}$: DTPA methods
- 1.0 mg Zn $kg^{-1}$: 0.05N HCl
- 1.5 mg Zn $kg^{-1}$: EDTA methods
- 2.0 mg Zn $kg^{-1}$: 0.1N HCl

Calcareous soils (pH >7) with moderate to high organic matter status (>1.5% organic C) are likely to be Zn-deficient due to the presence of large amounts of $HCO_3^-$ in solution.

A ratio for exchangeable Mg:Ca of >1 in soil may result in Zn deficiency.

## Causes of Zn deficiency

Zinc deficiency can be caused by one or more of the following factors:

- Small amount of available Zn in the soil.
- Planted varieties are susceptible to Zn deficiency (e.g., IR26).
- High pH (≥7 under anaerobic conditions). Solubility of Zn decreases by two orders of magnitude for each unit increase in pH. Zn is precipitated as sparingly

ZINC

soluble $Zn(OH)_2$ when pH increases in acid soil following flooding.

- High $HCO_3^-$ concentration, because of reducing conditions in calcareous soils with high organic matter content or because of large concentrations of $HCO_3^-$ in irrigation water.
- Depressed Zn uptake because of an increase in the availability of Fe, Ca, Mg, Cu, Mn, and P after flooding.
- Formation of Zn-phosphates following large applications of P fertilizer. High P content in irrigation water (only in areas with polluted water).
- Formation of complexes between Zn and organic matter in soils with high pH and high organic matter content or because of large applications of organic manures and crop residues.
- Precipitation of Zn as ZnS when pH decreases in alkaline soil following flooding.
- Excessive liming.
- Wide Mg:Ca ratio (i.e., >1) and adsorption of Zn by $CaCO_3$ and $MgCO_3$.
- Excess Mg in soils derived from ultrabasic rocks.

## Occurrence of Zn deficiency

Zn deficiency is the most widespread micronutrient disorder in rice. Its occurrence has increased with the introduction of modern varieties, crop intensification, and increased Zn removal. Soils particularly prone to Zn deficiency include the following types:

- Neutral and calcareous soils containing a large amount of bicarbonate. On these soils, Zn deficiency often occurs simultaneously with S deficiency (widespread in India and Bangladesh).
- Intensively cropped soils where large amounts of N, P, and K fertilizers (which do not contain Zn) have been applied in the past.
- Paddy soils under prolonged inundation (e.g., when three crops of rice are grown in one year) and very poorly drained soils with moderate to high organic matter status.
- Sodic and saline soils.
- Peat soils.
- Soils with high available P and Si status.
- Sandy soils.
- Highly weathered, acid, and coarse-textured soils containing small amounts of available Zn. Soils derived from serpentine (low Zn content in parent material) and laterite.
- Leached, old acid sulfate soils with a small concentration of K, Mg, and Ca.

## Effect of submergence on Zn availability and uptake

Zn deficiency is seldom found in upland, aerobic soil conditions. Under flooded conditions, Zn availability decreases because of the reduction in Zn solubility as pH increases; Zn is precipitated as $Zn(OH)_2$ in acid soils or ZnS in sodic and calcareous soils. Zn is also strongly adsorbed on $CaCO_3$ or $MgCO_3$ and on oxides of Zn and Mn. In calcareous soils, after the flush in microbial activity that follows submergence, $HCO_3^-$ is the predominant anion, which mainly decreases Zn transport from root to shoot, and to a lesser extent, Zn uptake by roots. Zn uptake is reduced by an increase in the concentration of organic acids that occurs under submerged conditions immediately after flooding, mainly under temperate climates or in problem soils. Zn also forms insoluble Zn-phosphates under anaerobic conditions.

The pH in the rhizosphere is acid due to:

- $H^+$ released from the rice roots to balance excess of cations over anion uptake, and
- $H^+$ generated when $Fe^{2+}$ is oxidized by $O_2$ released from the roots.

Under acid rhizosphere conditions, Zn is released from acid-soluble fractions (e.g., adsorbed Zn, organic matter, or $Fe(OH)_3$) and available for plant uptake. Because the concentration of Zn in soil is small, rice plants

*Table 16. Zn fertilizer sources for rice.*

| Name | Formula | Content (% Zn) | Comments |
|---|---|---|---|
| Zinc sulfate | $ZnSO_4 \cdot H_2O$ | 36 | Soluble, quick-acting |
| | $ZnSO_4 \cdot 7\ H_2O$ | 23 | |
| Zinc carbonate | $ZnCO_3$ | 52–56 | Quick-acting |
| Zinc chloride | $ZnCl_2$ | 48–50 | Soluble, quick-acting |
| Zinc chelate | $Na_2Zn$-EDTA | 14 | Quick-acting |
| | $Na_2Zn$-HEDTA | 9 | Quick-acting |
| Zinc oxide | ZnO | 60–80 | Insoluble, slow-acting |

absorb most Zn following solubilization in the rhizosphere.

## Crop Zn uptake and removal

Zn removal by rice ranges between 0.04 and 0.06 kg Zn $t^{-1}$ grain yield, with an average of 0.05 (Section 5.3).

A rice crop yielding 6 t $ha^{-1}$ takes up ~0.3 kg Zn $ha^{-1}$, of which 60% remains in the straw at maturity.

If the grain *only* is removed and straw is returned to the field, Zn removal is ~0.02 kg Zn $t^{-1}$ grain yield. Burning the straw results in no significant Zn losses.

## Preventive strategies for Zn management

Preventing Zn deficiency is an integral part of general crop management. General measures to prevent Zn deficiencies are as follows:

- Varieties: Select Zn-efficient varieties that are tolerant of high $HCO_3^-$ and low plant-available Zn concentration. Early modern varieties (e.g., IR26) were prone to Zn deficiency, but new lines are now screened for tolerance for low-Zn environments and some cultivars are particularly adapted to Zn stress (e.g., IR8192-31, IR9764-45). Tolerant varieties may not respond to Zn application on soils with only slight Zn deficiency.
- Nursery: Broadcast $ZnSO_4$ in nursery seedbed.
- Crop establishment: Dip seedlings or presoak seeds in a 2–4% ZnO suspension (e.g., 20–40 g ZnO $L^{-1}$ $H_2O$).
- Fertilizer management: Use fertilizers that generate acidity (e.g., substitute ammonium sulfate for urea). Apply organic manure. Apply 5–10 kg Zn $ha^{-1}$ as Zn sulfate, Zn oxide, or Zn chloride as a prophylactic, either incorporated in the soil before seeding or transplanting, or applied to the nursery seedbed a few days before transplanting (Table 16). The effect of Zn applications can persist up to 5 years depending on the soil and cropping pattern. On alkaline soils with severe Zn deficiency, the residual effect of applied $ZnSO_4$ is small, and therefore Zn must be applied to each crop. On most other soils, blanket applications of $ZnSO_4$ should be made every 2–8 crops, but soil Zn status should be monitored to avoid accumulating toxic concentrations of Zn.
- Water management: Allow permanently inundated fields (e.g., where three crops per year are grown) to drain and dry out periodically. Monitor irrigation water quality. pH is an approximate indicator for possibly excessive $HCO_3^-$ supply:
  - pH 6.5–8.0 → good-quality water
  - pH 8.0–8.4 → marginally acceptable, but check for $HCO_3^-$
  - pH >8.4 → do not use for irrigation unless diluted with water that has pH <6.5.

ZINC

## Treatment of Zn deficiency

Zn deficiencies are most effectively corrected by soil Zn application. Surface application is more effective than soil incorporation on high pH soils. Because of its high solubility in water, Zn sulfate is the most commonly used Zn source, although ZnO is less expensive. The following measures, either separately or in combination, are effective but should be implemented immediately at the onset of symptoms:

- If Zn deficiency symptoms are observed in the field, apply 10–25 kg $ha^{-1}$ $ZnSO_4 \cdot 7 H_2O$. Uptake of $ZnSO_4$ is more efficient when broadcast over the soil surface (compared with incorporated) particularly in direct-sown rice. To facilitate more homogeneous application, mix the Zn sulfate (25%) with sand (75%).
- Apply 0.5–1.5 kg Zn $ha^{-1}$ as a foliar spray (e.g., a 0.5% $ZnSO_4$ solution at about 200 L water $ha^{-1}$) for emergency treatment of Zn deficiency in growing plants. Starting at tillering (25–30 DAT), 2–3 repeated applications at intervals of 10–14 days may be necessary. Zn chelates (e.g., Zn-EDTA) can be used for foliar application, but the cost is greater.

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# 3.5 Sulfur Deficiency

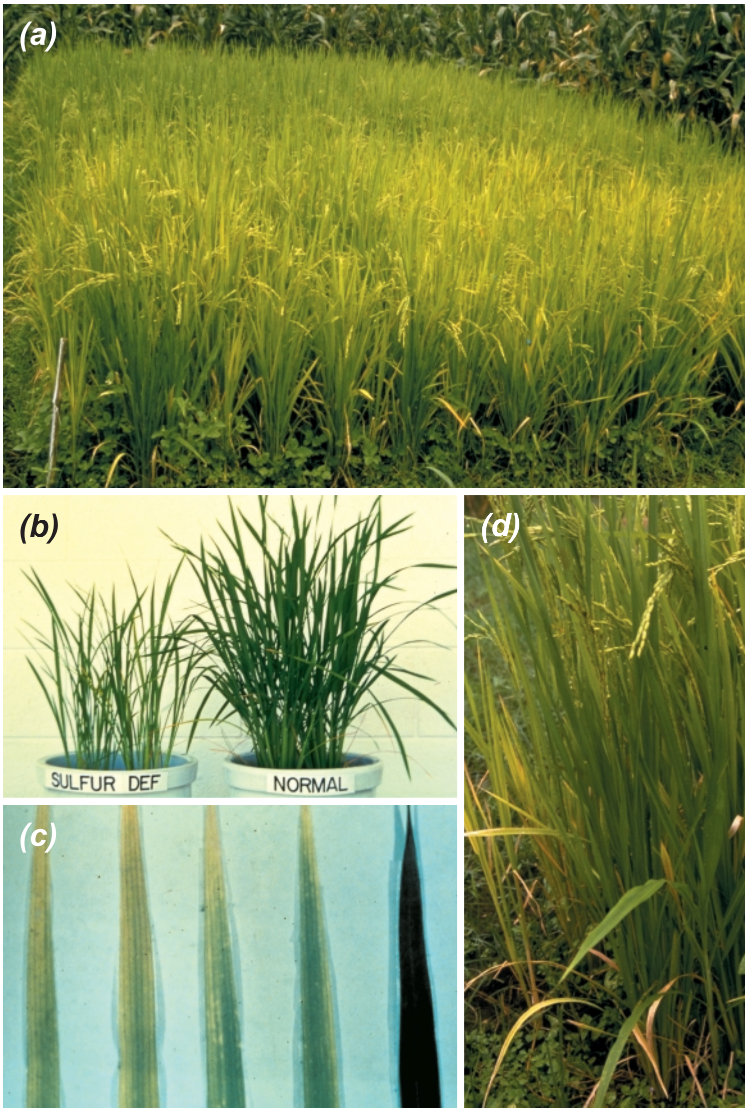
## *Function and mobility of S*

Sulfur is a constituent of essential amino acids (cysteine, methionine, and cystine) involved in chlorophyll production, and is thus required for protein synthesis and plant function and structure. It is also a constituent of coenzymes required for protein synthesis. S is contained in the plant hormones thiamine and biotine, both of which are involved in carbohydrate metabolism. S is also involved in some oxidation-reduction reactions.

It is less mobile in the plant than N so that deficiency tends to appear first on young leaves. S deficiency causes a reduction in the cysteine and methionine content in rice, and thus affects human nutrition.

## *S deficiency symptoms and effect on growth*

**Pale green plants, light green colored young leaves.**




***Sulfur deficiency symptoms in rice***

*(a), (b) The leaf canopy appears pale yellow due to yellowing of the youngest leaves, and plant height and tillering are reduced. (c), (d) Chlorosis is more pronounced in young leaves, where the leaf tips may become necrotic.*

*Table 17. Optimal ranges and critical levels of S in plant tissue.*

| Growth stage | Plant part | Optimum (%) | Critical level for deficiency (%) |
|---|---|---|---|
| Tillering | Y leaf | | <0.16 |
| Tillering | Shoot | 0.15–0.30 | <0.11 |
| Flowering | Flag leaf | 0.10–0.15 | <0.10 |
| Flowering | Shoot | | <0.07 |
| Maturity | Straw | | <0.06 |

In contrast to N deficiency (Section 3.1) where older leaves are affected first, S deficiency results in yellowing of the whole plant, and chlorosis is more pronounced in young leaves, the tips of which may become necrotic. There is, however, no necrosis of lower leaves of the type that occurs in N-deficient plants. Also, compared with N deficiency, leaves are a paler yellow in S-deficient plants.

Because the effect of S deficiency on yield is more pronounced during vegetative growth, symptoms should be detected and corrected early. S deficiency is often not properly diagnosed, as foliar symptoms are sometimes mistaken for N deficiency. Plant and soil analyses are important for the correct identification of S deficiency.

Other symptoms and effects on growth include the following:

- Reduced plant height and stunted growth (but plants are not dark-colored as in the case of P or K deficiency).
- Reduced number of tillers, fewer and shorter panicles, reduced number of spikelets per panicle.
- Plant development and maturity are delayed by 1–2 weeks.
- Seedlings in nursery beds become yellowish and growth is retarded.
- Seedling mortality after transplanting is high.
- S-deficient rice plants have less resistance to adverse conditions (e.g., cold).

## *Plant*

During vegetative growth before flowering, a shoot concentration of >0.15% S indicates that a response to applied S is unlikely.

Between tillering and flowering, <0.10% S in the shoot or an N:S ratio of >15–20 indicates S deficiency. At maturity, an S content of <0.06% or an N:S ratio of >14 in the straw (>26 in grain) may indicate S deficiency (Table 17).

## *Soil*

Soil tests for S are not reliable unless they include inorganic S as well as some of the mineralizable organic S fraction (ester sulfates).

The critical soil levels for occurrence of S deficiency are as follows:

- <5 mg S $kg^{-1}$: 0.05 M HCl,
- <6 mg S $kg^{-1}$: 0.25 M KCl heated at 40ºC for 3 hours, and
- <9 mg S $kg^{-1}$: 0.01 M $Ca(H_2PO_4)_2$.

## *Causes of S deficiency*

S deficiency can be caused by one or more of the following:

- Low available S content in the soil.
- Depletion of soil S as a result of intensive cropping.
- Use of S-free fertilizers (e.g., urea substituted for ammonium sulfate, triple superphosphate substituted for single superphosphate, and muriate of potash substituted for sulfate of potash).

SULFUR

- In many rural areas of developing countries, the amount of S deposition in precipitation is small due to low levels of industrial pollution.
- Sulfur concentrations in groundwater, however, may range widely. Irrigation water contains only small quantities of $SO_4^{2-}$.
- S contained in organic residues is lost during burning.

### Occurrence of S deficiency

Soils particularly prone to S deficiency include the following types:

- Soils containing allophane (e.g., Andisols).
- Soils with low organic matter status.
- Highly weathered soils containing large amounts of Fe oxides.
- Sandy soils, which are easily leached.

It often occurs in upland rice, but is also found in the lowland rice areas of Bangladesh, China, India, Indonesia, Myanmar, Pakistan, Philippines, Sri Lanka, and Thailand.

S deficiency is less common in rice production areas located near industrial centers where atmospheric pollution is great.

### Effect of submergence on S availability and uptake

S in soil occurs in four major forms: C-bonded S, ester sulfates, adsorbed $SO_4^{2-}$, and $SO_4^{2-}$ in soil solution. Plants acquire S in the form of $SO_4^{2-}$ from soil solution. Reduction of $SO_4^{2-}$ to elemental $S^-$, and the formation of sulfides, follow Fe reduction in flooded soils. S availability decreases as soil reduction proceeds. In neutral and alkaline soils, very high concentrations of $SO_4^{2-}$ may decrease to zero within six weeks of submergence.

The reduction of sulfate in flooded soils has three effects on rice growth, i.e.:

- S can become deficient,
- Fe, Zn, and Cu can become immobilized, and
- $H_2S$ toxicity can occur in soils containing small amounts of Fe.

### Crop S uptake and removal

S removal by rice ranges from 1 to 3 kg S $t^{-1}$ grain yield, with an average of 1.8 (Section 5.3). A rice crop yielding 6 t $ha^{-1}$ takes up ~11 kg S $ha^{-1}$, of which 40–50% remains in the straw at maturity.

If the grain *only* is removed and straw is returned to the field, S removal is ~1 kg S $t^{-1}$ grain yield. About 40–60% of the S contained in straw is lost on burning; losses are greatest when straw is burned in large heaps at very high temperatures.

### Preventive strategies for S management

On most lowland soils, S supply from natural sources or S-containing fertilizer is similar to or exceeds S removal in rice grain. The concentration of S in rainwater varies widely, and generally decreases with increasing distance from the ocean or from industrialized areas. In Asia, the annual S deposition in rainfall ranges from 2 to 50 kg S $ha^{-1}$. Irrigation water typically provides 10–30 kg S $ha^{-1}$ per crop in the form of sulfates.

S deficiency is easily corrected or prevented by using S-containing fertilizers (Table 18). General measures to prevent S deficiency are as follows:

- Natural inputs: Estimate the requirement for S input from the atmosphere.
- Nursery: Apply S to the seedbed (rice nursery) by using S-containing fertilizers (ammonium sulfate, single superphosphate).
- Fertilizer management: Replenish S removed in crop parts by applying N and P fertilizers that contain S (e.g., ammonium sulfate [24% S], single superphosphate [12% S]). This can be done at irregular intervals. Calculate the

*Table 18. S fertilizer sources for rice.*

| Name | Formula | Content | Comments |
|---|---|---|---|
| Ammonium sulfate | $(NH_4)_2SO_4$ | 24% S | Quick-acting |
| Single superphosphate | $Ca(H_2PO_4)_2 \cdot H_2O$ + $CaSO_4 \cdot 2\ H_2O$ | 12% S, 7–9 % P, 13–20% Ca | Soluble, quick-acting |
| Potassium sulfate | $K_2SO_4$ | 18% S | Quick-acting |
| Magnesium sulfate (Epsom salt) | $MgSO_4 \cdot 7\ H_20$ | 13% S ,10% Mg | Very quick-acting |
| Kieserite | $MgSO_4 \cdot H_20$ | 23% S, 17% Mg | Quick-acting |
| Langbeinite | $K_2SO_4 \cdot MgSO_4$ | 18% K, 11% Mg, 22% S | Quick-acting |
| Gypsum | $CaSO_4 \cdot 2\ H_2O$ | 17% S | Slow-acting |
| Elemental S | S | 97% S | Slow-acting |
| S-coated urea | $CO(NH_2)_2$ + S | 6–30% S, 30–40% N | Slow-acting |

cost-effectiveness of S supplied as S-coated urea or compound fertilizers containing S.

- Straw management: Incorporate straw instead of completely removing or burning it. About 40–60% of the S contained in straw is lost on burning.
- Soil management: Improve soil management to enhance S uptake, as follows:
  - maintain sufficient percolation (~5 mm per day), to avoid excessive soil reduction, or
  - carry out dry tillage after harvesting, to increase the rate of sulfide oxidation during the fallow period.

## *Treatment of S deficiency*

The requirement for S fertilizer and manure inputs depends on soil S status and S inputs from other sources, such as irrigation and the atmosphere. If S deficiency is identified during early growth, the response to S fertilizer is rapid, and recovery from S deficiency symptoms can occur within five days of S fertilizer application.

S deficiency should be treated as follows:

- Where soil S status is high and the water contains large amounts of S (i.e., near industrial and urban centers), no additional S input is required. Emphasis should be given to the preventive measures described earlier.
- Where moderate S deficiency is observed, apply 10 kg S $ha^{-1}$.
- On soils with severe S deficiency (e.g., parts of China, India, Indonesia, and Bangladesh), an application of 20–40 kg S $ha^{-1}$ is sufficient for large yields.
- Applying 15–20 kg S $ha^{-1}$ gives a residual effect that can supply the S needed for two subsequent rice crops.
- Usually, S is added as a constituent of fertilizers applied to correct other nutrient deficiencies. Water-soluble S forms such as kieserite and langbeinite are the most efficient fertilizers for treating S deficiency in growing crops. Use slow-acting S forms (gypsum, elemental S) if leaching is likely to be a problem.

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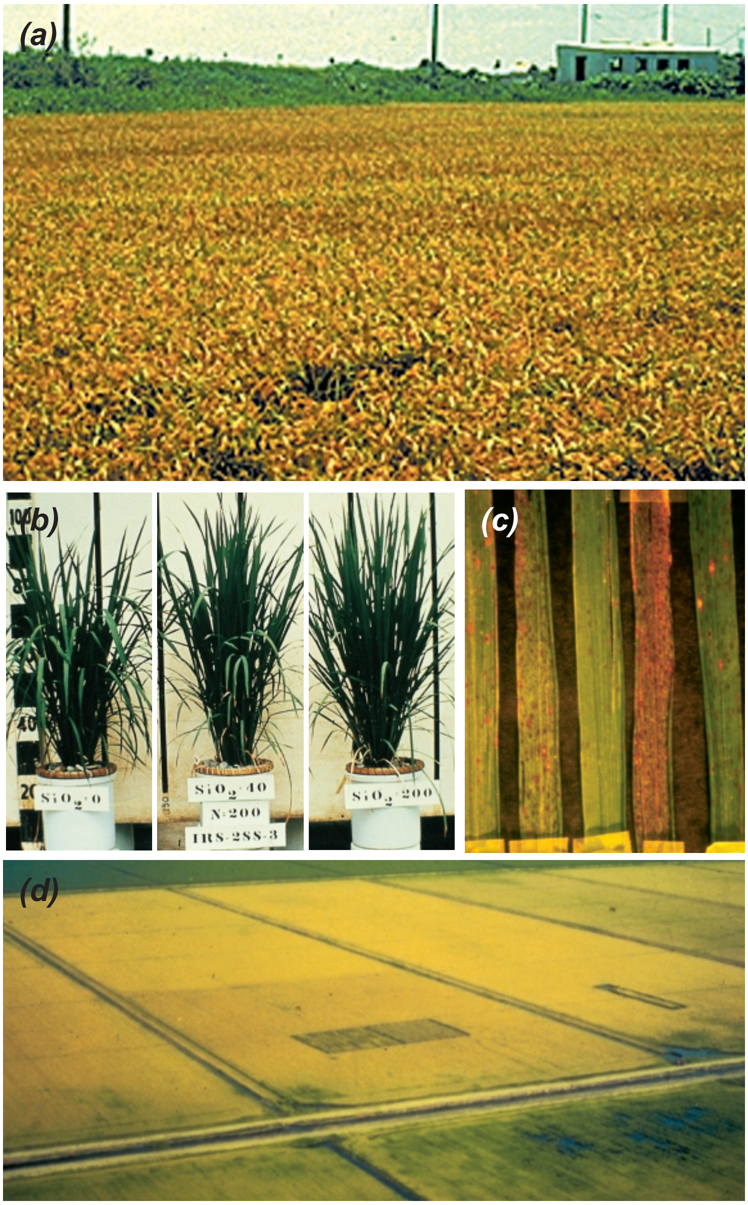
# 3.6 Silicon Deficiency

## *Function and mobility of Si*

Silicon is a ‘beneficial’ nutrient for rice but its physiological functions are not clearly understood. It is required for the development of strong leaves, stems, and roots. The formation of a thick silicated epidermal cell layer reduces the rice plant’s susceptibility to fungal and bacterial diseases, and insect (stem borers, planthoppers) and mite pests. Rice plants adequately supplied with Si have erect leaves and growth habit. This contributes to efficient light use, and thus high N use efficiency.




***Silicon deficiency symptoms in rice***

*(a) Si deficiency often results in decreased resistance to diseases such as* Bipolaris oryzae. *(b) Droopy leaves on Si-deficient rice plant (left), compared with normal rice plant (right). (c) Si deficiency is characterized by brown spots on leaves. (d) On organic soils in Florida, rice plants treated with Si amendments were more resistant to* Bipolaris oryzae *and* Pyricularia grisea *(lighter colored fields), compared with untreated fields (darker colored fields) (© Elsevier Science).*

*Table 19. Optimal ranges and critical levels of Si in plant tissue.*

| Growth stage | Plant part | Optimum (%) | Critical level for deficiency (%) |
|---|---|---|---|
| Tillering to panicle initiation | Y leaf | | <5 |
| Maturity | Straw | 8–10 | <5 |

Water-use efficiency is reduced in Si-deficient plants due to increased transpiration losses. Si increases P availability in soil, increases the oxidation power of roots, and alleviates Fe and Mn toxicity by reducing the uptake of these elements.

## Si deficiency symptoms and effects on growth

### Soft, droopy leaves and culms.

Leaves become soft and droopy; this increases mutual shading, which reduces photosynthetic activity and results in smaller grain yields. Increased occurrence of diseases such as blast (caused by *Pyricularia oryzae*) or brown spot (caused by *Helminthosporium oryzae*) may indicate Si deficiency. N fertilizer tends to produce droopy and flaccid leaves, whereas Si helps to keep leaves erect. Severe Si deficiency reduces the number of panicles per $m^2$ and the number of filled spikelets per panicle. Si-deficient plants are particularly susceptible to lodging.

## Soil

The critical soil concentration for occurrence of Si deficiency is 40 mg Si $kg^{-1}$ (1 M sodium acetate buffered at pH 4).

## Causes of Si deficiency

Si deficiency can be caused by one or more of the following:

- Low Si-supplying power because the soil is very old and strongly weathered.
- Parent material contains small amounts of Si.
- Removal of rice straw over long periods of intensive cropping results in the depletion of available soil Si.

## Occurrence of Si deficiency

Low Si content in rice plants (Table 19) indicates poor soil fertility (Si is very susceptible to leaching). Soils containing a small amount of Si are usually depleted of other nutrients, and *vice versa*. Si status is an indicator of general plant nutrient status, except in volcanic soils which often contain a large concentration of Si but small amounts of P, Ca, and Mg. Si deficiency is not yet common in the intensive irrigated rice systems of tropical Asia. Because application of Si is not common, however, and large amounts of straw are removed, Si balances are often negative (-150 to -350 kg Si $ha^{-1}$ per crop) and Si deficiency may become more widespread in these systems in the future.

Soils particularly prone to Si deficiency include the following types:

- Old, degraded paddy soils in temperate (e.g., Japan, Korea) or subtropical (e.g., North Vietnam) climates.
- Organic soils with small mineral Si reserves (e.g., peat soils in Florida, USA; Indonesia; and the Madagascar highlands).
- Highly weathered and leached tropical soils in the rainfed lowland and upland areas (e.g., northeast Thailand).

## Effect of submergence on Si availability and uptake

The concentration of plant available Si increases at submergence, particularly in soils containing a large amount of organic matter. The increase in Si availability is associated with the presence of reduced amorphous Al and $Fe^{3+}$ hydroxides in soils following flooding.

*Table 20. Si fertilizer sources for rice.*

| Name | Formula | Content | Comments |
|---|---|---|---|
| Blast furnace slag | $CaSiO_3$, $MgSiO_3$ | 14–19% Si, 25–32% Ca, 2–4% Mg | |
| Convertor slag | $CaSiO_3$, $MgSiO_3$ | 4–10% Si, 26–46% Ca, 0.5–9% Mg | |
| Silico-manganese slag | $CaSiO_3$, $MnSiO_3$ | 16–21% Si, 21–25% Ca, 0.5–2% Mn | |
| Fused magnesium phosphate | | 9% Si, 9% P, 7–9% Mg | Granular |
| Calcium silicate | Si, Ca, Mg | 14–19% Si, 1–4% Mg | Granular, slow-release fertilizer |
| Potassium silicate | K, Si | 14% Si, 17% K, 2.5% Mg | Granular, slow-release fertilizer |

## Crop Si uptake and removal

Silicon content in rice straw varies widely (2–10%), but is usually between 5 and 6 percent. Si removal by rice is in the range 50–110 kg Si $t^{-1}$ grain yield. Assuming an average removal of 80 kg Si $t^{-1}$ grain yield (Section 5.3), a rice crop yielding 6 t $ha^{-1}$ takes up ~480 kg Si $ha^{-1}$, of which 80% remains in the straw at maturity.

If the grain *only* is removed and straw is returned to the field, Si removal is ~15 kg Si $t^{-1}$ grain yield. Burning the straw does not result in significant Si losses, except when straw is burned in large heaps and Si is leached from the ash (due to irrigation or heavy rains).

## Preventive strategies for Si management

General measures to prevent Si deficiency are as follows:

- Natural inputs: Substantial input of Si from irrigation water occurs in some areas, particularly if groundwater from landscapes with volcanic geology is used for irrigation. Assuming average concentrations of 3–8 mg Si $L^{-1}$ and ~1,000 mm water $crop^{-1}$, the Si input in the irrigation water is 30–80 kg $ha^{-1}$ per crop.
- Straw management: In the long term, Si deficiency is prevented by not removing the straw from the field following harvest. Recycle rice straw (5–6% Si) and rice husks (10% Si).
- Fertilizer management: Avoid applying excessive and unbalanced amounts of N fertilizer, which increases yield and total uptake of N and Si but also decreases the Si concentration in straw (because of excessive biomass growth).
- Postharvest measures: If rice hulls or rice hull ash are available, recycle them to reduce the amount of Si removed from the soil.

## Treatment of Si deficiency

Apply calcium silicate slags regularly to degraded paddy soils or peat soils, at a rate of 1–3 t $ha^{-1}$.

Apply granular silicate fertilizers for more rapid correction of Si deficiency:

- Calcium silicate: 120–200 kg $ha^{-1}$
- Potassium silicate: 40–60 kg $ha^{-1}$

Calcium silicate fertilizers are prepared from various kinds of slags, which are by-products of the iron and alloy industries (Table 20).

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# 3.7 Magnesium Deficiency

## Function and mobility of Mg

Magnesium activates several enzymes. It is a constituent of chlorophyll, and thus is involved in $CO_2$ assimilation and protein synthesis. Mg also regulates cellular pH and cation-anion balance. Mg is very mobile and is retranslocated readily from old leaves to young leaves. Deficiency symptoms therefore tend to occur initially in older leaves.

## Mg deficiency symptoms and effects on growth

### Orange-yellow interveinal chlorosis on older leaves.

Mg-deficient plants are pale-colored, with interveinal chlorosis first appearing on older leaves, and later on younger leaves as deficiency becomes more severe. Green coloring appears as a 'string of beads', compared with K deficiency where green and yellow stripes run parallel to the leaf (Section 3.3). In severe cases, chlorosis progresses to yellowing and finally necrosis in older leaves. Leaf number and leaf length are greater in Mg-deficient plants (Table 21), and Mg-deficient leaves are wavy and droopy due to an expansion in the angle between the leaf sheath and leaf blade.

Other symptoms and effects of Mg deficiency are as follows:

- With moderate deficiency, plant height and tiller number are not affected greatly.
- Reduced number of spikelets and reduced 1,000-grain weight.
- May reduce grain quality (% milled rice, protein and starch content).
- Fe toxicity may be more pronounced where Mg is part of multiple nutrient deficiency stress involving K, P, Ca, and Mg.

## Plant

A Ca:Mg ratio of 1–1.5:1 in rice shoots between tillering and panicle initiation is considered optimal.

## Soil

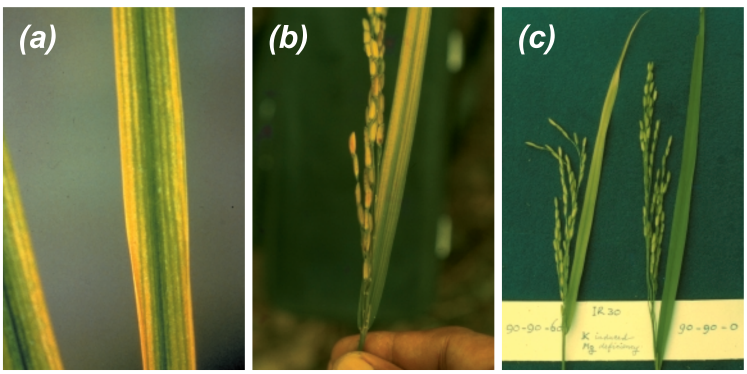
A concentration of <1 $cmol_c$ Mg $kg^{-1}$ soil indicates very low soil Mg status. Concentrations of >3 $cmol_c$ Mg $kg^{-1}$ are generally sufficient for rice.

For optimum growth, the ratio of exchangeable Ca:Mg should be 3–4:1 for soil forms and not exceed 1:1 in the soil solution.

## Causes of Mg deficiency

Mg deficiency can be caused by either of the following:

- Low available soil Mg.
- Decreased Mg uptake due to a wide ratio of exchangeable K:Mg (i.e., >1:1).




***Magnesium deficiency symptoms in rice***

*(a) Orange-yellow interveinal chlorosis usually appears first on older leaves. (b) Chlorosis may also appear on the flag leaf. (c) Mg deficiency may also be induced by large applications of K fertilizer on low Mg status soils.*

*Table 21. Optimal ranges and critical levels of Mg in plant tissue.*

| Growth stage | Plant part | Optimum (%) | Critical level for deficiency (%) |
|---|---|---|---|
| Tillering to panicle initiation | Y leaf | 0.15–0.30 | <0.12 |
| Tillering to panicle initiation | Shoot | 0.15–0.30 | <0.13 |
| Maturity | Straw | 0.20–0.30 | <0.10 |

## Occurrence of Mg deficiency

Mg deficiency is not frequently observed in the field because adequate amounts are usually supplied in irrigation water. Mg deficiency is more common in rainfed lowland and upland rice, where soil Mg has been depleted as a result of the continuous removal of Mg in crop products without the recycling of crop residues or replacement of Mg with mineral fertilizer. Many rainfed rice soils (e.g., in northeast Thailand) are inherently deficient in Mg.

Soils particularly prone to Mg deficiency include the following types:

- Acid, low-CEC soils in uplands and lowlands (e.g., degraded soils in North Vietnam, and coarse-textured, highly weathered acid soils in northeast Thailand, Lao PDR, and Cambodia).
- Coarse-textured sandy soils with high percolation rates and leaching losses.
- Leached, old acid sulfate soils with low base content (e.g., in Thailand).

## Effect of submergence on Mg availability and uptake

Although Mg is not directly involved in redox reactions in soils, the concentration of Mg in the soil solution tends to increase after flooding. This is usually attributed to displacement of exchangeable $Mg^{2+}$ by $Fe^{2+}$ produced by reduction of $Fe^{3+}$ compounds. The diffusive flux of $Mg^{2+}$ increases with increasing solution Mg concentration and soil moisture content. Therefore, diffusion of $Mg^{2+}$ in bulk soil to rice roots increases under irrigated conditions compared with rainfed lowland or upland rice.

## Crop Mg uptake and removal

Mg removal by rice is in the range 3–5 kg Mg $t^{-1}$ grain yield, with an average of 3.5 (Section 5.3). A rice crop yielding 6 t $ha^{-1}$ takes up ~21 kg Mg $ha^{-1}$, of which 60% remains in the straw at maturity.

If the grain *only* is removed and straw is returned to the field, Mg removal is ~1.5 kg Mg $t^{-1}$ grain yield. Burning the straw does not result in significant Mg losses, except when straw is burned in large heaps and Mg is leached from the ash (due to irrigation or heavy rains).

## Preventive strategies for Mg management

General measures to prevent Mg deficiency are as follows:

- Crop management: Apply sufficient amounts of Mg fertilizer, farmyard manure, or other materials to balance removal in crop products and straw.
- Water management: Minimize percolation rates (leaching losses) on coarse-textured soils, by compacting the subsoil during land preparation.
- Soil management: Minimize losses due to erosion and surface runoff in upland systems by taking appropriate soil conservation measures.

## Treatment of Mg deficiency

Mg deficiency should be treated as follows:

- Apply Mg-containing fertilizers (Table 22). Rapid correction of Mg deficiency symptoms is achieved by applying a soluble Mg source such as kieserite, langbeinite, or Mg chloride.

*Table 22. Mg fertilizer sources for rice.*

| Name | Formula | Content | Comments |
|---|---|---|---|
| Kieserite | $MgSO_4 \cdot H_2O$ | 17% Mg, 23% S | Soluble, quick-acting |
| Langbeinite | $K_2SO_4 \cdot MgSO_4$ | 18% K, 11% Mg, 22% S | Quick-acting |
| Magnesium chloride | $MgCl_2$ | 9% Mg | Soluble, quick-acting |
| Magnesia (Mg oxide) | MgO | 55–60% Mg | Slow-acting, for foliar application |
| Magnesite | $MgCO_3$ | 25–28% Mg | Slow-acting |
| Dolomite | $MgCO_3 + CaCO_3$ | 13% Mg, 21% Ca | Slow-acting, content of Ca and Mg varying |

- Foliar application of liquid fertilizers containing Mg (e.g., $MgCl_2$).
- On acid upland soils, apply dolomite or other slow-acting Mg sources to supply Mg and increase soil pH (to alleviate Al toxicity, Section 4.5).

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# 3.8 Calcium Deficiency

## *Function and mobility of Ca*

Calcium is a constituent of Ca pectates, which are important cell wall constituents that are also involved in biomembrane maintenance. Ca is important for maintaining cell wall integrity, is an enzyme activator, and is required for osmoregulation and the maintenance of cation-anion balance in cells.

Ca is less mobile than Mg and K in rice plants. Because Ca is not retranslocated to new growth, deficiency symptoms usually appear first on young leaves. Ca deficiency also results in impaired root function, and may predispose the rice plant to Fe toxicity (Section 4.1).

An adequate supply of Ca increases resistance to diseases such as bacterial leaf blight (caused by *Xanthomonas oryzae*) or brown spot (caused by *Helminthosporium oryzae*). The rate of Ca uptake is proportional to the rate of biomass production.

## *Ca deficiency symptoms and effects on growth*

### Chlorotic-necrotic split or rolled tips of younger leaves.

Symptoms are usually visible only under severe Ca deficiency (e.g., in pot experiments and soil exhaustion experiments). The tips of the youngest leaves become white (bleached), rolled, and curled. Necrotic tissue may develop along the lateral margins of leaves, and old leaves eventually turn brown and die. Ca deficiency may resemble B deficiency (Section 3.12), and therefore plant tissue analysis may be required to distinguish the cause of symptoms.

There is little change in the general appearance of the plant except in cases of acute Ca deficiency (Table 23). Extreme deficiency results in stunting and death of the growing point.

## *Plant*

A Ca:Mg ratio of 1–1.5:1 in rice shoots at tillering to panicle initiation stages is considered optimal. White leaf tips may occur when Ca:Mg is <1.

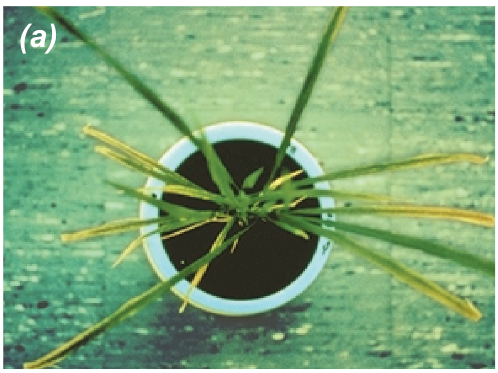
## *Soil*

Ca deficiency is likely when soil exchangeable Ca is <1 $cmol_c\ kg^{-1}$, or when the Ca saturation is <8% of the CEC. For optimum growth, Ca saturation of the CEC should be >20%.

For optimum growth, the ratio of Ca:Mg should be >3–4:1 for exchangeable soil forms and 1:1 in soil solution.

## *Causes of Ca deficiency*

Ca deficiency can be caused by one or more of the following:





***Calcium deficiency symptoms in rice***

*(a), (b) Symptoms only occur under severe Ca deficiency, when the tips of the youngest leaves may become chlorotic-white.*

*Table 23. Optimal ranges and critical levels of Ca in plant tissue.*

| Growth stage | Plant part | Optimum (%) | Critical level for deficiency (%) |
|---|---|---|---|
| Tillering to panicle initiation | Y leaf | 0.2–0.6 | <0.15 |
| Maturity | Straw | 0.3–0.5 | <0.15 |

- Small amounts of available Ca in soil (degraded, acid, sandy soils).
- Alkaline pH with a wide exchangeable Na:Ca ratio resulting in reduced Ca uptake. Use of irrigation water containing large amounts of $NaHCO_3$.
- Wide soil Fe:Ca or Mg:Ca ratios, resulting in reduced Ca uptake. Long-term irrigated rice cultivation may lead to higher Mg:Ca and Fe:Ca ratios.
- Excessive N or K fertilizer application, resulting in wide $NH_4$:Ca or K:Ca ratios and reduced Ca uptake.
- Excessive P fertilizer application, which may depress the availability of Ca (due to formation of Ca phosphates in alkaline soils).

## Occurrence of Ca deficiency

Ca deficiency is very uncommon in lowland rice soils because there is usually sufficient Ca in the soil, from mineral fertilizer applications and irrigation water.

Soils particularly prone to Ca deficiency include the following types:

- Acid, strongly leached, low-CEC soils in uplands and lowlands.
- Soils derived from serpentine rocks.
- Coarse-textured sandy soils with high percolation rates and leaching.
- Leached, old acid sulfate soils with low base content.

## Effect of submergence on Ca availability and uptake

Although Ca is not directly involved in redox reactions in soils, the concentration of Ca in the soil solution tends to increase after flooding. This is usually attributed to displacement of exchangeable $Ca^{2+}$ by $Fe^{2+}$ produced by reduction of $Fe^{3+}$ compounds. The diffusive flux of $Ca^{2+}$ increases with increasing solution Ca concentration and soil moisture content. Therefore, diffusion of $Ca^{2+}$ in bulk soil to rice roots increases under irrigated conditions compared with rainfed lowland or upland rice.

## Crop Ca uptake and removal

Ca removal by rice is in the range 3–6 kg Ca $t^{-1}$ grain yield, with an average of 4 (Section 5.3). A rice crop yielding 6 t $ha^{-1}$ takes up ~24 kg Ca $ha^{-1}$, of which >80% remains in the straw at maturity.

If the grain *only* is removed and straw is returned to the field, Ca removal is ~0.5 kg Ca $t^{-1}$ grain yield. Burning the straw does not result in significant Ca losses, except when straw is burned in large heaps and Ca is leached from the ash (due to irrigation or heavy rainfall).

## Preventive strategies for Ca management

General measures to prevent Ca deficiency are as follows:

- Crop management: Apply farmyard manure or straw (incorporated or burned) to balance Ca removal in soils containing small concentrations of Ca.
- Fertilizer management: Use single superphosphate (13–20% Ca) or triple superphosphate (9–14% Ca) as a Ca source (Table 24).

## Treatment of Ca deficiency

Ca deficiency should be treated as follows:

- Apply $CaCl_2$ (solid or in solution) or Ca-containing foliar sprays for rapid treatment of severe Ca deficiency.

CALCIUM

*Table 24. Ca fertilizer sources for rice.*

| Name | Formula | Content | Comments |
|---|---|---|---|
| Calcium chloride | $CaCl_2 \cdot 6\ H_2O$ | 18% Ca | Soluble, quick-acting, does not raise pH |
| Gypsum | $CaSO_4 \cdot 2\ H_2O$ | 23% Ca, 18% S | Slightly soluble, slow-acting, for saline and alkaline soils |
| Dolomite | $MgCO_3 + CaCO_3$ | 13% Mg, 21% Ca | Slow-acting, content of Ca and Mg varying |
| Lime | $CaCO_3$ | 40% Ca | Slow-acting, for acid soils |

- Apply gypsum on Ca-deficient high pH soils, e.g., on sodic and high-K soils.
- Apply lime on acid soils to increase pH and Ca availability.
- Apply Mg or K in conjunction with Ca, because Ca may induce deficiency of these nutrients.
- Apply pyrites to mitigate the inhibitory effects of $NaHCO_3$-rich water on Ca uptake.

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# 3.9 Iron Deficiency

## Function and mobility of Fe

Iron is required for electron transport in photosynthesis and is a constituent of iron porphyrins and ferredoxins, both of which are essential components in the light phase of photosynthesis. Fe is an important electron acceptor in redox reactions and an activator for several enzymes (e.g., catalase, succinic dehydrogenase, and aconitase). Fe deficiency may inhibit K absorption. On alkaline soils, Fe is immobilized in the roots by precipitation. Because Fe is not mobile within rice plants, young leaves are affected first.

## Fe deficiency symptoms and effects on growth

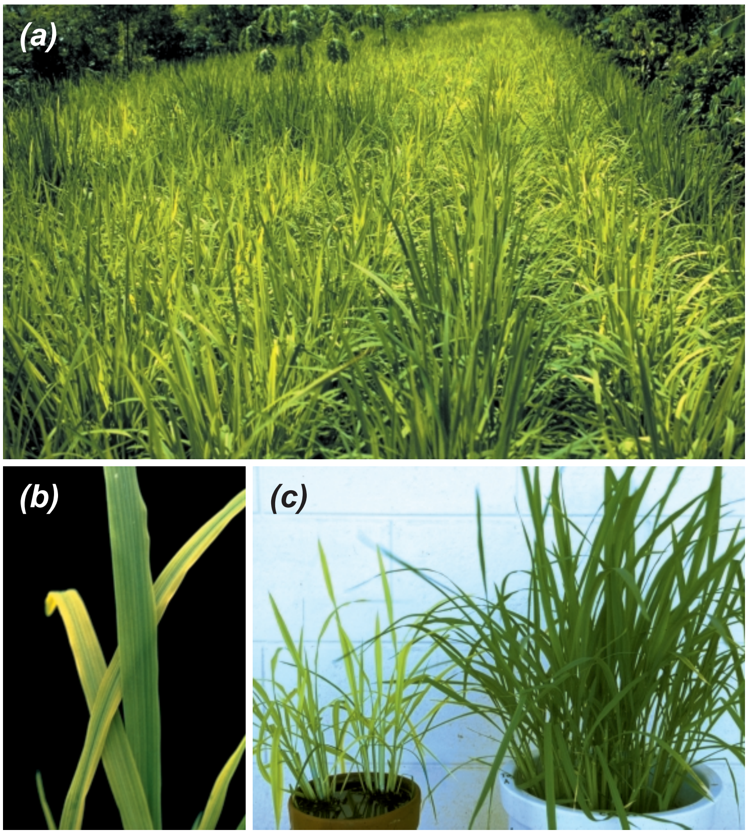
**Interveinal yellowing and chlorosis of emerging leaves.**

Whole leaves become chlorotic and very pale. The entire plant becomes chlorotic and dies if Fe deficiency is very severe. Fe deficiency is very important on dryland soils but often disappears one month after planting. Fe deficiency results in decreased dry matter production, reduced chlorophyll concentration in leaves, and reduced activity of enzymes involved in sugar metabolism.

## Plant

Active Fe content may be more useful than total Fe content (Table 25) as an indicator of Fe nutritional status in leaves. The critical limit for active ferrous Fe at 40 DAT is 45 mg $kg^{-1}$ leaf tissue.

Critical Fe deficiency contents are much larger in fast-growing merismatic and expanding tissues (e.g., shoot apices), with ~200 mg Fe




***Iron deficiency symptoms in rice***

*(a) Fe deficiency is mainly a problem on upland soils. (b) Symptoms appear as interveinal yellowing of emerging leaves. (c) Under conditions of severe Fe deficiency, plants are stunted and have narrow leaves (left).*

*Table 25. Optimal ranges and critical levels of Fe in plant tissue.*

| Growth stage | Plant part | Optimum ($mg\ kg^{-1}$) | Critical level for deficiency ($mg\ kg^{-1}$) |
|---|---|---|---|
| Tillering to panicle initiation | Y leaf | 75–150 | <70 |
| Tillering to panicle initiation | Shoot | 60–100 | <50 |

$kg^{-1}$ for total Fe and 60–80 mg Fe $kg^{-1}$ for active Fe.

## Soil

Fe deficiency is likely when soil Fe concentration is either

- <2 mg Fe $kg^{-1}$: $NH_4$-acetate, pH 4.8, or
- <4–5 mg Fe $kg^{-1}$: DTPA-$CaCl_2$, pH 7.3.

## Causes of Fe deficiency

Fe deficiency can be caused by one or more of the following:

- Low concentration of soluble $Fe^{2+}$ in upland soils.
- Insufficient soil reduction under submerged conditions (e.g., low organic matter status soils).
- High pH of alkaline or calcareous soils following submergence (i.e., decreased solubility and uptake of Fe due to large bicarbonate concentrations).
- Wide P:Fe ratio in the soil (i.e., Fe bound in Fe phosphates, possibly due to excessive application of P fertilizer).
- Excessive concentrations of Mn, Cu, Zn, Mo, Ni, and Al in soil.
- Cultivars with low potential for excretion of organic acids to solubilize Fe (in upland soils only).
- Increased rhizosphere pH after the application of large amounts of $NO_3$-N fertilizer (in upland crops only).

## Occurrence of Fe deficiency

Fe deficiency does not occur widely in flooded lowland soils. It is more common in high-pH aerobic upland soils.

Soils particularly prone to Fe deficiency include the following types:

- Neutral, calcareous and alkaline upland soils.
- Alkaline and calcareous lowland soils with low organic matter status.
- Lowland soils irrigated with alkaline irrigation water.
- Coarse-textured soils derived from granite.

## Effect of submergence on Fe availability and uptake

Fe availability increases after flooding. Solubility of Fe increases when $Fe^{3+}$ is reduced to the more soluble $Fe^{2+}$ during organic matter decomposition. In flooded soils, Fe deficiency may occur when there is insufficient organic matter decomposition to drive the reduction of $Fe^{3+}$ to $Fe^{2+}$. The amount of $Fe^{2+}$ produced and the rate of reduction also depend on the amount of active Fe and soil temperature. In flooded soils, Fe may become deficient if the redox potential (Eh) remains high (i.e., >200 mV) at pH 7 after flooding, due to the presence of reducible Mn and active Fe. In such cases, total Fe may be large but Fe concentration in the soil solution remains small. Under these circumstances, Fe and P deficiency may result from the adsorption of P by Fe. Rice roots control the absorption of Fe by exclusion (i.e., the oxidation of $Fe^{2+}$ to $Fe^{3+}$ in the rhizosphere because of the secretion of $O_2$). In low-Fe soils, the oxidation of $Fe^{2+}$ in the rhizosphere may lead to poor Fe absorption capacity, and this makes rice more susceptible to Fe chlorosis than other crops.

*Table 26. Fe fertilizer sources for rice.*

| Name | Formula | Content (% Fe) | Comments |
|---|---|---|---|
| Ferrous sulfate | $FeSO_4 \cdot H_2O$ | 33 | Quick-acting, soluble |
| | $FeSO_4 \cdot 7\ H_2O$ | 20 | |
| Ferrous ammonium sulfate | $(NH_4)_2SO_4 \cdot FeSO_4 \cdot 6\ H_2O$ | 14 | Quick-acting, soluble |
| Fe chelate | NaFeDTPA | 10 | Quick-acting |
| Fe chelate | NaFeEDTA | 5–14 | Quick-acting |
| Fe chelate | NaFeEDDHA | 6 | More stable in neutral soils |

## Crop Fe uptake and removal

Fe removal by rice is in the range of 0.2–0.8 kg Fe $t^{-1}$ grain yield, with an average of 0.5 (Section 5.3). A rice crop yielding 6 t $ha^{-1}$ takes up ~3 kg Fe $ha^{-1}$, of which 40–50% remains in the straw at maturity.

If the grain *only* is removed and straw is returned to the field, Fe removal is ~0.2 kg Fe $t^{-1}$ grain yield. Burning the straw does not cause significant Fe losses.

## Preventive strategies for Fe management

General measures to prevent Fe deficiency are as follows:

- Varieties: Screen and breed for tolerance for low soil Fe availability. Grow Fe-efficient cultivars. Selection of high-Fe rice cultivars is in progress to improve Fe nutrition in children and pregnant women in developing countries.
- Soil management: Apply organic matter (e.g., crop residues, manure). Apply waste materials from mining and other industrial operations (provided that they do not contain toxic concentrations of pollutants).
- Fertilizer management: Use acidifying fertilizers (e.g., ammonium sulfate instead of urea) on high-pH soils. Use fertilizers containing Fe as a trace element (Table 26).

## Treatment of Fe deficiency

Fe deficiency is the most difficult and costly micronutrient deficiency to correct. Soil applications of inorganic Fe sources are often ineffective in controlling Fe deficiency, except when application rates are large.

Fe deficiency should be treated as follows:

- Apply solid $FeSO_4$ (~30 kg Fe $ha^{-1}$) next to rice rows, or broadcast (larger application rate required).
- Foliar applications of $FeSO_4$ (2–3% solution) or Fe chelates. Because of low Fe mobility in the plant, 2–3 applications at 2-week intervals (starting at tillering) are necessary to support new plant growth.

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# 3.10 Manganese Deficiency

## Function and mobility of Mn

Manganese is involved in oxidation-reduction reactions in the electron transport system, and $O_2$ evolution in photosynthesis. Mn also activates certain source enzymes (e.g., oxidase, peroxidase, dehydrogenase, decarboxylase, kinase). Mn is required for the following processes:

- Formation and stability of chloroplasts.
- Protein synthesis.
- $NO_3^-$ reduction.
- TCA (tricarboxylic acid) cycle.

$Mn^{2+}$ catalyzes the formation of phosphatidic acid in phospholipid synthesis for cell membrane construction. Mn mitigates against Fe toxicity. Mn is required to maintain a low $O_2$ supply in the photosynthetic apparatus. Mn accumulates in roots before it moves to aboveground shoots. There is some translocation of Mn from old to young leaves.

## Mn deficiency symptoms and effects on growth

### Interveinal chlorosis starting at the tip of younger leaves.

Pale grayish green interveinal chlorosis spreads from the tip of the leaf to the leaf base. Necrotic brown spots develop later, and the leaf becomes dark brown. Newly emerging leaves are short, narrow, and light green. At tillering, deficient plants are shorter, have fewer leaves, weigh less, and have a smaller root system than plants supplied with sufficient Mn. Plants are stunted but tillering is not affected. Affected plants are more susceptible to brown


***Manganese deficiency symptoms in rice***

*(a) Deficiency is mainly a problem in rice grown in upland and organic soils with low Mn status.*
*(b), (c) Leaves are affected by interveinal chlorosis that appears at the tip of younger leaves.*

*Table 27. Optimal ranges and critical levels of Mn in plant tissue.*

| Growth stage | Plant part | Optimum (mg $kg^{-1}$) | Critical level for deficiency (mg $kg^{-1}$) |
|---|---|---|---|
| Tillering to panicle initiation | Y leaf | 40–700 | <40 |
| Tillering | Shoot | 50–150 | <20 |

spot (caused by *Helminthosporium oryzae*). Mn-deficient rice plants (Table 27) are often deficient in P. In soils where both Mn deficiency and Fe toxicity occur, Mn-deficient rice plants contain a large concentration of Fe, and may also show symptoms of bronzing (Section 4.1).

## Plant

An Fe:Mn ratio >2.5:1 in the shoot during early growth (tillering) indicates Mn deficiency.

## Soil

The critical soil levels for occurrence of Mn deficiency are as follows:

- 1 mg Mn $kg^{-1}$, TPA + $CaCl_2$, pH 7.3.
- 12 mg Mn $kg^{-1}$, 1N $NH_4$-acetate + 0.2% hydroquinone, pH 7.
- 15–20 mg Mn $kg^{-1}$, 0.1N $H_3PO_4$ + 3N $NH_4H_2PO_4$.

The application of Mn is unnecessary in soils with >40 mg $kg^{-1}$ 0.1 M HCl extractable Mn. The optimum concentration of Mn in soil solution is in the range of 3–30 mg $L^{-1}$.

## Causes of Mn deficiency

Mn deficiency can be caused by one or more of the following factors:

- Small available Mn content in soil.
- Fe-induced Mn deficiency, due to a large concentration of Fe in soil. Increased Fe absorption reduces Mn uptake in rice plants, resulting in a wide Fe:Mn ratio.
- Reduced Mn uptake because of large concentrations of $Ca^{2+}$, $Mg^{2+}$, $Zn^{2+}$, or $NH_4^+$ in soil solution.
- Excessive liming of acid soils, resulting in an increase in the amount of Mn complexed by organic matter or adsorbed and occluded by Fe and Al hydroxides and oxides.
- Reduced Mn uptake, due to hydrogen sulfide accumulation.

## Occurrence of Mn deficiency

Mn deficiency occurs frequently in upland rice, and is uncommon in rainfed or lowland rice because the solubility of Mn increases under submerged conditions.

Soils particularly prone to Mn deficiency include the following types:

- Acid upland soils (Ultisols, Oxisols).
- Alkaline and calcareous soils with low organic matter status and small amounts of reducible Mn.
- Degraded paddy soils containing large amounts of active Fe.
- Leached, sandy soils containing small amounts of Mn.
- Leached, old acid sulfate soils with low base content.
- Alkaline and calcareous organic soils (Histosols).
- Highly weathered soils with low total Mn content.

## Effect of submergence on Mn availability and uptake

Mn availability increases with flooding as $Mn^{4+}$ is reduced to the more plant-available $Mn^{2+}$.

## Crop Mn uptake and removal

Compared with other crops, rice takes up relatively large amounts of Mn. Removal by rice is in the range 0.2–0.7 kg Mn $t^{-1}$ grain yield, with an average of 0.5 (Section 5.3). A rice

*Table 28. Mn fertilizer sources for rice.*

| Name | Formula | Content (% Mn) | Comments |
|---|---|---|---|
| Mn sulfate | $MnSO_4 \cdot H_2O$ | 24–30 | Soluble, quick-acting |
| Mn chloride | $MnCl_2$ | 17 | Soluble, quick-acting |
| Mn carbonate | $MnCO_3$ | 31 | Insoluble, slow-acting |
| Mn chelate | $Na_2MnEDTA$ | 5–12 | Quick-acting |
| Mn oxide | $MnO_2$ | 40 | Insoluble, slow-acting |

crop yielding 6 t $ha^{-1}$ takes up ~3 kg Mn $ha^{-1}$, of which 90% remains in the straw at maturity.

If the grain *only* is removed and straw is returned to the field, Mn removal is ~0.05 kg Mn $t^{-1}$ grain yield. Burning the straw does not cause significant Mn losses.

## Preventive strategies for Mn management

General measures to prevent Mn deficiency are as follows:

- Crop management: Apply farmyard manure or straw (incorporated or burned) to balance Mn removal and enhance $Mn^{4+}$ reduction in soils containing small amounts of Mn and organic matter.
- Fertilizer management: Use acid-forming fertilizers, e.g., ammonia sulfate, $(NH_4)_2SO_4$, instead of urea.

## Treatment of Mn deficiency

Mn deficiencies can be corrected by foliar application of Mn or by banding Mn with an acidifying starter fertilizer (Table 28). Broadcast Mn undergoes rapid oxidation so that large application rates are required (>30 kg Mn $ha^{-1}$). Large application rates of Mn and Fe may be antagonistic and reduce yield.

Mn deficiency should be treated as follows:

- Apply $MnSO_4$ or finely ground MnO (5–20 kg Mn $ha^{-1}$) in bands along rice rows.
- Apply foliar $MnSO_4$ for rapid treatment of Mn deficiency (1–5 kg Mn $ha^{-1}$ in about 200 L water $ha^{-1}$). Multiple applications may be required, starting at tillering when sufficient foliage has developed.
- Chelates are less effective because Fe and Cu displace Mn.

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# 3.11 Copper Deficiency

## *Function and mobility of Cu*

Copper is required for lignin synthesis (and thus cellular defense mechanisms) and is a constituent of ascorbic acid, the enzymes oxidase and phenolase, and plastocyanin. It is a regulatory factor in enzyme reactions (effector, stabilizer, and inhibitor) and a catalyst of oxidation reactions. It plays a key role in the following processes:

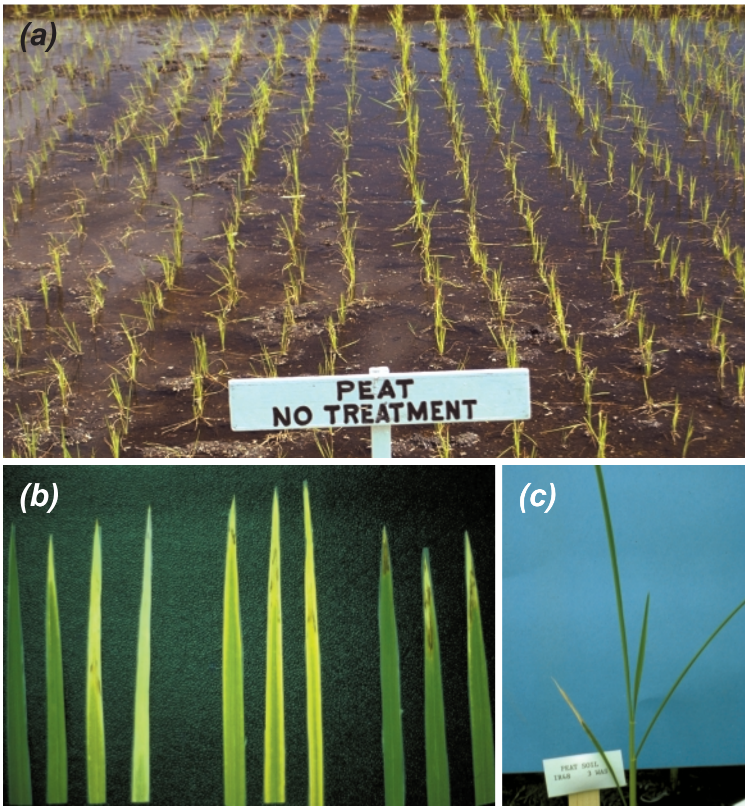
- N, protein, and hormone metabolism.
- Photosynthesis and respiration.
- Pollen formation and fertilization.

The mobility of Cu in rice plants depends partly on leaf N status; little retranslocation of Cu occurs in N-deficient plants. Cu deficiency symptoms are more common on young leaves.

## *Cu deficiency symptoms and effects on growth*

**Chlorotic streaks, bluish green leaves, which become chlorotic near the tips.**

Cu-deficient leaves (Table 29) develop chlorotic streaks on either side of the midrib, followed by the appearance of dark brown necrotic lesions on leaf tips. Cu-deficient leaves are often bluish green and chlorotic near the leaf tip. New leaves do not unroll and the leaf tip maintains a needle-like appearance, while the leaf base appears normal. Tillering is reduced. Pollen viability is reduced under Cu deficiency, resulting in increased spikelet sterility and many unfilled grains (revealed by an analysis of yield




***Copper deficiency symptoms in rice***

*(a) Deficiency mainly occurs in organic soils. (b) Chlorotic streaks and dark brown necrotic lesions may develop on the tips of younger leaves. (c) New leaves may have needle-like appearance.*

*Table 29. Optimal ranges and critical levels of Cu in plant tissue.*

| Growth stage | Plant part | Optimum ($mg\ kg^{-1}$) | Critical level for deficiency ($mg\ kg^{-1}$) |
|---|---|---|---|
| Tillering to panicle initiation | Y leaf | 7–15 | <5 |
| Maturity | Straw | – | <6 |

components). Absorption of Cu from the soil solution is inhibited by Zn and *vice versa.*

## Soil

The critical soil levels for occurrence of Cu deficiency are as follows:

- 0.1 mg Cu $kg^{-1}$, 0.05N HCl, or
- 0.2–0.3 mg Cu $kg^{-1}$, DTPA + $CaCl_2$, pH 7.3.

## Causes of Cu deficiency

Cu deficiency can be caused by one or more of the following:

- Small amount of available Cu in soil.
- Strong adsorption of Cu on humic and fulvic acids (peat soils).
- Small amounts of Cu in parent materials (sandy soils derived from quartz).
- Large NPK rates of fertilizer application, resulting in rapid plant growth rate and exhaustion of Cu in soil solution.
- Overliming of acid soils, resulting in an increase in the amount of Cu complexed by organic matter or adsorbed and occluded by hydroxides and oxides.
- Excessive Zn in the soil, inhibiting Cu uptake.

## Occurrence of Cu deficiency

Soils particularly prone to Cu deficiency include the following types:

- High organic matter status soils (Histosols, humic volcanic ash soils, peat soils).
- Lateritic, highly weathered soils (Ultisols, Oxisols).
- Soils derived from marine sediments (limestone).
- Sandy-textured soils.
- Calcareous soils.

## Effect of submergence on Cu availability and uptake

The availability of Cu decreases at flooding, because of the formation of insoluble Cu sulfides and Cu ferrite ($Cu_2Fe_2O_4$), and complexes with organic matter. The plant availability of Cu decreases with increasing pH and organic matter content.

## Crop Cu uptake and removal

Cu removal by rice is in the range of 0.005–0.02 kg Cu $t^{-1}$ grain yield, with an average of 0.012 (Section 5.3). A rice crop yielding 6 t $ha^{-1}$ takes up ~0.072 kg Cu $ha^{-1}$, of which 25% remains in the straw at maturity.

If the grain *only* is removed and straw is returned to the field, Cu removal is ~0.009 kg Cu $t^{-1}$ grain yield. Burning the straw does not cause significant Cu losses.

## Preventive strategies for Cu management

General measures to prevent Cu deficiency are as follows:

- Crop management: Dip seedling roots in 1% $CuSO_4$ suspensions for an hour before transplanting.
- Soil management: Avoid overliming of acid soils because it may reduce Cu uptake.
- Fertilizer management: On Cu-deficient soils, apply CuO or $CuSO_4$ (5–10 kg Cu

*Table 30. Cu fertilizer sources for rice.*

| Name | Formula | Content (% Cu) | Comments |
|---|---|---|---|
| Cupric sulfate | $CuSO_4 \cdot H_2O$ | 35 | Soluble, quick-acting, low cost |
| | $CuSO_4 \cdot 5\ H_2O$ | 25 | |
| Cu oxide | CuO | 75 | Insoluble, slow-acting |

ha$^{-1}$ at 5-year intervals) for long-term maintenance of available soil Cu (broadcast and incorporate in soil). Cupric sulfate (Table 30) is hygroscopic, i.e., it cannot blend with macronutrient fertilizers and may form insoluble compounds if mixed with P fertilizers. Cu applied to the soil has a high residual value. For this reason, Cu is not included in properly manufactured compound fertilizers.

## Treatment of Cu deficiency

Cu deficiency should be treated as follows:

- Apply $CuSO_4$ (solid or liquid form) for rapid treatment of Cu deficiency (~1–5 kg Cu ha$^{-1}$). For soil application, fine $CuSO_4$ material is either broadcast (or banded) on the soil or incorporated as a basal application.
- Foliar Cu can be applied during tillering to panicle initiation growth stages, but may cause leaf burn in growing tissues. Apply cupric sulfate solution or Cu chelates as foliar spray only for corrective treatment of Cu deficiency.
- Avoid applying excessive Cu because the range between Cu deficiency and toxicity levels is narrow.

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# 3.12 Boron Deficiency

## *Function and mobility of B*

Boron has a primary role in cell wall biosynthesis, and structure and plasma membrane integrity. It is required for carbohydrate metabolism, sugar transport, lignification, nucleotide synthesis, and respiration. B deficiency results in reduced pollen viability. B is not an enzyme constituent and does not affect enzyme activities. It is relatively immobile in rice plants. Because B is not retranslocated to new growth, deficiency symptoms usually appear first on young leaves.

## *B deficiency symptoms and effects on growth*

**White, rolled leaf tips of young leaves.**

B deficiency results in reduced plant height, and the tips of emerging leaves are white and rolled (as in Ca deficiency, Section 3.8). Severe deficiency (Table 31) results in the death of the growing point, but new tillers continue to be produced. Rice plants may fail to produce panicles if they are affected by B deficiency at the panicle formation stage.

## *Soil*

The critical soil level for occurrence of B deficiency is 0.5 mg B kg$^{-1}$ hot water extraction (range of critical level 0.1–0.7 mg B kg$^{-1}$).

## *Causes of B deficiency*

B deficiency can be caused by one or more of the following factors:

- Small amount of available B in soil.
- B adsorption on organic matter, clay minerals, and sequioxides.
- Reduction in B mobility due to drought.
- Excessive liming.

## *Occurrence of B deficiency*

B deficiency is not very common in rice, but can occur in the following soils:

- Highly weathered, acid red soils and sandy rice soils in China.
- Acid soils derived from igneous rocks. Soils formed from marine sediments contain more B than those formed from igneous rocks.
- High organic matter status soils in Japan.

## *Effect of submergence on B availability and uptake*

When pH<6, B is present mostly as undissociated boric acid, $B(OH)_3$, and plant uptake depends on mass flow. When pH>6, $B(OH)_3$ is increasingly dissociated and hydrated to $B(OH)_4^-$ and uptake is actively regulated by the plant. B adsorption to organic matter, sequioxides, and clay minerals increases with increasing pH. Therefore, B availability decreases in acid soils and increases in alkaline soils after flooding. For example, in rice-wheat systems, B deficiency is common in wheat but less common in the rice crop grown on the same soil. When wetland soils are drained, the pH decreases and B is desorbed and may be leached.

*Table 31. Optimal ranges and critical levels of B in plant tissue.*

| Growth stage | Plant part | Optimum (mg kg$^{-1}$) | Critical level for deficiency (mg kg$^{-1}$) |
|---|---|---|---|
| Tillering to panicle initiation | Y leaf | 6–15 | <5 |
| Maturity | Straw | – | <3 |

*Table 32. B fertilizer sources for rice.*

| Name | Formula | Content (% B) | Comments |
|---|---|---|---|
| Anhydrous borax | $Na_2B_4O_2$ | 20 | Soluble, quick-acting |
| Fertilizer borate | $Na_2B_4O_2 \cdot 5\ H_2O$ | 14 | Soluble, quick-acting |
| Borax | $Na_2B_4O_2 \cdot 10\ H_2O$ | 11 | Soluble, quick-acting |
| Colemanite | $Ca_2B_6O_{11} \cdot 5\ H_2O$ | 10 | Slightly soluble, slow-acting |

## Crop B uptake and removal

B removal by rice is in the range of 0.01–0.10 kg B $t^{-1}$ grain yield, with an average of 0.015 (Section 5.3). A rice crop yielding 6 t $ha^{-1}$ takes up ~0.09 kg B $ha^{-1}$, of which >60% remains in the straw at maturity.

If the grain *only* is removed and straw is returned to the field, B removal is ~0.005 kg B $t^{-1}$ grain yield. Burning the straw does not cause significant B losses.

## Preventive strategies for B management

General measures to prevent B deficiency are as follows:

- Water management: Avoid excessive leaching (percolation). B is very mobile in flooded rice soils.
- Fertilizer management: On B-deficient soils, apply slow-acting B sources (e.g., colemanite, Table 32) at intervals of 2–3 years. B fertilizers have a longer residual effect in silty and clayey soils (apply 2–3 kg B $ha^{-1}$) than in sandy soils (apply 3–5 kg B $ha^{-1}$). In rice-wheat systems, B applied to wheat can alleviate B deficiency in the subsequent rice crop. Do not apply excessive amounts of B as this may induce B toxicity (Section 4.3).

## Treatment of B deficiency

B deficiency should be treated as follows:

- Apply B in soluble forms (borax) for rapid treatment of B deficiency (0.5–3 kg B $ha^{-1}$), broadcast and incorporated before planting, topdressed, or as foliar spray during vegetative rice growth.
- Borax and fertilizer borates should not be mixed with ammonium fertilizers as this will cause $NH_3$ volatilization.

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# 4

# Mineral Toxicities

***In this chapter***

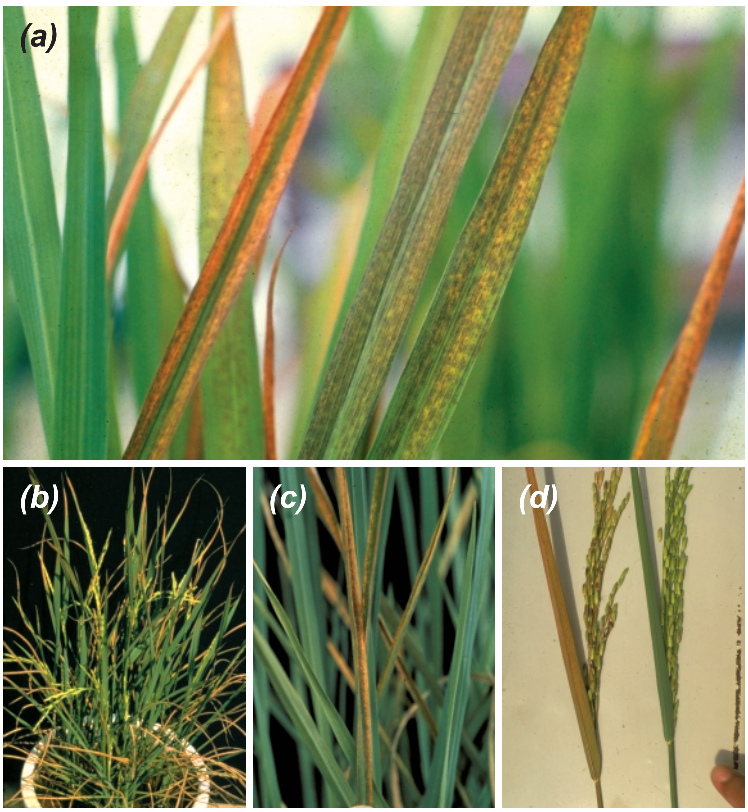
# 4.1 Iron Toxicity

## *Mechanism of Fe toxicity*

Iron toxicity is primarily caused by the toxic effects of excessive Fe uptake due to a large concentration of Fe in the soil solution. Recently transplanted rice seedlings may be affected when large amounts of $Fe^{2+}$ accumulate immediately after flooding. In later growth stages, rice plants are affected by excessive $Fe^{2+}$ uptake due to increased root permeability and enhanced microbial Fe reduction in the rhizosphere. Excessive Fe uptake results in increased polyphenol oxidase activity, leading to the production of oxidized polyphenols, the cause of leaf bronzing. Large amounts of Fe in plants can give rise to the formation of oxygen radicals, which are phytotoxic and responsible for protein degradation and peroxidation of membrane lipids.

Varieties differ in susceptibility to Fe toxicity. The major adaptive mechanisms by which rice plants overcome Fe toxicity are as follows:

- Fe stress avoidance because of $Fe^{2+}$ oxidation in the rhizosphere. The precipitation of $Fe^{3+}$ hydroxide in the rhizosphere by healthy roots (indicated by reddish brown coatings on the roots) prevents excessive $Fe^{2+}$ uptake. In strongly reduced soils containing very large amounts of Fe, however, there may be insufficient oxygen at the root surface to oxidize $Fe^{2+}$. In such cases, Fe uptake is excessive and roots appear black because of the presence of Fe sulfide. Root oxidation power includes the excretion of $O_2$ (transported from the shoot to the root through aerenchyma) from roots and oxidation mediated by



***Iron toxicity symptoms in rice***

*(a) Tiny brown spots develop on the leaf tip and spread towards the leaf base. (b) Symptoms first appear on older leaves.*
*(a), (c) Under severe Fe toxicity, the whole leaf surface is affected.*
*(d) Leaf bronzing occurs in K-deficient rice plants which are unable to maintain sufficient root oxidation power (left).*

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enzymes such as peroxidase or catalase. An inadequate supply of nutrients (K, Si, P, Ca, and Mg) and excessive amounts of toxic substances ($H_2S$) reduce root oxidation power. Rice varieties differ in their ability to release $O_2$ from roots to oxidize $Fe^{2+}$ in the rhizosphere and thus protect the plant from Fe toxicity.

- Fe stress tolerance may be due to the avoidance or tolerance of toxin accumulation. Another mechanism involves the retention of Fe in root tissue (oxidation of $Fe^{2+}$ and precipitation as $Fe^{3+}$).

Fe toxicity is related to multiple nutritional stress, which leads to reduced root oxidation power. The roots of plants deficient in K, P, Ca, and/or Mg exude more low-molecular-weight metabolites (soluble sugars, amides, amino acids) than plants with an adequate nutrient supply. In periods of intense metabolic activity (e.g., tillering), this results in an increased rhizoflora population, which in turn leads to increased demand for electron acceptors. Under such conditions, facultative and obligate anaerobic bacteria reduce $Fe^{3+}$ to $Fe^{2+}$. The continuous reduction of $Fe^{3+}$ contained in $Fe_2O_3$ root coatings may result in a breakdown in Fe oxidation, leading to an uncontrolled influx of $Fe^{2+}$ into the rice plant roots. A black stain of Fe sulfide (a diagnostic indication of excessively reduced conditions and Fe toxicity) may then form on the root surface.

## Fe toxicity symptoms and effects on growth

### Tiny brown spots on lower leaves starting from the tip or whole leaves colored orange-yellow to brown. Black coating on root surfaces.

Symptoms first appear 1–2 weeks (but sometimes >2 months) after transplanting. First, tiny brown spots appear on lower leaves, starting from the leaf tips, and spread toward the leaf base. Later, spots combine on leaf interveins and leaves turn orange-brown and die. Leaves are narrow but often remain green. Where Fe toxicity is severe, leaves appear purple-brown. In some varieties, leaf tips become orange-yellow and dry up. Rice plants are more susceptible to Fe toxicity during early growth stages when root oxidation capacity is small.

Other effects of Fe toxicity are as follows:

- Stunted growth, greatly reduced tillering.
- Coarse, sparse, damaged root system with a dark brown to black coating on the root surface and many dead roots. Freshly uprooted rice hills often have poor root systems with many black roots (stained by Fe sulfide). In contrast, healthy roots are uniformly coated with a smooth covering of orange-brown $Fe^{3+}$ oxides and hydroxides.
- The bronzing symptoms in rice leaf tissue can also be caused indirectly by toxicity of Fe, Mn, and Al, resulting in P deficiency, K deficiency, Mg deficiency, and Ca deficiency (Sections 3.2, 3.3, 3.7, and 3.8, respectively). When the concentrations of Fe, Mn, and Al in the soil solution are large, root growth is limited and roots become coated with $Fe^{2+}$ and $Mn^{2+}$ oxides. This reduces the capacity of roots to absorb nutrients from the soil.
- Fe toxicity may be combined with Zn deficiency where bronzing or yellowing is accompanied by retarded growth. Fe competes with Zn for uptake sites on rice roots and may induce Zn deficiency. Zn deficiency, however, is more likely on alkaline soils, whereas Fe toxicity occurs on acid-neutral soils with low available K content.

Fe toxicity is also referred to as ‘bronzing’ or ‘Akagare Type I disease’ (in Japan). In recent years, new disorders such as ‘yellow leaf’ or ‘red stripe’ have become widespread in rice-growing regions in Southeast Asia (e.g., Vietnam, Cambodia). Leaf symptoms may sometimes resemble Fe toxicity, but no causal

*Table 33. Optimal range and critical level for occurrence of Fe toxicity.*

| Growth stage | Plant part | Optimum ($mg\ kg^{-1}$) | Critical level for toxicity ($mg\ kg^{-1}$) |
|---|---|---|---|
| Tillering to panicle initiation | Y leaf | 100–150 | >300–500 |

relationships with either soil characteristics or pathogens have yet been identified.

### Plant

Fe content in affected plants is usually (but not always) high (300–2,000 mg Fe $kg^{-1}$), but the critical Fe content (Table 33) depends on plant age and general nutritional status. The critical threshold is lower in low fertility status soils where nutrient supply is not properly balanced.

Fe-toxic plants have low K content in leaves (often <1% K). A K:Fe ratio of <17–18:1 in straw and <1.5:1 in roots may indicate Fe toxicity.

### Soil

The critical concentration for the occurrence of Fe toxicity is >300 mg Fe $L^{-1}$ in the soil. Critical Fe solution concentrations for the occurrence of Fe toxicity vary widely. Reported values range from 10 to 1,000 mg Fe $L^{-1}$, implying that Fe toxicity is not related to the Fe concentration in soil solution alone. The difference between critical solution Fe concentrations is caused by differences in the potential of rice roots to resist the effects of Fe toxicity, depending on crop growth stage, physiological status of the plant, and variety grown (root oxidation power).

No critical levels for soil test results have been established, but soils with pH <5.0 (in $H_2O$) are prone to Fe toxicity. Similarly, soils containing small amounts of available K, P, Ca, and Mg contents are prone to Fe toxicity.

### Effect of submergence on Fe toxicity

The concentration of $Fe^{2+}$ in soil solution is controlled by the duration of submergence, pH, and organic matter and $Fe^{3+}$ content. In most mineral soils, the concentration of $Fe^{2+}$ peaks at 2–4 weeks following submergence. In general, solution $Fe^{2+}$ increases sharply after flooding, but maximum values may range from <20 mg Fe $L^{-1}$ (in low organic matter calcareous soils) to >1,000 mg Fe $L^{-1}$ (in acid soils) where Fe toxicity occurs. A large concentration of $Fe^{2+}$ in the soil may retard K and P uptake. Under strongly reducing conditions, the production of $H_2S$ and FeS may contribute to Fe toxicity by reducing root oxidation power.

The oxidation of $Fe^{2+}$ to $Fe^{3+}$ because of the release of oxygen by rice roots causes acidification in the rice rhizosphere (important for P uptake) and the formation of a brownish coating on rice roots.

### Causes of Fe toxicity

Principal causes of Fe toxicity are as follows:

- Large $Fe^{2+}$ concentration in soil solution because of strongly reducing conditions in the soil and/or low pH.
- Low and unbalanced crop nutrient status. Poor root oxidation and $Fe^{2+}$ exclusion power because of P, Ca, Mg, or K deficiency. K deficiency (Section 3.3) is often associated with low soil base content and low soil pH, which are associated with a large concentration of Fe in the soil solution.
- Poor root oxidation ($Fe^{2+}$ exclusion) power because of the accumulation in the rhizosphere of substances that inhibit respiration, e.g., $H_2S$, FeS, organic acids (Section 4.2).
- Application of large amounts of undecomposed organic residues.
- Continuous supply of Fe into soil from groundwater or lateral seepage from hills.
- Application of urban or industrial sewage with a high Fe content.

### *Occurrence of Fe toxicity*

Fe toxicity occurs on a wide range of soils, but generally in lowland rice soils with permanent flooding during crop growth. Common features of Fe-toxic sites are poor drainage and low soil CEC and macronutrient content, but Fe toxicity occurs over a wide range of soil pH (4–7). Soils prone to Fe toxicity include the following types:

- Poorly drained soils (Aquents, Aquepts, Aquults) in inland valleys receiving inflow from acid upland soils (Indonesia, Philippines, and Sri Lanka).
- Kaolinitic soils with low CEC and small amounts of available P and K (Indonesia's outer islands, and Madagascar).
- Alluvial or colluvial acid clayey soils (Indonesia and the Philippines).
- Young acid sulfate soils (Sulfaquepts in Indonesia, Senegal, and Thailand).
- Acid lowland or highland peat (swamp) soils (Burundi, Indonesia, Liberia, and Madagascar).

### *Preventive strategies for Fe toxicity management*

General measures to prevent Fe toxicity are as follows:

- Varieties: Plant rice varieties tolerant of Fe toxicity (e.g., IR8192-200, IR9764-45, Kuatik Putih, Mahsuri). If nutrients are supplied in sufficient amounts, hybrid rice varieties have a more vigorous root system and higher root oxidation power, and do not tend to absorb excessive amounts of Fe from Fe-toxic soils.
- Seed treatment: In temperate climates where direct seeding is practiced, coat seeds with oxidants (e.g., Ca peroxide at 50–100% of seed weight) to improve germination and seedling emergence by increasing the $O_2$ supply.
- Crop management: Delay planting until the peak in $Fe^{2+}$ concentration has passed (i.e., not less than 10–20 days after flooding).
- Water management: Use intermittent irrigation and avoid continuous flooding on poorly drained soils containing a large concentration of Fe and organic matter.
- Fertilizer management: Balance the use of fertilizers (NPK or NPK + lime) to avoid nutrient stress. Apply sufficient K fertilizer (Section 3.3). Apply lime on acid soils. Do not apply excessive amounts of organic matter (manure, straw) on soils containing large amounts of Fe and organic matter or where drainage is poor. Use urea (less acidifying) instead of ammonium sulfate (more acidifying).
- Soil management: Carry out dry tillage after the rice harvest to increase Fe oxidation during the fallow period. This reduces $Fe^{2+}$ accumulation during the subsequent flooding period.

### *Treatment of Fe toxicity*

Preventive management strategies (see above) should be followed because treatment of Fe toxicity during crop growth is difficult. Options for treatment are as follows:

- Apply additional K, P, and Mg fertilizers.
- Incorporate lime in the topsoil to raise pH in acid soils.
- Incorporate about 100–200 kg $MnO_2$ $ha^{-1}$ in the topsoil to decrease $Fe^{3+}$ reduction.
- Carry out midseason drainage to remove accumulated $Fe^{2+}$. At the midtillering stage (25–30 DAT/DAS), drain the field and keep it free of floodwater (but moist) for about 7–10 days to improve oxygen supply during tillering.

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# 4.2 Sulfide Toxicity

## Mechanism of sulfide toxicity

An excessive concentration of hydrogen sulfide in the soil results in reduced nutrient uptake due to a decrease in root respiration. Hydrogen sulfide has an adverse effect on metabolism when an excessive amount is taken up by the rice plant.

Rice roots release $O_2$ to oxidize $H_2S$ in the rhizosphere. $H_2S$ toxicity therefore depends on the strength of root oxidizing power, $H_2S$ concentration in the soil solution, and root health as affected by nutrient supply. Young rice plants are particularly susceptible to sulfide toxicity before the development of oxidizing conditions in the rhizosphere. Physiological disorders attributed to $H_2S$ toxicity include 'Akiochi' in Japan and 'straighthead' in the southern United States.

## Sulfide toxicity symptoms and effects on growth

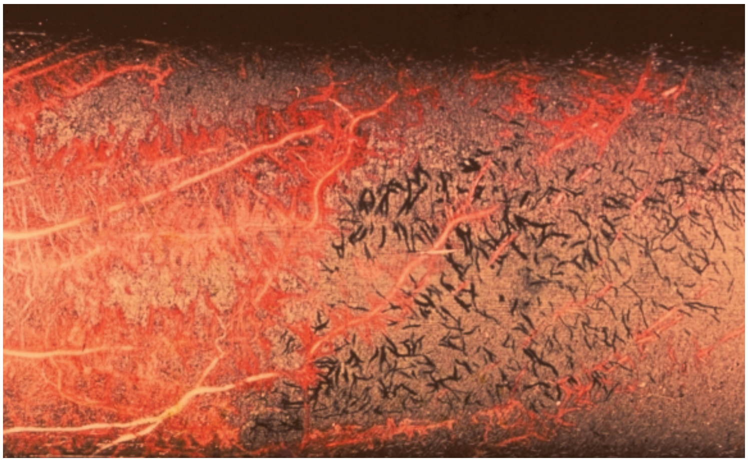
**Interveinal chlorosis of emerging leaves. Coarse, sparse and blackened roots.**

Leaf symptoms of sulfide toxicity are similar to those of chlorosis caused by Fe deficiency (Section 3.9). Other diagnostic criteria are similar to those of Fe toxicity (but Fe toxicity has different visual leaf deficiency symptoms, Section 4.1):

- Coarse, sparse, dark brown to black root system. Freshly uprooted rice hills often have poorly developed root systems with many black roots (stains of Fe sulfide). In contrast, healthy roots are covered with a uniform and smooth orange-brown coating of $Fe^{3+}$ oxides and hydroxides.
- Small concentration of K, Mg, Ca, Mn, and Si content in plant tissue.
- Increased occurrence of diseases, such as brown spot (caused by *Helminthosporium oryzae*), because of unbalanced plant nutrient content caused by $H_2S$ toxicity.

## Normal ranges and critical levels for occurrence of sulfide toxicity

No critical levels have been established. Sulfide toxicity depends on the concentration of sulfide in soil solution relative to the oxidation power of rice roots. $H_2S$ toxicity can occur when the concentration of $H_2S$ >0.07 mg $L^{-1}$ in the soil solution.



***Sulfide toxicity symptoms in rice***

*Roots of affected plants are coarse, sparse, and blackened.*

### *Effect of submergence on sulfide toxicity*

The reduction of sulfate to sulfide in flooded soils has three implications for rice culture:

- S may become deficient,
- Fe, Zn, and Cu may become immobilized, and
- $H_2S$ toxicity may occur in soils containing small amounts of Fe.

In submerged soils, sulfate is reduced to $H_2S$ at low redox potential (<-50 mV at pH 7), which then forms insoluble sulfides such as FeS:

$$H_2S + Fe^{2+} \rightarrow FeS + 2\ H^+$$

Depending on the soil solution pH, $H_2S$, $HS^-$, and $S^{2-}$ may be present in different proportions. $H_2S$ is the predominant S species for flooded soils in the pH range of 4–8. $H_2S$ is phytotoxic and the concentration of free $H_2S$ in soil solution ranges from <0.0001 to >0.5 mg $L^{-1}$. Fe sulfides are not toxic to rice, but they reduce nutrient uptake (Section 4.1).

### *Causes of sulfide toxicity*

Sulfide toxicity can be caused by one or more of the following:

- Large concentration of $H_2S$ in the soil solution (due to strongly reducing conditions and little precipitation of FeS).
- Poor and unbalanced crop nutrient status, causing reduced root oxidation power (due to deficiencies of K in particular but also of P, Ca, or Mg).
- Excessive application of sulfate in fertilizers or urban or industrial sewage on poorly drained, strongly reducing soils.

### *Occurrence of sulfide toxicity*

If sufficient amounts of free Fe ($Fe^{2+}$) are present, the concentration of $H_2S$ is usually low due to the formation of insoluble FeS. Toxicity is therefore associated with low-Fe soils (Section 3.9). Because the bacteria that reduce $SO_4^{2-}$ to $H_2S$ become active when the soil pH is >5, $H_2S$ toxicity mainly occurs after prolonged flooding. Soils prone to $H_2S$ toxicity include the following types:

- Well-drained sandy soils with low active Fe status.
- Degraded paddy soils with low active Fe status.
- Poorly drained organic soils.
- Acid sulfate soils.

Soils prone to sulfide toxicity and Fe toxicity are similar in containing a large amount of active Fe, small CEC, and small concentration of exchangeable bases.

### *Preventive strategies for sulfide toxicity management*

General measures to prevent sulfide toxicity are as follows:

- Varieties: Grow rice varieties that tolerate sulfide toxicity because of their greater capacity to release $O_2$ from roots. For example, hybrid rice varieties have a more vigorous root system and greater root oxidation power if sufficient nutrients (NPK) have been applied.
- Seed treatment: In temperate climates, coat seeds with oxidants (e.g., Ca peroxide) to increase the $O_2$ supply and improve seed germination.
- Water management: Avoid continuous flooding and use intermittent irrigation in soils that contain large concentrations of S, high organic matter status soils, and poorly drained soils.
- Fertilizer management: Balance the use of fertilizer nutrients (NPK or NPK + lime) to avoid nutrient stress and improve root oxidation power. Apply sufficient K fertilizer (Section 3.3). Avoid using excessive amounts of organic residues (manure, straw) in soils containing large amounts of Fe and organic matter, and in poorly drained soils.
- Soil management: Carry out dry tillage after harvest to increase S and Fe

oxidation during the fallow period. This technique slows down the decrease in soil redox potential and the accumulation of $Fe^{2+}$ and $H_2S$ during the subsequent period of flooding.

## Treatment of sulfide toxicity

Preventive management strategies should be followed because treatment of sulfide toxicity during crop growth is difficult. Options for treatment of sulfide toxicity are as follows:

- Apply K, P, and Mg fertilizers.
- Apply Fe (salts, oxides) on low-Fe soils to increase immobilization of $H_2S$ as FeS.
- Carry out midseason drainage to remove accumulated $H_2S$ and $Fe^2$ – drain the field at the midtillering stage (25–30 DAT/DAS), and maintain floodwater-free (but moist) conditions for about 7–10 days to improve oxygen supply during tillering.

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# 4.3 Boron Toxicity

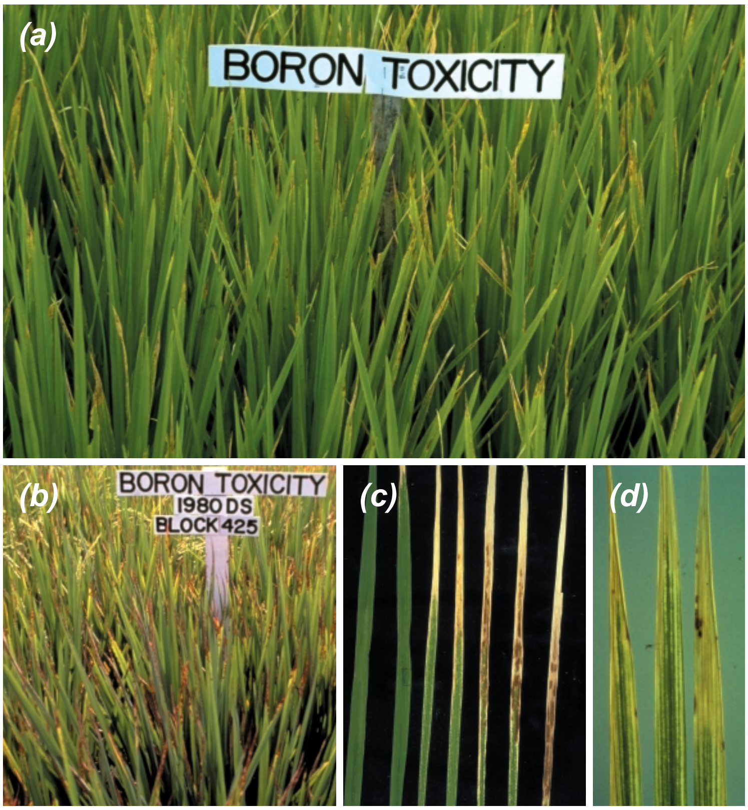
## *Mechanism of B toxicity*

The physiology of B tolerance and B toxicity is not well understood. B uptake is closely related to the B concentration of the soil solution and the rate of water transpiration by rice plants. When the B concentration in the soil solution is large, B is distributed throughout the plant in the normal transpiration stream, causing the accumulation of B in leaf margins and leaf tips. Excess B appears to inhibit the formation of starch from sugars or results in the formation of B-carbohydrate complexes, resulting in retarded grain filling but normal vegetative growth. Varieties with a large B requirement are less susceptible to B toxicity and *vice versa*.

## *B toxicity symptoms and effects on growth*

### Brownish leaf tips and dark brown elliptical spots on leaves.

B toxicity first appears as chlorosis of the tips and margins of older leaves. Two to four weeks later, dark brown elliptical spots appear on these discolored areas, which then turn brown and dry up. Necrotic spots are most prominent at panicle initiation. Some varieties exhibit discoloration only at leaf tips and margins. Vegetative growth is not markedly reduced. The extent of yield reduction on high-B status soils varies among varieties and is not clearly related to the severity of typical necrotic symptoms.




***Boron toxicity symptoms in rice***

*(a) Brownish leaf tips are a typical characteristic of B toxicity, appearing first as marginal chlorosis on the tips of older leaves. (b), (c), (d) 2–4 weeks later, brown elliptical spots develop on the discolored areas.*

*Table 34. Optimal ranges and critical levels for occurrence of B toxicity.*

| Growth stage | Plant part | Optimum (mg $kg^{-1}$) | Critical level for toxicity (mg $kg^{-1}$) |
|---|---|---|---|
| Tillering | Y leaf | 6–15 | 100 |
| Panicle initiation | Shoot | – | 35 |
| Maturity | Straw | – | 100 |

## Plant

Critical toxicity limits of B in leaves have to be interpreted with caution (Table 34).

- There is a steep concentration gradient of B within a leaf blade, from low values at the leaf base to high values at the leaf tip.
- Critical toxicity levels in field-grown rice are lower than those of plants grown in the greenhouse because of B leaching from leaves due to rain.
- The effect on yield differs significantly among rice varieties.

## Soil

The critical toxicity limits of B in the soil are as follows:

- >4 mg B $kg^{-1}$: 0.05N HCl.
- >5 mg B $kg^{-1}$: hot-water soluble B.
- >2.5 mg B $L^{-1}$: soil solution.

## Irrigation water

B concentration is hazardous at >2 mg B $L^{-1}$.

## Effect of submergence on B toxicity

When soil pH is <6, B is present mostly as undissociated boric acid – $B(OH)_3$ – and uptake depends on mass flow. Above pH 6, $B(OH)_3$ is increasingly dissociated and hydrated to $B(OH)_4^-$ and plant uptake becomes actively regulated. An increase in soil pH results in a greater amount of B adsorbed to organic matter, sequioxides, and clay minerals. Therefore, flooding acid soils decreases B availability, whereas flooding alkaline soils increases B availability. The pH of wetland soils decreases upon drying so that B is desorbed and can be leached out. B toxicity may also be related to B concentration in the irrigation water and the amount used. B toxicity may become more severe in the dry season when B concentration in deep-well irrigation water is larger and there is little rainwater to dilute the large B concentration in irrigation water and/or leach B from the soil and rice plants.

## Causes of B toxicity

B toxicity can be caused by one or more of the following:

- Large B concentration in the soil solution because of the use of B-rich groundwater and high temperature (e.g., in arid regions, very deep tube-wells, or wells in areas affected by geothermal activities).
- Large B concentration in the soil solution because of B-rich parent material. B content is large in some marine sediments, plutonic rocks, and other volcanic materials (e.g., tuff), but the concentration in igneous rocks is small.
- Excess application of borax or large applications of municipal waste (compost).

## Occurrence of B toxicity

B toxicity is most common in arid and semiarid regions, but has also been reported in rice in other areas. Soils prone to B toxicity include the following types:

- Soils formed on volcanic parent material, usually associated with the use of irrigation water pumped from deep wells containing a large B concentration (e.g., IRRI farm, Los Baños, and Albay, Philippines).
- Some coastal saline soils.

## Preventive strategies for B toxicity management

General measures to prevent B toxicity are as follows:

- Varieties: Plant B-toxicity tolerant varieties (e.g., IR42, IR46, IR48, IR54, IR9884-54). B-toxicity tolerant varieties can yield up to 2 t $ha^{-1}$ more than susceptible varieties.
- Water management: Use surface water with a low B content for irrigation. Groundwater must be monitored regularly if used for irrigation. If the B concentration is too great, dilute the water with water from a different source containing a small concentration of B.
- Soil management: Plow when the soil is dry so that B accumulates in the topsoil. Then leach with water containing a small amount of B.

## Treatment of B toxicity

Leach with low-B irrigation water if percolation is sufficient and a suitable water source is available.

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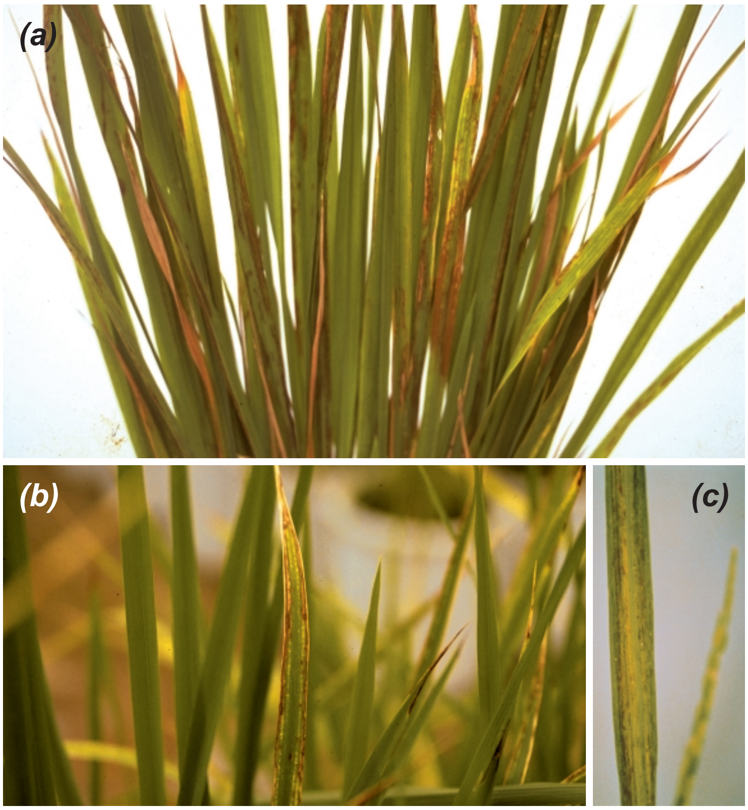
# 4.4 Manganese Toxicity

## Mechanism of Mn toxicity

Manganese concentration in the soil solution can increase at low soil pH or when the redox potential is low after flooding. Excessive amounts of Mn in the soil solution can lead to excess Mn uptake in cases where exclusion or tolerance mechanisms in roots are not functioning adequately. A large concentration of Mn in plant tissue changes metabolic processes (e.g., enzyme activities and organic compounds) that lead to visible Mn toxicity symptoms such as chlorosis (photo-oxidation of chlorophyll) or necrosis (accumulation of oxidized phenolic compounds, e.g., anthocyanin).

Varieties differ in their susceptibility to Mn toxicity. The major adaptive mechanisms by which rice plants overcome Mn toxicity are as follows:

- Mn stress avoidance: Release of $O_2$ from roots (root oxidation power) to oxidize $Mn^{2+}$ in the rhizosphere. Differences in root anatomy and morphology, and the supply of K, Si, P, Ca, and Mg as well as toxic substances ($H_2S$), affect root oxidation power.
- Mn stress tolerance: Retention of Mn in root tissue (oxidation and accumulation of $Mn^{2+}$ in cell walls). Concentration of excess Mn in metabolically inactive forms within the plant.



**_Manganese toxicity symptoms in rice_**

*(a), (b), (c) Interveinal yellowish brown spots develop on lower leaf blades and leaf sheaths.*

*Table 35. Optimal ranges and critical levels for occurrence of Mn toxicity.*

| Growth stage | Plant part | Optimum (mg $kg^{-1}$) | Critical level for toxicity (mg $kg^{-1}$) |
|---|---|---|---|
| Tillering | Y leaf, shoot | 40–700 | >800–2,500 |
| Tillering | Shoot | 50–150 | – |
| Maturity | Straw | 0.10–0.15 | <0.06 |

## Mn toxicity symptoms and effects on growth

**Yellowish brown spots between leaf veins, extending to the whole interveinal area.**

Brown spots develop on the veins of lower leaf blades and leaf sheaths. Leaf tips dry out eight weeks after planting. Mn toxicity can also cause chlorosis of younger (upper) leaves, with symptoms similar to those of Fe chlorosis (Section 3.9). Plants are stunted and tillering is reduced. Sterility results in reduced grain yield. Excess Mn uptake reduces Si, P, and Fe uptake and translocation of P to the panicle. A high leaf Si content can prevent the occurrence of brown necrotic spots typical of Mn toxicity.

## Plant

Rice is more resistant to Mn toxicity than most upland crops but critical plant concentrations for the occurrence of Mn toxicity are poorly defined. As with Fe toxicity (Section 4.1), the concentration of active forms of Mn may be a better indicator of Mn toxicity than total Mn content in plant tissue. In some cases, rice plants with 3,000 mg Mn $kg^{-1}$ do not show Mn toxicity symptoms and yield is not affected.

## Soil

Mn content of rice plants may be positively related to the concentration of easily reduced Mn in the soil, but no critical soil levels have been described.

## Effect of submergence on Mn toxicity

Flooding affects Mn toxicity in rice because of the following factors:

- Increased Mn solubility with decreasing redox potential.
- Reduced Mn oxidation by roots because of lack of oxygen.

## Causes of Mn toxicity

Mn toxicity can be caused by one or more of the following:

- Large concentration of $Mn^{2+}$ in the soil solution because of low soil pH (<5.5) and/or low redox potential.
- Poor and unbalanced crop nutrient status. Poor root oxidation and $Fe^{2+}$-excluding power because of
  - deficiencies of Si, K, P, Ca, or Mg, and
  - substances that inhibit respiration (e.g., $H_2S$, FeS, and organic acids) (Section 4.2).
- Application of urban or industrial waste with large Mn content.

## Occurrence of Mn toxicity

Mn toxicity rarely occurs in lowland rice. Despite large Mn concentrations in solution, Mn toxicity is uncommon because rice is comparatively tolerant of large Mn concentrations (Table 35). Rice roots are able to exclude Mn and rice has a high internal tolerance for large tissue Mn concentrations. Soils where Mn toxicity can occur are as follows:

- Acid upland soils (pH <5.5); Mn toxicity often occurs together with Al toxicity (Section 4.5).
- Lowland soils containing large amounts of easily reducible Mn.
- Acid sulfate soils.
- Areas affected by Mn mining (e.g., Japan).

## Preventive strategies for Mn toxicity management

General measures to prevent Mn toxicity are as follows:

- Seed treatment: In a temperate climate, coat seeds with oxidants (e.g., Ca peroxide) to improve germination and seedling emergence by increasing the supply of $O_2$.
- Water management: Mn absorption may be accelerated when surface drainage is practiced.
- Fertilizer management: Balance the use of fertilizers (NPK or NPK + lime) to avoid nutrient stress as a source of Mn toxicity. Apply sufficient K fertilizer (Section 3.3). Apply lime on acid soils to reduce the concentration of active Mn. Do not apply excessive amounts of organic matter (manure, straw) on soils containing large concentrations of Mn and organic matter, and on poorly drained soils. Use less-acidifying ammonium fertilizers as N sources (e.g., urea). Mn uptake is less in the presence of ammonia-N compared with nitrate-N.
- Straw management: Recycle straw or ash to replenish Si and K removed from the field. An adequate Si supply prevents Mn toxicity of rice plants by decreasing plant Mn uptake (increased root oxidation) and by increasing the internal tolerance for an excessive amount of Mn in plant tissue.

## Treatment of Mn toxicity

Options for treatment of Mn toxicity are as follows:

- Apply lime to alleviate soil acidity on upland soils.
- Apply silica slags (1.5–3 t $ha^{-1}$) to alleviate Si deficiency (Section 3.6).

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# 4.5 Aluminum Toxicity

## *Mechanism of Al toxicity*

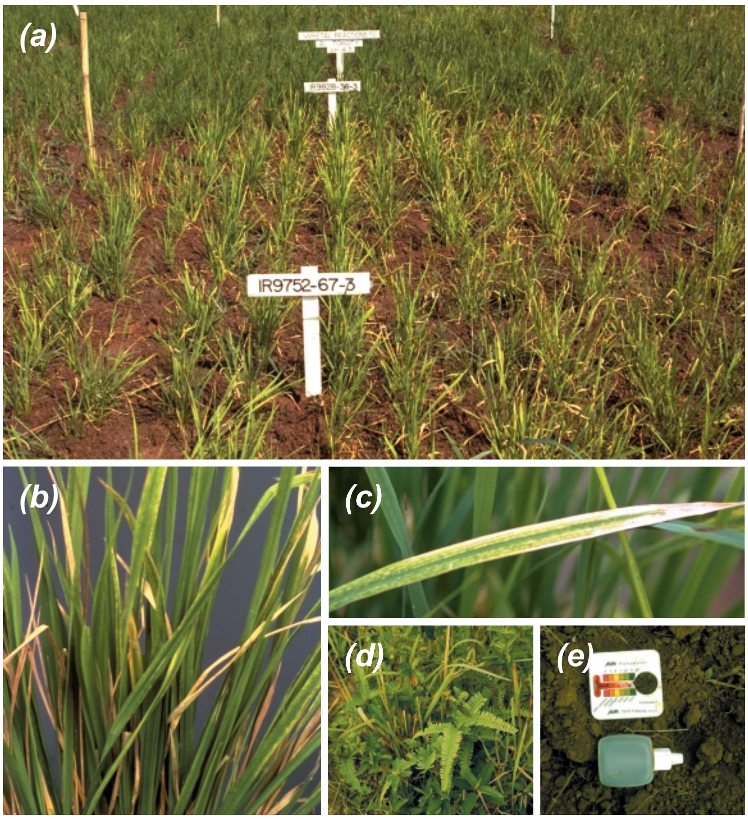
Aluminum accumulates preferentially in the root tips at sites of cell division and cell elongation. The most important symptom of Al toxicity is the inhibition of root growth. This can be due to the effect of Al on cell walls, as well as the toxic effects of Al on the plasma membrane of younger and outer cells in roots or on the root symplasm. Aluminum affects plasma-membrane functions and decreases the influx of $Ca^{2+}$ and $Mg^{2+}$. Some varieties are resistant to large Al concentrations by excluding Al from the root apex or through plant tissue tolerance of Al in the symplasm. Long-term exposure of plants to Al also inhibits shoot growth by inducing nutrient (Mg, Ca, P) deficiencies, drought stress, and phytohormone imbalances.

Genotypic differences in susceptibility to Al toxicity in rice are as follows:

- Al stress avoidance, due to the exclusion of Al from sensitive sites or decreased $Al^{3+}$ activity in the rhizosphere, thus reducing the inhibition of $Ca^{2+}$ and $Mg^{2+}$ influx by Al.
- Al stress tolerance, due to high tissue tolerance of Al, immobilization of Al in non-toxic forms, or high internal nutrient use efficiency for P.

## *Al toxicity symptoms and effects on growth*

**Orange-yellow interveinal chlorosis on leaves. Poor growth, stunted plants.**




***Aluminum toxicity symptoms in rice***

*(a) Aluminum toxicity is mainly a problem in acid upland soils but varieties differ in their susceptibility. (b) Yellow to white mottling of interveins is followed by leaf tip death. (c) Leaf margin scorch. (d) Indicator plants, e.g., tropical bracken (*Dicranopteris linearis*), Straits rhododhendron (*Melastoma malabathricum*), and alang-alang (*Imperata cylindrica*) provide a proxy indicator of acid soil conditions and low soil P status. (e) A pocket pH meter provides a reliable indication of soil pH.*

*Table 36. Optimal range and critical level for occurrence of Al toxicity.*

| Growth stage | Plant part | Optimum ($mg\ kg^{-1}$) | Critical level for toxicity ($mg\ kg^{-1}$) |
|---|---|---|---|
| Tillering to panicle initiation | Shoot | 15–18 | >100 |

Yellow to white mottling of interveins is followed by leaf tip death and leaf margin scorch. Necrosis of chlorotic areas occurs if Al toxicity is severe (Table 36). Aluminum toxicity reduces shoot and root growth. Varieties differ in their tolerance of Al toxicity. In susceptible cultivars, roots are stunted and deformed. Growth is stunted, but tillering may be normal. Retarded root growth results in reduced nutrient uptake and less drought tolerance. Al also affects growth indirectly by inducing Mg deficiency.

## Plant

Tillering capacity (total number of tillers per plant) appears to be a useful, early indicator for assessment of the effect of Al on grain production. Al-resistant and Al-sensitive varieties cannot be differentiated by biomass production or mineral concentrations (K, Ca, Mg, P, Al) in the shoots and roots of rice plants.

## Soil

Al saturation of >30%, soil pH ($H_2O$) <5.0, and >1–2 mg Al $L^{-1}$ in soil solution indicate potential Al toxicity.

## Effect of submergence on Al toxicity

Al toxicity is a major constraint in upland soils under aerobic and acid soil conditions. Upon flooding, soil pH increases and Al concentration in soil solution decreases and generally falls below the critical level for Al toxicity. Under such conditions, Fe toxicity (Section 4.1) is more likely to occur than Al toxicity.

## Causes of Al toxicity

Excess $Al^{3+}$ concentration in soil solution is caused by low soil pH (<5). The concentration of Al in soil solution depends on soil pH as well as the concentration of organic and inorganic compounds that can form complexes with Al.

## Occurrence of Al toxicity

Al toxicity rarely occurs in lowland rice except in some soils where soil reduction after flooding proceeds very slowly. Aluminum toxicity is one of the major factors limiting crop production on acid upland soils, however, and is often associated with strong P fixation and P deficiency (Section 3.2). Al toxicity occurs on the following soils:

- Acid upland soils (Ultisols, Oxisols) with large exchangeable Al content. Al toxicity often occurs together with Mn toxicity (Section 4.4).
- Acid sulfate soils, particularly when rice is grown as an upland crop for a few weeks before flooding (e.g., Thailand).
- Flooded soils with pH <4 before Fe toxicity symptoms appear.

## Preventive strategies for Al toxicity management

General measures to prevent Al toxicity are as follows:

- Varieties: Plant Al-tolerant cultivars, which accumulate less Al in their foliage and absorb Ca and P efficiently even in the presence of Al. Al-tolerant cultivars include IR43, CO 37, and Basmati 370 (India), Agulha Arroz, Vermelho, and IAC3 (Brazil), IRAT 109 (Côte d'Ivoire), and Dinorado (Philippines).
- Crop management: Delay planting until pH has increased sufficiently after flooding (to immobilize Al).
- Water management: Provide crops with sufficient water to maintain reduced soil

*Table 37. Materials for treating Al toxicity in rice.*

| Name | Formula | Content | Comments |
|---|---|---|---|
| Lime | $CaCO_3$ | 40% Ca | |
| Dolomite | $MgCO_3$ + $CaCO_3$ | 13% Mg, 21% Ca | Slow-acting, content of Ca and Mg varies |
| Gypsum | $CaSO_4 \cdot 2\ H_2O$ | 23% Ca, 18% S | Slightly soluble, slow-acting |
| Kieserite | $MgSO_4 \cdot 7\ H_20$ | 23% S, 16% Mg | Quick-acting |
| Langbeinite | $K_2SO_4 \cdot MgSO_4$ | 18% K, 11% Mg, 22% S | Quick-acting |
| Partly acidulated rock phosphate | $Ca_3(PO_4)_2$ | 10–11% P | >1/3 water-soluble |
| Rock phosphate, finely powdered | $Ca_3(PO_4)_2$ | 11–17% P, 33–36% Ca | Very slow acting (25–39% $P_2O_5$) |
| Single superphosphate | $Ca(H_2PO_4)_2 \cdot H_2O$ + $CaSO_4 \cdot 2\ H_2O$ | 12% S, 7–9 % P, 13–20% Ca | Soluble, quick-acting |

conditions. Prevent the topsoil from drying out.

- Fertilizer management: On acid upland soils with Al toxicity, pay special attention to Mg fertilization (Table 37) (Section 3.7). Al toxicity decreases when sufficient Mg is supplied. Liming with $CaCO_3$ may not be sufficient, whereas the application of dolomite instead of $CaCO_3$ not only raises the pH but also supplies Mg. Kieserite and langbeinite can be part of an integrated management strategy on acid upland soils to reduce Al toxicity, but are less cost-efficient than finely ground dolomite. Small amounts of kieserite and langbeinite (50 kg $ha^{-1}$) may have an effect similar to that of liming with more than 1,000 kg $CaCO_3$.

## Treatment of Al toxicity

Options for treatment of Al toxicity are as follows:

- Apply 1–3 t lime $ha^{-1}$ to raise pH. Determine the exact amount needed based on a lime requirement test.
- Ameliorate subsoil acidity to improve root growth below the plow layer by leaching Ca into the subsoil from lime applied to the soil surface. Supply anions $SO_4^{2-}$ or $NO_3^-$ to accompany $Ca^{2+}$ moving into the subsoil by applying gypsum, green manure crop, or urea with additional lime to neutralize the acidity generated in nitrification. $Cl^-$ is not an effective counter-ion.
- On acid upland soils, install soil erosion traps and incorporate 1 t $ha^{-1}$ of reactive rock phosphate to alleviate P deficiency (Section 3.2).

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# 4.6 Salinity

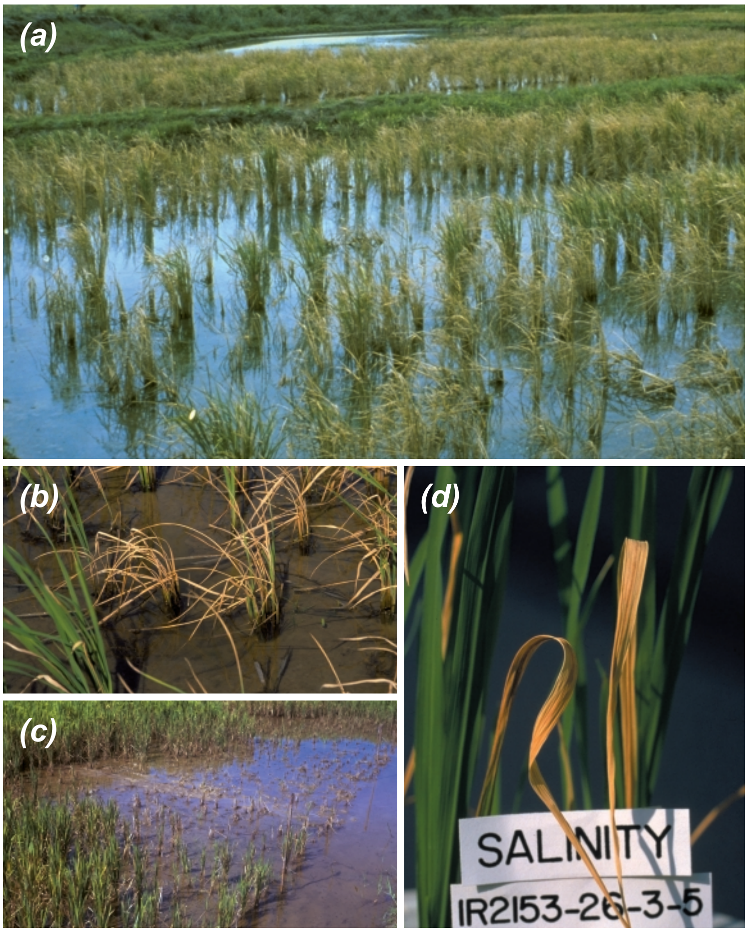
## *Mechanism of salinity injury*

Salinity is defined as the presence of excessive amounts of soluble salts in the soil (usually measured as electrical conductivity, EC). Na, Ca, Mg, chloride, and sulfate are the major ions involved. Effects of salinity on rice growth are as follows:

- Osmotic effects (water stress).
- Toxic ionic effects of excess Na and Cl uptake.
- Reduction in nutrient uptake (K, Ca) because of antagonistic effects.

The primary cause of salt injury in rice is excessive Na uptake (toxicity) rather than water stress, but water uptake (and rice plant transpiration) is reduced under high salinity. Plants adapt to saline conditions and avoid dehydration by reducing the osmotic potential of plant cells. Growth rate, however, is reduced. Antagonistic effects on nutrient uptake may occur, causing deficiencies, particularly of K (Section 3.3) and Ca (Section 3.8) under conditions of excessive Na supply. For example, Na is antagonistic to K uptake in sodic soils with moderate to high soil K status, resulting in high Na:K ratios in the rice plant and reduced K transport rates.

Sodium-induced inhibition of Ca uptake and transport limits shoot growth. Increasing salinity inhibits nitrate reductase activity,




***Salinity symptoms in rice***

*(a) Rice growth is characteristically patchy in soils affected by salinity. (b) Where saline irrigation water is used, patches of affected plants are found adjacent to water inlets. (c), (d) Plants are stunted and have white leaf tips.*

decreases chlorophyll content and photosynthetic rate, and increases the respiration rate and N content in the plant. Plant K and Ca contents decrease but the concentrations of $NO_3$-N, Na, S, and Cl in shoot tissue increase. Rice tolerates salinity during germination, is very sensitive during early growth (1–2-leaf stage), is tolerant during tillering and elongation, but becomes sensitive again at flowering.

Several factors affect the tolerance of different rice varieties to salinity:

- Transpiration rate and potential for osmotic adjustment.
- Differences in nutrient uptake under Na stress. Tolerant cultivars have a narrower Na:K ratio (greater K uptake) and greater leaf $Ca^{2+}$ content than susceptible cultivars.
- Efficient exclusion of $Na^+$ and $Cl^-$. Salt-tolerant rice varieties have reduced $Na^+$ and $Cl^-$ uptake rates compared with less tolerant cultivars.
- Rapid vegetative growth results in salt dilution in plant tissue.

## Salinity symptoms and effects on growth

### White leaf tips and stunted, patchy growth in the field.

Tips of affected leaves are white, and chlorotic patches appear on some leaves. Salinity results in plant stunting and reduced tillering. Field growth is very patchy. Symptoms appear in the first leaf, followed by the second, and then in the growing leaf. Rice is more tolerant of salinity at germination, but plants may become affected at transplanting, young seedling, and flowering stages. Salinity or sodicity may be accompanied by P deficiency (Section 3.2), Zn deficiency (Section 3.4), Fe deficiency (Section 3.9), or B toxicity (Section 4.3).

Further effects on rice growth are as follows:

- Reduced germination rate.
- Reduced plant height and tillering.
- Poor root growth.
- Increased spikelet sterility.
- Decreased 1,000-grain weight and total protein content in grain due to excess Na uptake (does not affect cooking quality).
- Decreased biological $N_2$ fixation and soil N mineralization.

## Plant

Greater Na content in rice plants may indicate salinity injury leading to yield loss. The critical concentration of salt (NaCl) in leaf tissue at which toxicity symptoms appear, however, differs widely between varieties. Varieties showing the greatest tolerance for salt within plant tissues are not necessarily those showing the greatest overall phenotypic resistance to salinity.

A correlation between Na:K ratio and salinity tolerance has been shown, but no critical ratio has been established in plant tissue. A Na:K ratio of <2:1 in the grain may indicate salt-tolerant rice varieties.

The Na:Ca ratio in plant tissue does not seem to be a good indicator of salinity. No effects on growth or NaCl concentration in the shoot were found over the range of Na:Ca ratios (5–25:1) commonly found in the field.

## Soil

For rice growing in flooded soil, EC is measured in the soil solution or in a saturation extract ($EC_e$). For upland rice grown at field capacity or below, EC in soil solution is about twice as great as that of the saturation extract. A rough approximation of the yield decrease caused by salinity is

$$\text{Relative yield (\%)} = 100 - [12(EC_e - 3)]$$

- $EC_e$ <2 dS $m^{-1}$: optimum, no yield reduction
- $EC_e$ >4 dS $m^{-1}$: slight yield reduction (10–15%)
- $EC_e$ >6 dS $m^{-1}$: moderate reduction in growth and yield (20–50%)

- $EC_e$ >10 dS $m^{-1}$: >50% yield reduction in susceptible cultivars

Exchangeable sodium percentage (ESP):

- ESP <20%: no significant yield reduction
- ESP >20–40%: slight yield reduction (10%)
- ESP >80%: 50% yield reduction

Sodium adsorption ratio (SAR):

- SAR >15: sodic soil (measured as cations in saturation extract)

## Irrigation water

- pH 6.5–8, EC <0.5 dS $m^{-1}$: high-quality irrigation water
- pH 8–8.4, EC 0.5–2 dS $m^{-1}$: medium- to poor-quality irrigation water
- pH >8.4, EC >2 dS $m^{-1}$: unsuitable for irrigation
- SAR <15: high-quality irrigation water, low Na
- SAR 15–25: medium- to poor-quality irrigation water, high Na
- SAR >25: unsuitable for irrigation, very high Na

## NOTES:

- Measurement of EC as an indicator of salinity is rapid and simple. EC alone, however, is insufficient to assess the effects of salinity on plant growth, because salt concentrations at the root surface can be much greater than in the bulk soil. In addition, EC only measures the total salt content, not its composition.
- Na and B (Section 4.3) must be considered as well. Salinity is highly variable in the field, both between seasons and within individual fields. Individual EC values must be treated with caution unless they are based on representative soil samples.
- From EC, the osmotic potential of the saturation extract can be estimated as

  *Osmotic potential (MPa) = EC x 0.036*

- If the samples do not contain much gypsum, EC measurements can be converted as follows:

  $EC_e = 2.2 \times EC_{1:1}$ *($EC_{1:1}$ measured in 1:1 soil:water suspension)*

  $EC_e = 6.4 \times EC_{1:5}$ *($EC_{1:5}$ measured in 1:5 soil:water suspension)*

## Effect of submergence on salinity

Submergence has two effects on salinity:

- An increase in EC because of the greater solubility of salts and the reduction of less soluble to soluble Fe and Mn compounds.
- Continuous percolation of the soil due to irrigation. If the EC in the irrigation water exceeds that of the soil solution, the concentration of salt in the soil will increase.

## Causes of salinity

Plant growth on saline soils is mainly affected by high levels of soluble salts (NaCl) causing ion toxicity, ionic imbalance, and impaired water balance. On sodic soils, plant growth is mainly affected by high pH and high $HCO_3^-$ concentration. The major causes of salinity or sodicity are as follows:

- Poor irrigation practice or insufficient irrigation water in seasons/years with low rainfall.
- High evaporation. Salinity is often associated with alkaline soils in inland areas where evaporation is greater than precipitation.
- An increase in the level of salinity in groundwater.
- Intrusion of saline seawater in coastal areas (e.g., Mekong Delta, Vietnam).

## Occurrence of salinity

Salt-affected soils (~11 M ha in South and Southeast Asia) are found along coastlines or in inland areas where evaporation is greater than precipitation. Salt-affected soils vary in their chemical and physical properties. Salinity is often accompanied by P and Zn deficiency, whereas Fe toxicity is common in acid sulfate saline soils.

Salt-affected soils can be grouped into:

- saline soils (EC >4 dS m$^{-1}$, ESP <15%, pH <8.5),
- saline-sodic soils (EC  4 dS m$^{-1}$, ESP >15%, pH ~8.5), and
- sodic soils (EC <4 dS m$^{-1}$, ESP >15%, pH >8.5, SAR >15).

Examples of salt-affected soils include:

- saline coastal soils (widespread along coasts in many countries),
- saline acid sulfate soils (e.g., Mekong Delta, Vietnam),
- neutral to alkaline saline, saline-sodic, and sodic inland soils (e.g., India, Pakistan, Bangladesh), and
- acid sandy saline soils (Korat region of northeast Thailand).

## *Preventive strategies for salinity management*

Varieties that tolerate salinity are available, but their use does not substitute for proper water and irrigation management. It is unlikely that breeders will be able to produce varieties with ever-increasing tolerance of salinity! A variety adapted to present levels of salinity may not survive if salinity increases because water management practices have not been corrected. Rice is a suitable crop for the reclamation of both sodic and saline soils. On sodic soils, rice cultivation results in a large cumulative removal of Na. On saline soils, cultivation practices lead to the loss of salts by leaching.

Management of salinity or sodicity must include a *combination* of measures. Major choices include the following:

- Cropping system: In rice-upland crop systems, change to double-rice cropping if sufficient water is available and climate allows. After a saline soil is leached, a cropping pattern that includes rice and other salt-tolerant crops (e.g., legumes such as clover or *Sesbania*) must be followed for several years.
- Varieties: Grow salt-tolerant varieties (e.g., Pobbeli, Indonesia; IR2151, Vietnam; AC69-1, Sri Lanka; IR6, Pakistan; CSR10, India; Bicol, Philippines). This is a short-term solution that may result in increased salinity over the longer term if other amelioration measures are not implemented.
- Seed treatment: In temperate climates where rice is direct-seeded, coat seed with oxidants (e.g., Ca peroxide at 100% of seed weight) to improve germination and seedling emergence by increased Ca and $O_2$ supply. Alternatively, treat rice seeds with $CaCl_2$ to increase seed $Ca^{2+}$ concentration.
- Water management: Submerge the field for two to four weeks before planting rice. Do not use sodic irrigation water or alternate between sodic and non-sodic irrigation water sources. Leach the soil after planting under intermittent submergence to remove excess salts. Collect and store rainwater for irrigation of dry-season crops (e.g., by establishing reservoirs). In coastal areas, prevent intrusion of salt water.
- Fertilizer management: Apply Zn (5–10 kg Zn ha$^{-1}$) to alleviate Zn deficiency (Section 3.4). Apply sufficient N, P, and K. The application of K (Section 3.3) is important because it improves the K:Na, K:Mg, and K:Ca ratios in the plant. Use ammonium sulfate as N source and apply N as topdressing at critical growth stages (Section 3.1) (basal N is less efficient on saline and sodic soils). In sodic soils, the replacement of Na by Ca (through the application of gypsum) may reduce P availability and result in an increased requirement for P fertilizer.
- Organic matter management: Organic amendments facilitate the reclamation of sodic soils by increasing the partial $CO_2$ pressure and decreasing pH. Apply rice

straw to recycle K. Apply farmyard manure.

## Treatment of salinity

Options for treatment of salinity are as follows:

- Saline soils: Salinity can only be reduced by leaching with salt-free irrigation water. Because rice has a shallow root system, only the topsoil (0–20 cm) needs to be leached. Cost, availability of suitable water, and soil physical and hydraulic characteristics determine the feasibility of leaching. To reduce the level of salinity in affected soils, electrical conductivity in the irrigation water should be <0.5 dS $m^{-1}$). Where high-quality surface water is used (EC ~0), the amount of water required to reduce a given $EC_e$ to a critical-level $EC_c$ can be calculated as follows:

  $$A_{iw} = A_{sat} [(EC_e/EC_c) + 1]$$

  where $A_{iw}$ represents the amount of irrigation water (cm) added during irrigation; and $A_{sat}$ is the amount of water (cm) in the soil under saturated conditions.

  For example, to lower an initial $EC_e$ of 16 dS $m^{-1}$ to 4 dS $m^{-1}$ in the top 20 cm of a clay loam soil ($A_{sat}$ = 8–9 cm), ~40 cm of fresh water is required. Subsurface drains are required for leaching salts from clay-textured soils.
- Sodic soils: Apply gypsum ($CaSO_4$) to reduce Na saturation of the soil (ESP, Na:K ratio). Because of complex chemical and physical interactions, it is difficult to calculate the exact amount of gypsum required. The amount of $Ca^{2+}$ contained in gypsum required to reduce the ESP to a target level can be estimated as follows:

  $$Ca\ (kg\ ha^{-1}) = (ESP_0 - ESP_d) \times CEC \times B \times D \times 20.04$$

  where $ESP_0$ is the original, $ESP_d$ is the target ESP value (% of CEC), CEC is in $cmol_c\ kg^{-1}$, B is the bulk density (g $cm^{-3}$), and D is the soil depth (m) to be reclaimed.
- Foliar application of K, particularly if a low-tolerance variety is grown on saline soil. Apply at the late tillering and panicle initiation stages.

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# 5

# Tools and Information

### *In this chapter*

# 5.1 Soil Zones, the Fate of Fertilizer Nitrogen, and the Rhizosphere in Lowland Paddy Soils

Lowland 'paddy' rice fields undergo a unique sequence of chemical and microbial transformations related to the changes in soil water content that occur during a cropping cycle. It is necessary to understand these processes to optimize the management of N and other nutrients.

## *Soil zones and N transformations*

Flooding a soil causes several chemical changes:

- Depletion of oxygen.
- Reduction of $NO_3^-$ and $NO_2^-$ to $N_2$ and $N_2O$.
- Reduction of $SO_4^{2-}$ to $S^{2-}$.
- Reduction of $Mn^{4+}$ to $Mn^{2+}$.
- Reduction of $Fe^{3+}$ to $Fe^{2+}$.
- Generation of $CO_2$ and $CH_4$.
- Decrease in soil redox potential.
- Increase in pH in acid soils and decrease in pH in alkaline soils.
- Increase in electrical conductivity in the soil solution.

Many of these processes increase the availability of nutrients such as P, K, Si, and Mo, but may decrease the availability of Zn, S, and Cu.

Several distinct zones develop in paddy rice soils following submergence:

- Beneath the aerated floodwater, a thin layer of soil (usually <10 mm) remains oxidized after flooding because of the diffusion of $O_2$ from the oxygenated floodwater above.
- Below this layer lies the bulk soil in a reduced state, because of the activity of anaerobic soil microorganisms that use nitrate ($NO_3^-$), sulfate ($SO_4^{2-}$), oxidized iron ($Fe^{3+}$), and manganese ($Mn^{4+}$), as terminal electron acceptors in the absence of $O_2$.
- A layer of compacted soil, the traffic pan, lies beneath the reduced layer.
- Below this zone, the soil may be oxidized (pseudogleys) or reduced (stagnogley) depending on the paddy field's position in the landscape and local hydrology.

The rice plant's rhizosphere remains oxidized even in the reduced bulk soil zone because of the transfer of $O_2$ from the atmosphere to the rhizosphere via aerenchyma in the rice plant. Healthy rice plant roots are thus orange-brown because iron compounds in the rhizosphere are in the oxidized $Fe^{3+}$ state.

Ammonium-N fertilizer placed in the reduced bulk soil (e.g., incorporated basally or by deep placement of materials such as urea tablets or briquettes) is hydrolyzed quickly. The resulting $NH_4^+$ ions may be absorbed by the rice plant, leached into the subsoil, temporarily immobilized in the soil organic-N pool, or adsorbed on the exchange complex (Figure 11). Some $NH_4^+$ ions may diffuse into the oxidized soil layer where they may be taken up by the rice plant, lost because of volatilization, or nitrified and leached back into the reduced soil, where denitrification may result in the loss of $NO_3$-N as N gases that percolate through puddled soil and escape at the soil surface.

When ammonium-N fertilizer (e.g., urea, ammonium sulfate) is topdressed over the surface of the floodwater, N may be lost as ammonia due to volatilization. Ammonia volatilization depends on the concentration of $NH_4^+$, temperature, wind speed, and diurnal fluctuations in pH because of biological activity in the floodwater. Alternatively, $NH_4^+$ ions

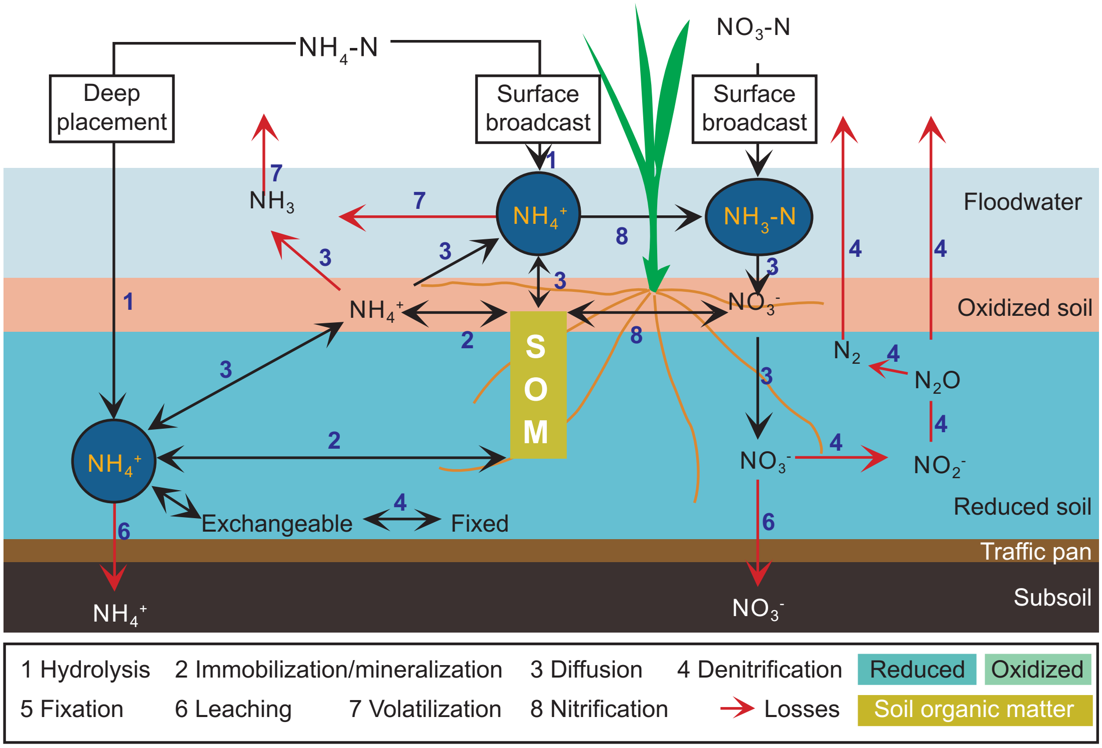


*Figure 11. Nitrogen cycle and N transformations in a flooded rice soil.*

diffuse into the oxidized soil following hydrolysis and are absorbed by the rice plant either directly or following nitrification, or become temporarily immobilized in the soil organic-N pool.

Following the nitrification of $NH_4$-N in the oxidized layer, $NO_3$-N is either taken up by rice roots or leached into the reduced soil layer, where it is denitrified and lost as $N_2O$ and $N_2$ gas. Ammonium ions may also diffuse into the reduced soil, where they are either absorbed by the rice plant, adsorbed on the exchange complex, or temporarily immobilized in the soil organic-N pool. $NH_4$-N may also be fixed in the interlayers of 2:1 lattice clays or bound abiotically to aromatic organic compounds such as phenols.

## The rhizosphere

Three main processes modify soil conditions near rice roots growing in anaerobic soil (Figure 12):

- Release of $O_2$ from roots, causing oxidation of ferrous iron $Fe^{2+}$ (due to soil reduction) and release of acidity:

$$4\ Fe^{2+} + O_2 + 10\ H_2O \rightarrow 4\ Fe(OH)_3 + 8\ H^+$$

- Release of $H^+$ ions from rice roots to balance cation-anion intake (i.e., maintain electrical neutrality across the root-soil interface), with nitrogen being taken up chiefly as the cation $NH_4^+$.
- Because of high partial pressure of $CO_2$ occurring in the anaerobic soil, roots may either release $CO_2$ or take it up from the soil. This results in corresponding changes in soil pH.

These changes in the rhizosphere occur as a result of rice growth in flooded soil and affect the solubilization and mobility of nutrients and toxins. Some of the known effects are as follows:

- Increased solubilization of P because of root-induced acidification (i.e., dissolution of acid-soluble, inorganic-P pools).

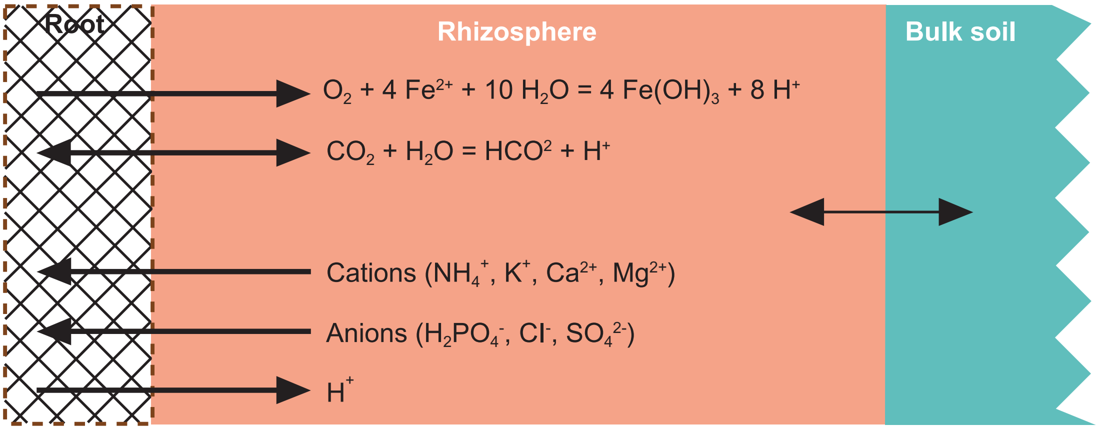


*Figure 12. Processes causing acidification of the rhizosphere of rice under submerged conditions.*

- Increased solubilization of Zn because of root-induced acidification (i.e., dissolution of acid-soluble, inorganic-Zn pools).
- Decreasing mobility of cations in the rhizosphere, because of a lack of counter anions (i.e., $HCO_3^-$ is the dominant anion species in many flooded, reduced soils, but its concentration in an acidified rhizosphere below pH 5.5 is decreased).
- Increased release of nonexchangeable K (i.e., replacement of interlayer K by $H^+$ formed during rhizosphere acidification).

Some of the mechanisms involved are not yet fully understood, but rice varieties differ in their capacity to release $O_2$ and oxidize the rhizosphere. Moreover, rice plants under nutrient stress, may actively increase the excretion of $O_2$ as well as organic acids to accelerate the release of nutrients from soil solids. This has been shown for P.

Maintaining a healthy, oxidized rhizosphere is important for optimal plant nutrition in rice as well as for tolerance for Fe (Section 4.1), sulfide (Section 4.2), and Mn toxicity (Section 4.4). A balanced supply of nutrients such as K, P, Ca, and Mg is required to sustain high root oxidation power in rice.

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## 5.2 Diagnostic Key for Identifying Nutrient Deficiencies in Rice

Nutrient deficiency symptoms in rice are mainly expressed in the color and size of the leaves, stems, and roots, plant height and tillering habit, the development of the root system, and the effect of nutrient deficiency on crop phenology, particularly in terms of advanced or delayed maturity. Most deficiencies are best detected during early stages of rice growth.

| Localized on older leaves first | | | | Localized on younger leaves first | | | | | | | Not localized symptoms |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Light green, narrow, short leaves | Dark green, narrow, erect leaves | Green to dark green leaves<br>Chlorotic-necrotic leaf margins<br>Rusty brown necrotic spots<br>Green and yellow stripes running parallel<br>Leaf rolling | Orange-yellow interveinal chlorosis, patchy<br>Pale overall color<br>Green coloring remains patchy (no stripes) | Soft, droopy leaves and culms | Light green, pale leaves<br>Chlorotic upper leaves<br>Whole plant affected, but upper leaves affected first | Chlorotic-necrotic split or rolled leaf tips<br>Symptoms only visible under severe deficiency | Interveinal yellowing and chlorosis of emerging leaves<br>Reduced chlorophyll content in leaves<br>Later, entire leaves chlorotic or whitish | Pale grayish green interveinal chlorosis at the tip of young leaves<br>Necrotic spotting | Chlorotic streaks<br>Bluish green leaves<br>Wilting young leaves | White, rolled leaf tips of young leaves<br>Death of growth point if severe | Soft, droopy leaves |
| Stunted plants<br>Poor tillering | Stunted plants<br>Poor tillering | Shorter plants | | Stunted plants<br>Poor tillering | Stunted plants<br>Reduced tillering | | | Shorter plants | Reduced tillering | Reduced plant height | |
| Whole field appears yellowish<br>Early maturity | Delayed maturity | Early wilting and maturity<br>Unhealthy root system<br>Increased incidence of diseases | Unhealthy root system | Uneven, patchy field growth | Delayed maturity | Unhealthy root system<br>Very rare in irrigated rice | Only on dry soil<br>Very rare in irrigated rice | Only on dry soil<br>Very rare in irrigated rice | Increased spikelet sterility | Panicle emergence fails<br>Very rare in irrigated rice | Lodging<br>Increased incidence of disease |
| **N** | **P** | **K** | **Mg** | **Zn** | **S** | **Ca** | **Fe** | **Mn** | **Cu** | **B** | **Si** |

# 5.3 Nutrient Concentrations in Plant Tissue

*Table 38. Optimal ranges and critical levels for occurrence of mineral deficiencies or toxicities in rice tissue.*

| Element | Growth stage | Plant part | Optimum range | Critical level for deficiency | Critical level for excess or toxicity |
|---|---|---|---|---|---|
| N | Tillering–PI | Y leaf | 2.9–4.2% | <2.5% | >4.5% |
| | Flowering | Flag leaf | 2.2–2.5% | <2.0% | |
| | Maturity | Straw | 0.6–0.8% | | |
| P | Tillering–PI | Y leaf | 0.20–0.40% | <0.10% | >0.50% |
| | Flowering | Flag leaf | 0.20–0.30% | <0.18% | |
| | Maturity | Straw | 0.10–0.15% | <0.06% | |
| K | Tillering–PI | Y leaf | 1.8–2.6% | <1.5% | >3.0% |
| | Flowering | Flag leaf | 1.4–2.0% | <1.2% | |
| | Maturity | Straw | 1.5–2.0% | <1.2% | |
| Zn | Tillering–PI | Y leaf | 25–50 mg $kg^{-1}$ | <20 mg $kg^{-1}$ | >500 mg $kg^{-1}$ |
| | Tillering | Shoot | 25–50 mg $kg^{-1}$ | <10 mg $kg^{-1}$ | >500 mg $kg^{-1}$ |
| S | Tillering | Y leaf | | <0.16% | |
| | Tillering | Shoot | 0.15–0.30% | <0.11% | |
| | Flowering | Flag leaf | 0.10–0.15% | <0.10% | |
| | Flowering | Shoot | | <0.07% | |
| | Maturity | Straw | | <0.06% | |
| Si | Tillering | Y leaf | | <5% | |
| | Maturity | Straw | 8–10% | <5% | |
| Mg | Tillering–PI | Y leaf | 0.15–0.30% | <0.12% | >0.50% |
| | Tillering–PI | Shoot | 0.15–0.30% | <0.13% | |
| | Maturity | Straw | 0.20–0.30% | <0.10% | |
| Ca | Tillering | Y leaf | 0.2–0.6% | <0.15% | >0.7% |
| | Tillering–PI | Shoot | 0.3–0.6% | <0.15% | |
| | Maturity | Straw | 0.3–0.5% | <0.15% | |
| Fe | Tillering | Y leaf | 75–150 mg $kg^{-1}$ | <70 mg $kg^{-1}$ | >300 mg $kg^{-1}$ |
| | Tillering | Shoot | 60–100 mg $kg^{-1}$ | <50 mg $kg^{-1}$ | |
| Mn | Tillering | Y leaf | 40–700 mg $kg^{-1}$ | <40 mg $kg^{-1}$ | >800 mg $kg^{-1}$ |
| | Tillering | Shoot | 50–150 mg $kg^{-1}$ | <20 mg $kg^{-1}$ | |
| Cu | Tillering | Y leaf | 7–15 mg $kg^{-1}$ | <5 mg $kg^{-1}$ | >25 mg $kg^{-1}$ |
| | Maturity | Straw | | <6 mg $kg^{-1}$ | >30 mg $kg^{-1}$ |
| B | Tillering | Y leaf | 6–15 mg $kg^{-1}$ | <5 mg $kg^{-1}$ | >100 mg $kg^{-1}$ |
| | Maturity | Straw | | <3 mg $kg^{-1}$ | >100 mg $kg^{-1}$ |
| Al | Tillering | Shoot | 15–18 mg $kg^{-1}$ | <5 mg $kg^{-1}$ | >100 mg $kg^{-1}$ |

*PI = panicle initiation*

*Table 39. Average nutrient removal of modern irrigated rice varieties and mineral concentrations in grain and straw.*

| N | P | K | Zn | S | Si | Mg | Ca | Fe | Mn | Cu | B |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Total nutrient removal with grain + straw (kg $t^{-1}$ grain yield) | | | | | | | | | | | |
| 17.5 | 3.0 | 17.0 | 0.05 | 1.8 | 80 | 3.5 | 4.0 | 0.50 | 0.5 | 0.012 | 0.015 |
| Nutrient removal with grain (kg nutrient in grain $t^{-1}$ grain yield) | | | | | | | | | | | |
| 10.5 | 2.0 | 2.5 | 0.02 | 1.0 | 15 | 1.5 | 0.5 | 0.20 | 0.05 | 0.009 | 0.005 |
| Nutrient removal with straw (kg nutrient in straw $t^{-1}$ grain yield) | | | | | | | | | | | |
| 7.0 | 1.0 | 14.5 | 0.03 | 0.8 | 65 | 2.0 | 3.5 | 0.30 | 0.45 | 0.003 | 0.010 |
| Mineral content in grain (%) | | | | | | | | | | | |
| 1.10 | 0.20 | 0.29 | 0.002 | 0.100 | 2.0 | 0.15 | 0.05 | 0.025 | 0.005 | 0.0010 | 0.005 |
| Mineral content in straw (%) | | | | | | | | | | | |
| 0.65 | 0.10 | 1.40 | 0.003 | 0.075 | 5.5 | 0.20 | 0.30 | 0.035 | 0.045 | 0.0003 | 0.0010 |

*Source: Summarized from various literature sources and recent measurements in farmers' fields and long-term experiments in Asia.*

# 5.4 Grain Yield and Yield Components

The grain yield (GY) of rice can be divided into its component parts (Table 40) (Section 5.9):

*GY (t ha$^{-1}$) = panicle number m$^{-2}$ x spikelet number per panicle x % filled spikelets x 1,000-grain weight (g) x10$^{-7}$*

*= spikelet number m$^{-2}$ x % filled spikelets x 1,000-grain weight (g) x 10$^{-7}$*

Each yield component is determined at a particular growth stage and is affected by weather conditions, nutrient supply, and crop management:

- Panicle number m$^{-2}$: In transplanted rice, tillering performance determines panicle number (PAN) m$^{-2}$, whereas in direct-seeded rice it largely depends on sowing rate and emergence percentage.
- Spikelet number per panicle: Determined during the reproductive stage (panicle initiation to heading), i.e., it depends on the overall number of differentiated primordia and the number of degenerated spikelets (SP).
- % filled spikelets: Determined before, at, and after heading. Unfavorable weather during anthesis, pests, or nutrient deficiencies (e.g., Cu) can cause spikelet sterility and reduce grain filling.
- 1,000-grain weight (TGW): Stable varietal characteristic controlled by size of hull.

Examples of typical model yield components for a transplanted (TP) or broadcast-sown (BS) rice crop yielding 8 t ha$^{-1}$ are as follows:

*TP: 8 t ha$^{-1}$ = 385 PAN m$^{-2}$ x 100 SP per panicle x 90% filled SP x 23 g TGW x 10$^{-7}$*

*BS: 8 t ha$^{-1}$ = 645 PAN m$^{-2}$ x 60 SP per panicle x 90% filled SP x 23 g TGW x 10$^{-7}$*

*Table 40. Ranges of grain yield and yield components in irrigated rice.*

| Parameter | Unit | Mean | Standard deviation | Min. | 25% Quartile | Median | 75% Quartile | Max. |
|---|---|---|---|---|---|---|---|---|
| Grain yield (14% MC) | t ha$^{-1}$ | 5.2 | 1.4 | 1.5 | 4.2 | 5.2 | 6.1 | 9.9 |
| Straw yield (DW) | t ha$^{-1}$ | 5.0 | 1.2 | 1.7 | 4.1 | 4.9 | 5.8 | 10.1 |
| Total dry matter | t ha$^{-1}$ | 9.9 | 2.3 | 3.2 | 8.4 | 10.0 | 11.4 | 17.1 |
| Grain to straw ratio | g g$^{-1}$ | 0.95 | 0.20 | 0.36 | 0.81 | 0.95 | 1.09 | 1.97 |
| Harvest index | g g$^{-1}$ | 0.47 | 0.05 | 0.25 | 0.44 | 0.47 | 0.51 | 0.63 |
| 1,000-grain weight | g | 23 | 3 | 15 | 21 | 23 | 25 | 31 |
| Panicles (PAN) m$^{-2}$ | PAN m$^{-2}$ | 490 | 206 | 146 | 330 | 488 | 617 | 1,573 |
| Spikelets (SP) m$^{-2}$ | SP m$^{-2}$ | 28,666 | 8,793 | 11,486 | 22,464 | 27,469 | 33,529 | 65,036 |
| SP PAN$^{-1}$ | | 67 | 26 | 19 | 46 | 60 | 87 | 152 |
| Filled SP PAN$^{-1}$ | | 54 | 23 | 14 | 35 | 48 | 72 | 135 |
| Filled SP % | % | 80 | 8 | 51 | 76 | 82 | 87 | 97 |

*Source: Farmers' fields in six tropical Asian countries; about 700 samples collected during 1995–97. (Witt et al 1999)*

# 5.5 Assessing Nitrogen Efficiency

The approach described below is equally applicable to other nutrients such as P and K, but N is used as an example.

Research that seeks to identify technologies for increasing N efficiency must use appropriate methods and performance standards to quantify N efficiency and make comparisons among different systems or genotypes. The efficiency of applied N fertilizer and N taken up by the rice crop can be assessed using five different indices:

1 Partial factor productivity (PFP)
2 Agronomic efficiency (AE)
3 Recovery efficiency (RE)
4 Physiological efficiency (PE)
5 Internal efficiency (IE)

All five indices can be estimated from field experiments using the so-called 'difference method.' Measurements are taken for fertilizer N use, grain yield, and total N uptake for several treatments, including one where no N is applied (control).

## Partial factor productivity (PFP) from applied nitrogen

*PFP answers the question: How much yield do I produce for each kg of N applied?*

$PFP_N$ = kg grain kg$^{-1}$ N applied:

$$PFP_N = GY_{+N} / FN \qquad (1)$$

where $GY_{+N}$ is the grain yield (kg ha$^{-1}$) and FN is the amount of fertilizer N applied (kg ha$^{-1}$).

Because GY at a given level of FN represents the sum of yield without N inputs ($GY_{0\,N}$) plus the increase in yield from applied N ($\Delta GY_{+N}$),

$$PFP_N = (GY_{0\,N} + \Delta GY_{+N})/FN \qquad (2)$$

or

$$PFP_N = (GY_{0\,N}/FN) + (\Delta GY_{+N}/FN) \qquad (3)$$

and by substitution with equation (5):

$$PFP_N = (GY_{0\,N}/FN) + AE_N \qquad (4)$$

where $AE_N$ is the agronomic efficiency of applied N (see below).

Equation (4) shows that $PFP_N$ can be increased by increasing the uptake and use of indigenous soil-N resources (measured as $GY_{0\,N}$) and increasing the efficiency of applied N use ($AE_N$).

Typically, $PFP_N$ in farmers' fields in Asia is 40–50 kg grain kg$^{-1}$ N applied, but can range from 15 to 100 kg kg$^{-1}$. With proper nutrient and crop management, $PFP_N$ should be >50 kg grain kg$^{-1}$ N applied.

## Agronomic efficiency (AE) of applied nitrogen

*AE answers the question: How much additional yield do I produce for each kg of N applied?*

$AE_N$ = kg grain yield increase kg$^{-1}$ N applied (often-used synonym: N use efficiency):

$$AE_N = (GY_{+N} - GY_{0\,N})/FN) \qquad (5)$$

where $GY_{+N}$ is the grain yield in a treatment with N application; $GY_{0\,N}$ is the grain yield in a treatment without N application; and FN is the amount of fertilizer N applied, all in kg ha$^{-1}$.

$AE_N$ represents the product of the efficiency of nutrient recovery from applied nutrient sources (= recovery efficiency, $RE_N$) and the efficiency with which the plant uses each unit of nutrient acquired (= physiological efficiency, $PE_N$):

$$AE_N = PE_N \times RE_N \qquad (6)$$

Both $RE_N$ and $PE_N$ thus contribute to $AE_N$, and each can be improved by crop and soil management practices, including general crop management practices and those specific to nutrient management, e.g., a more balanced N:P:K ratio or improved splitting and timing of N applications.

Because $AE_N = PE_N \times RE_N$, it is necessary to quantify the relative contribution of each component to explain measured differences in agronomic efficiency that result from different nutrient or crop management strategies.

Typically, the agronomic efficiency of N in farmers' fields in Asia is 10–15 kg grain $kg^{-1}$ N applied, but can range from 0 to 35 kg $kg^{-1}$. With proper nutrient and crop management, $AE_N$ should be in the range of 20–25 kg grain yield increase $kg^{-1}$ N applied.

## *Recovery efficiency (RE) of applied nitrogen*

*RE answers the question: How much of the N I applied was recovered and taken up by the crop?*

$RE_N$ = kg N taken up $kg^{-1}$ N applied:

$$RE_N = (UN_{+N} - UN_{0\,N})/FN \qquad (7)$$

where $UN_{+N}$ is the total plant N uptake measured in aboveground biomass at physiological maturity (kg $ha^{-1}$) in plots that received applied N at the rate of FN (kg $ha^{-1}$); and $UN_{0\,N}$ is the total N uptake without the addition of N.

Thus, the most common estimate of $RE_N$ is obtained by the 'nutrient difference' method based on measured differences in plant nutrient accumulation in treatment plots with and without applied nutrient (Equation 7). Recovery efficiency of applied nutrient is estimated more accurately when two treatments with a *small* difference in the application rate are compared:

$$RE_N = (UN_2 - UN_1)/(FN_2 - FN_1) \qquad (8)$$

where $RE_N$ is the recovery efficiency (kg N uptake $kg^{-1}$ N applied); UN is the total N uptake with grain and straw (kg $ha^{-1}$); and FN is the amount of fertilizer N added (kg $ha^{-1}$) in two different N treatments, e.g., Treatment 2 receiving a larger N rate than Treatment 1.

Equation 8 is also preferred over Equation 7 for nutrients such as P and K.

$RE_N$ largely depends on the fit between plant demand and quantity of N released from applied N (mineral or organic sources). Practical measures to increase $RE_N$ include the following:

1 Balanced nutrition of all nutrients.
2 Adjustment of FN according to supply of N from native resources (soil supply).
3 Adequate timing of split applications according to critical growth stages and plant N status, including the use of diagnostic tools such as the leaf color chart or chlorophyll meter.
4 Use of modified fertilizer materials and deep placement into the reduced soil layer (controlled-release fertilizer, urea supergranules, S-coated urea) to reduce N losses.
5 Urease or nitrification inhibitors.

Options 4 and 5 often have limited practical applicability due to the high cost of these fertilizer materials or the additional labor requirement for deep fertilizer placement. $RE_N$ is also affected by many crop management practices: variety, seed quality, crop establishment, water supply, and pest management.

Typically, the recovery efficiency of N in farmers' fields in Asia is 0.30–0.40 kg N $kg^{-1}$ N applied (30–40%), but can range from 0 to 90%. With proper crop management and plant-based N management strategies, recovery efficiencies of 50–70% can be achieved at the farm level.

## *Physiological efficiency (PE) of applied nitrogen*

*PE answers the question: How much additional yield do I produce for each additional kg of N uptake?*

$PE_N$ = kg grain yield increase $kg^{-1}$ fertilizer N taken up:

$$PE_N = (GY_{+N} - GY_{0\,N})/(UN_{+N} - UN_{0\,N}) \qquad (9)$$

where $GY_{+N}$ is the grain yield in a treatment with N application (kg $ha^{-1}$); $GY_{0\,N}$ is the grain yield in a treatment without N application; and UN is the total N uptake (kg $ha^{-1}$) in the two treatments.

$PE_N$ represents the ability of a plant to transform a given amount of acquired fertilizer nutrient into economic yield (grain) and largely depends on genotypic characteristics such as harvest index and internal nutrient use efficiency, which is also affected by general crop and nutrient management.

In a healthy rice crop with no significant constraints to growth, $PE_N$ should be close to 50 kg grain $kg^{-1}$ N taken up from fertilizer. Values below this suggest suboptimal growth conditions, which may include nutrient deficiencies, toxicities, water stress, and pest and disease incidence.

## Internal efficiency (IE) of nitrogen

*IE answers the question: How much yield is produced per kg N taken up from both fertilizer and indigenous (soil) nutrient sources?*

$IE_N$ = kg grain $kg^{-1}$ N taken up:

$$IE_N = GY/UN \qquad (10)$$

where GY is the grain yield (kg $ha^{-1}$), and UN is the total N uptake (kg $ha^{-1}$).

This definition of $IE_N$ includes N taken up from indigenous and fertilizer sources. $IE_N$ largely depends on genotype, harvest index, interactions with other nutrients (Section 2.5) and other factors that affect flowering and grain filling.

In farmers' fields, the typical $IE_N$ values are 50–60 kg $kg^{-1}$ with fertilizer N application, compared with 60–80 kg $kg^{-1}$ if no N is applied.

## Interpretation of N efficiencies

N efficiencies for irrigated rice in South and Southeast Asia are shown in Table 41. Most of the values are well below the N efficiencies usually obtained in well-managed research experiments ('optimum value'), and this suggests that there is significant potential for improving N efficiency on rice farms.

The following points should be considered when assessing N use efficiency:

- $PFP_N$ is the most important parameter for farmers because it integrates the use efficiency of both indigenous and applied nutrient resources. Increasing the uptake and use of indigenous soil N resources and increasing the efficiency of applied N use ($AE_N$) are equally important in improving the level of N efficiency ($PFP_N$) in the system.
- Both $RE_N$ and $PE_N$ contribute to $AE_N$, and each can be improved by crop and soil management practices, including general crop management practices and those specific to nutrient management, i.e., balanced nutrition and optimum splitting, timing, and placement of N applications.

*Table 41. Current N use efficiencies in irrigated lowland rice fields in Asia.*

| | Median | IQ range | Optimum value |
|---|---|---|---|
| Fertilizer N (kg $ha^{-1}$) | 111 | 86–139 | – |
| GY (kg $ha^{-1}$) | 5,150 | 4,000–5,900 | – |
| $GY_{0\,N}$ (kg $ha^{-1}$) | 4,000 | 3,100–5,000 | – |
| INS (kg N $ha^{-1}$) | 52 | 41–62 | – |
| $PFP_N$ (kg grain $kg^{-1}$ N) | 44 | 32–58 | ≥50 |
| $AE_N$ (kg grain $kg^{-1}$ N) | 10 | 4–17 | ≥20 |
| $RE_N$ (kg N $kg^{-1}$ N) | 0.26 | 0.14–0.43 | ≥0.50 |
| $PE_N$ (kg grain $kg^{-1}$ N) | 35 | 22–49 | ≥50 |
| $IE_N$ (kg grain $kg^{-1}$ N) | 58 | 51–68 | 68 |

*Source: Farmers' fields in six tropical Asian countries; about 700 samples collected during 1995–97. (Witt et al 1999)*

- Estimates of AE are confounded by crop management options (e.g., crop establishment method, water regime, weed control). $AE_N$ and $RE_N$ are *not* appropriate indices for comparing N fertilizer efficiency in different cropping practices when there are significant differences in the grain yield between the control treatments (0 N applied). In this case, $PFP_N$ is a more appropriate index for making comparisons.
- Comparisons of $RE_N$ and $PE_N$ among genotypes should use agronomically fit varieties or lines, and avoid comparisons with 'inferior germplasm' not adapted to the particular growth conditions in the experiment.
- Crop nutrient requirements should be estimated based on nutrient interactions that determine physiological efficiency and internal efficiency of nutrient use (Section 2.5).

## Factors affecting N response curves

Nitrogen response curves and related N use efficiencies depend on many factors: overall soil and crop management, splitting and timing of fertilizer N applications, genotype, and economic conditions. In Figure 13, the four different quadratic N response curves (of the form $Y = b_0 + b_1FN - b_2FN^2$) illustrate how some of these factors affect N response functions and the different parameters of N use efficiency.

## Applicability

For farmers to accept new technologies, there must be an economically significant increase in grain yield. Thus, technologies must focus on increasing yield *and* N efficiency. Proper general crop management, in combination with balanced nutrition and dynamic N management, offers the greatest promise for this.

Technologies that only save some fertilizer but do not lead to significant yield increases are less likely to be accepted, as there is little profit to be gained from the additional hassle, or the cost involved may be large. This is currently the case for many deep-placement technologies and slow-release fertilizers.

Technologies for N management should never be treated as stand-alone technologies but should always be seen in the context of integrated crop management.

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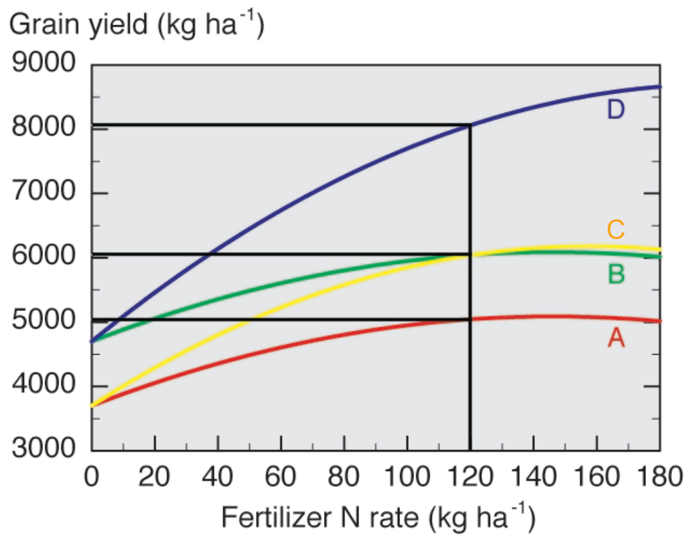



*Figure 13. Examples of different N response functions and associated N use efficiencies at N rate of 120 kg ha$^{-1}$.*

| | Example | | | |
|---|---|---|---|---|
| | A | B | C | D |
| $GY_{0\,N}$ (kg ha$^{-1}$) | 3,700 | 4,700 | 3,700 | 4,700 |
| $GY_{120\,N}$ (kg ha$^{-1}$) | 5,040 | 6,040 | 6,040 | 8,060 |
| $AE_{120\,N}$ (kg grain kg$^{-1}$ N) | 11 | 11 | 20 | 28 |
| $RE_{120\,N}$ (kg N kg$^{-1}$ N) | 0.30 | 0.30 | 0.40 | 0.55 |
| $PE_{120\,N}$ (kg grain kg$^{-1}$ N) | 38 | 38 | 50 | 50 |
| $PFP_{120\,N}$ (kg grain kg$^{-1}$ N) | 42 | 50 | 50 | 67 |

***Example A***

Typical average N response function found in many farmers' fields in Asia. The soil has moderate fertility ($GY_{0\,N}$ = 3.7 t ha$^{-1}$) and nitrogen fertilizer use efficiencies (AE, RE, PE, PFP) are low. This is a poor N response curve because N applications are not congruent with soil supply and crop N demand or because other constraints to growth (poor crop establishment, mineral deficiencies/toxicities, water stress, pests) occur and limit grain yield.

***Example B***

Upward-shifted N response function, i.e., increase in the intercept ($GY_{0\,N}$) and $GY_{120\,N}$ but no change in the curvature. In this case, $GY_{0\,N}$ (= the indigenous N supply) increased by ~1 t ha$^{-1}$, whereas fertilizer use efficiencies remained the same. Only PFP increased because of the greater grain yield. An increase in $GY_{0\,N}$ may be due to an improved variety, amelioration of mineral toxicities or deficiencies that restricted uptake of indigenous N, or measures that increased the indigenous N supply. The latter can include an upland crop grown before rice, a longer and thoroughly dry fallow period, or application of organic materials such as crop residues or farmyard manure, including residual effects from previously grown crops. Despite the yield increase, however, AE, RE, and PE are the same as in Example A, suggesting poor fertilizer N management or the existence of other constraints to growth (poor crop establishment, mineral deficiencies/toxicities, water stress, pests).

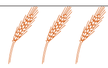
***Example C***

Shift in the curvature of the N response function, i.e., increase in $GY_{120\,N}$ but no change in $GY_{0\,N}$ (INS). In this case, $GY_{0\,N}$ has remained the same as in Example A (3.7 t $ha^{-1}$), but the slope of the response function has increased. At 120 kg N $ha^{-1}$ applied, grain yield is the same (6 t $ha^{-1}$) as in Example B. We can assume that this was achieved either by better timing and amount of split applications or by improved crop management (more balanced mineral nutrition, less pests) or both. Compared with Example A, all N efficiency parameters (AE, RE, PE, PFP) as well as yield have increased significantly. This is a typical response curve found in many on-station field experiments, but also achieved by better-practice farmers. The maximum yield achieved, however, is only ~6.2 t $ha^{-1}$, suggesting that management is not optimal yet.

***Example D***

Shift in the intercept and curvature of the N response function, i.e., increase in both $GY_{0\,N}$ and slope through a combination of measures. We can interpret this curve as an optimal N response curve, i.e., full exploitation of yield potential coupled with high nutrient efficiency. This is achieved by full implementation of a site-specific, integrated crop management approach, including measures to increase $GY_{0\,N}$ (high-yielding variety, excellent seed quality and crop establishment, soil drying, etc.) as well as dynamic N management to match supply and crop demand as closely as possible. As a result, grain yield, AE, RE, PE, and PFP are high. The maximum yield achieved is ~8.6 t $ha^{-1}$, suggesting excellent soil, crop, and fertilizer management. Applying >120 kg N $ha^{-1}$ still results in significant yield increases, whereas in Examples A–C other factors prevent yield response beyond this N level.

The effect of different measures on N response functions can be summarized below:

| | Influence on $GY_{0\,N}$ | Influence on fertilizer N efficiency (i.e., response curve) |
|---|---|---|
| Soil drying, longer fallow periods, early, dry soil tillage |  |  |
| Upland crop grown before rice |  |  |
| Manure, crop residues |  |  |
| Balanced nutrition and amelioration of mineral toxicities/deficiencies |  |  |
| Variety |  |  |
| Adequate land preparation and crop establishment |  |  |
| Adequate water management |  |  |
| Improved timing and amount of topdressed applications | - |  |
| New fertilizer products (slow-release fertilizers, supergranules, inhibitors) | - |  |
| Deep placement of fertilizer N | - |  |

 = weak  = moderate  = strong

# 5.6 Tools for Optimizing Topdressed N Applications

Monitoring plant N status is an important means to improve the congruence between crop N demand and N supply from soil and applied fertilizer. Because leaf N content is closely related to photosynthetic rate and biomass production, it is a sensitive indicator of dynamic changes in crop N demand within a growing season. The N concentration of the most recent, fully expanded leaf is an index for determining the need for N topdressing.

Farmers generally use leaf color as a visual and subjective indicator of the crop's nitrogen status and need for N fertilizer application. Simple diagnostic tools have been developed to monitor plant N status for fine-tuning of N management. They allow farmers to adjust N applications in real time, i.e., based on the present plant N status, which is closely related to the indigenous N supply and season-specific climatic conditions that affect crop growth. Applying these tools may reduce N fertilizer requirements, increase N use efficiency, and reduce susceptibility to pest attack.

*[Note: The primary research done on SPAD and LCC is described in more detail in the references listed.]*

## Portable chlorophyll meter for N management in rice

The chlorophyll meter ('SPAD meter') is a simple, portable diagnostic tool used for monitoring crop N status *in situ* in the field. It provides a simple, quick, and nondestructive method for estimating the N concentration of the index leaf. When properly calibrated to locally important rice varieties and crop-growing conditions, it serves as an efficient tool for developing need-based, variable-rate N applications for rice crops. The method involves measuring a dimensionless 'SPAD value' which is then compared with a critical threshold value to decide whether and how much N needs to be applied.

## Critical SPAD values

For target grain yields approaching maximum yield levels, the N concentration of the uppermost, fully expanded leaf must be maintained at or above 1.4 g N $m^{-2}$ (expressed on a leaf area basis). Leaves with N at this critical level give a SPAD value of 35 regardless of development stage or genotype.

- A SPAD threshold of 35 works well for TPR in the dry season with semidwarf indica varieties.
- The threshold has to be adjusted downward to ~32 for wet-season TPR in the Philippines, where solar radiation is constrained by continuous, heavy cloud cover during the rainy season.
- For WSR in the Philippines, a SPAD threshold of 29–30 has been found optimum for broadcast WSR with a planting density of 800 productive tillers $m^{-2}$, and 32 for row WSR with 650 productive tillers $m^{-2}$.
- The SPAD threshold has to be kept at 35 for the kharif (wet) season, and 37 for the rabi (dry) season for rice in India, to obtain high yields, probably because of high radiation in both seasons.

Thus, local adaptation of the chlorophyll meter is important to fix the critical values for local conditions.

## Guidelines for using the chlorophyll meter for N management in rice

- SPAD measurements start at 14 DAT (for TPR) or 21 DAS (for WSR). Readings are taken once every 7–10 days, or close to critical growth stages, and continue until the crop starts flowering (first flowering).

*Table 42. Proposed amounts of N to be applied each time the SPAD value is below the critical level.*

| Growth period | Dry season | Wet season |
|---|---|---|
| | (kg N $ha^{-1}$) | |
| Early growth stage (TP–MT) | 30 | 20 |
| Rapid growth stage (MT–PI)* | 45 | 30 |
| Late growth stage (PI–FL) | 30 | 20 |

* *Apply the large N dose of 30 kg $ha^{-1}$ in the monsoon season or 45 kg $ha^{-1}$ in the dry season only once during the fast growing stage.*

- The *uppermost fully expanded leaf* (Y leaf) is chosen for SPAD measurement. The reading is taken on one side of the midrib of the leaf blade, midway between the leaf base and leaf tip. In the early stages, the leaf blade may be too narrow for measurements without touching the midrib. In this case, readings can be taken near the tip of the leaf, or even on the midrib.
- During measurement, *always shade the leaf being measured with* your body. Do not take readings under open sunlight.
- Take a *minimum of 10* readings from hills chosen randomly for each plot and calculate the average SPAD value.
- If the average SPAD reading is less than the established critical value 7–10 days after N application, topdress N without delay (Table 42).

Using a single SPAD threshold value requires frequent field measurements to determine the date of application. There is also the risk of missing applications at critical growth stages.

An alternative mode of operation is to use the SPAD meter for adjusting the amount of N applied at critical growth stages. In this case, SPAD readings are only taken at three to four predetermined growth stages, and grades of SPAD values are used as a means to determine how much N to apply. Table 43 shows preliminary recommendations for this, which, however, require further validation.

## Leaf color chart (LCC) for N management in rice

The first leaf color chart was developed in Japan. Chinese researchers at Zhejiang Agricultural University developed a much improved LCC and calibrated it for indica, japonica, and hybrid rice. This chart later became a model for the LCC currently distributed by IRRI's Crop Resources and Management Network (CREMNET) described here.

A leaf color chart for determining the N fertilizer needs of rice crops is a simple, easy-to-use, and inexpensive tool to increase N use efficiency in rice. The chart contains six green strips with the color ranging from yellowish green (No. 1) to dark green (No. 6). It has been calibrated with the chlorophyll meter and is used to guide nitrogen topdressing for rice crops. A simple instruction sheet in the local language accompanies the chart and explains to farmers how to determine the correct time of N application. The color chart is an ideal tool to optimize N use in rice cropping, irrespective of the nitrogen source applied – inorganic, organic, or biofertilizers.

## Critical color grades or LCC values

The critical leaf color reading for N topdressing ranges from 3 for varieties with light green foliage, (e.g., scented or aromatic rice varieties) to 4 for semidwarf indica varieties and 5 for rice hybrids. Similarly, the critical LCC grade is 4 for TPR and 3 for direct WSR under Philippine conditions. Crops showing a leaf

*Table 43. Proposed amounts of N to be applied depending on SPAD values at critical growth stages.*

| Growth stage | Transplanted rice (TPR) DAT | SPAD value | N (kg ha$^{-1}$) | Direct-seeded rice (DSR) DAS | SPAD value | N (kg ha$^{-1}$) |
|---|---|---|---|---|---|---|
| Early tillering | 14–20 | > 36 | 0 | 15–25 | >34 | 0 |
| | | 34–36 | 20 | | 32–34 | 20 |
| | | < 34 | 30 | | <32 | 30 |
| Active tillering | 20–35 | > 36 | 30 | 25–35 | >34 | 30 |
| | | 34–36 | 40 | | 32–34 | 40 |
| | | < 34 | 50 | | <32 | 50 |
| Panicle initiation | 40–50 | > 36 | 40 | 40–50 | >34 | 50 |
| | | 34–36 | 50 | | 32–34 | 60 |
| | | < 34 | 60 | | <32 | 70 |
| Heading to flowering | 55–65 | > 36 | 0 | 55–65 | >34 | 0 |
| | | 34–36 | 15 | | 32–34 | 15 |
| | | < 34 | 20 | | <32 | 20 |

*Values shown are for dry season crops with a yield target of 6–8 t ha$^{-1}$ and currently undergo further validation. They apply to semidwarf indica varieties (100–120 days) in transplanted and direct-seeded rice systems. Lower N rates must be used in the WSR.*

color below the critical values suffer from N deficiency and require immediate N fertilizer application to prevent yield losses. For locally important varieties and crop establishment methods, the critical LCC values can be redefined after 1–2 test seasons.

## Guidelines for using the leaf color chart

- LCC readings start at 14 DAT (for TPR) or 21 DAS (for WSR). Readings are taken once every 7–10 days until the first flowering.
- The *uppermost fully expanded leaf* (Y leaf) is chosen for LCC measurement because it best reflects the N status of rice plants. The color of a single leaf is measured by comparing the color of the middle part of the leaf with the standard color chart. If the leaf color falls between two grades, the mean of the two values is taken as the LCC reading. For example, if the leaf color lies between chart values 3 and 4, it is noted as 3.5.
- During measurement, *always shade the leaf being measured* with your body because the leaf color reading is affected by the sun's angle and sunlight intensity. If possible, all LCC readings should be taken at the same *time* of day by the same *person*.
- Take readings of *10 leaves from hills chosen randomly* in a field. If six or more leaves show color grades below the established critical values, apply N fertilizer without delay.
- For semidwarf indica varieties, the proposed amounts of N to be applied at different growth stages are the same as for using the SPAD meter (as indicated in Table 42).

## NOTES:

✍ Elimination of a basal N application may reduce tillering in fields with low soil N-supplying capacity. Therefore, decide whether basal application is required (as outlined in Section 2.1) and use SPAD or LCC to fine-tune the subsequent topdressed N applications.

- SPAD- or LCC-based N management will be most successful as part of an integrated, site-specific nutrient management strategy. To achieve optimum response to N fertilizer, other nutrients (P, K, S, Zn) must not be limiting. Therefore, adequate levels of other nutrients should be applied based on soil tests or local recommendations.
- P or K deficiencies (Sections 3.2 and 3.3, respectively) may cause darker leaf color, which leads to erroneous LCC readings. SPAD readings are less affected by this.
- Local calibration of SPAD or LCC is always required. A chlorophyll meter costs US$1,400 and individual farmers usually cannot afford one. Field researchers, extension soils specialists, crop consultants, and farmer cooperatives, however, can purchase chlorophyll meters to monitor crop N status and advise farmers on N fertilization, to verify the adequacy of existing N fertilizer recommendations, and to locally calibrate the less costly leaf color chart.

## *Further reading*

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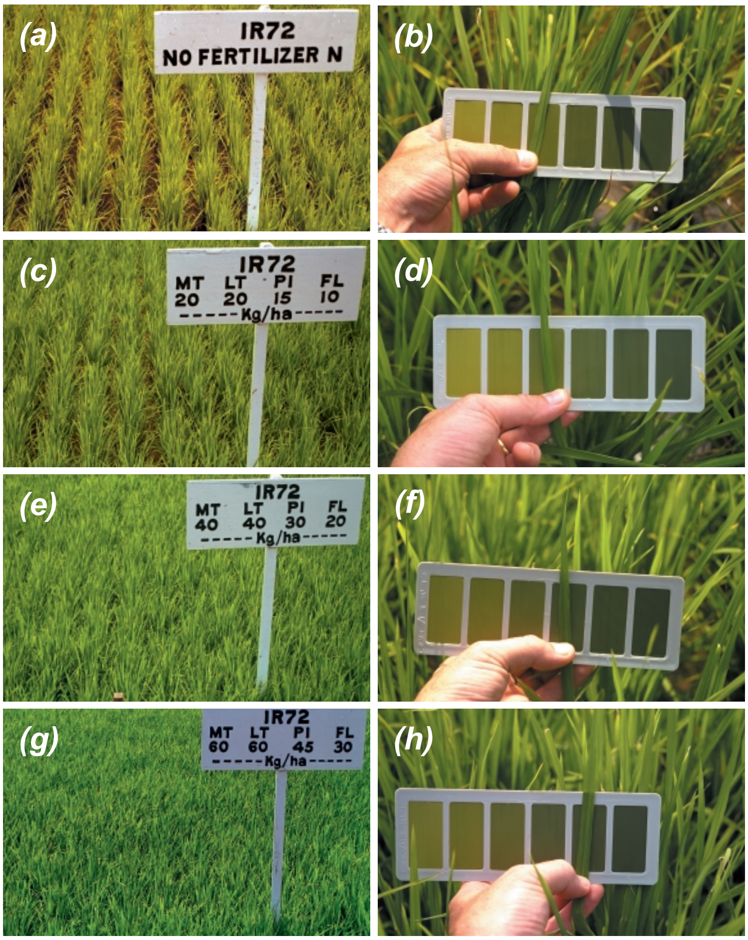


***Leaf color chart***

*Differences in leaf color between four N treatments at the late tillering stage can be measured using a leaf color chart (LCC). Note the greater tillering and darker green leaf color in the treatments supplied with larger amounts of N fertilizer (e.g., compare (g), (h) with the control plot (a), (b).*

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# 5.7 Soil- and Season-Specific Blanket Fertilizer Recommendations

Blanket fertilizer recommendations must be used with caution because climatic conditions (and therefore $Y_{max}$), varieties, crop management practices (crop establishment and water management), and soil fertility (indigenous nutrient supply) vary widely. The data shown in Table 44 give a general guide on how much N, P, and K must be applied to achieve a particular yield target, but further adjustments to local conditions should be made. This refers particularly to the splitting and timing of N applications (Section 3.1), which depends on variety, crop establishment method, and water management.

The fertilizer recommendations in Table 44 are valid for the following conditions:

- Variety: Modern high-yielding variety with a harvest index of 0.45–0.50, short- to medium-growth duration (100–120 days), and a potential yield ($Y_{max}$) of 10 t $ha^{-1}$ under favorable climate (dry season) and 7–8 t $ha^{-1}$ under humid, cloudy wet-season conditions.
- Crop establishment: Transplanted or direct-seeded, but with optimal plant density.
- Water management: Irrigated conditions. No severe drought stress or submergence during growth. River or canal water containing small amounts of nutrients is used for irrigation. If groundwater is used and contains significant amounts of K, the K rates recommended in Table 44 can be reduced.
- Pest management: Proper control of all major pests, including weeds, insects, diseases, snails, and rats.
- Fertilizer recovery
  - N: first crop recovery efficiency of 40–50%
  - P: first crop recovery efficiency of 15–25%
  - K: first crop recovery efficiency of 40–50%
- N management: Dynamic N application scheme based on splitting according to critical growth stages and monitoring of actual plant N status (Sections 3.1 and 5.9). Basal N is applied on soils with INS of <40 kg N $ha^{-1}$. Late N doses around the flowering stage are only given in the favorable (dry) season.
- P management: All P applied basally (incorporated in soil, transplanted rice) or 10–14 DAS in direct-seeded rice.
- K management: K dose split into two applications of 50% at planting (or 10–14 DAS in direct-seeded rice) and 50% at panicle initiation.
- Infertile soil: A soil with low inherent fertility because of one or more of the following:
  - Coarse soil texture (S, lS, sL).
  - Low organic matter content (<1% organic C).
  - Low CEC (<10 $cmol_c$ $kg^{-1}$).
  - Low available nutrient content (Olsen-P <5 mg $kg^{-1}$, exchangeable K <0.15 $cmol_c$ $kg^{-1}$).
  - Acid pH after submergence (i.e., <6.5).
  - Possibly other nutritional disorders (micronutrients or toxicities).

Indigenous nutrient supply in a favorable season:

- Unfertilized grain yield ($GY_0$): 2.5 t $ha^{-1}$
- INS: 30 kg N $ha^{-1}$
- IPS: 10 kg P $ha^{-1}$
- IKS: 50 kg K $ha^{-1}$

*Table 44. General soil- and season-specific fertilizer recommendations for irrigated rice.*

| Target yield | Dry season ($Y_{max}$ ~10 t $ha^{-1}$) | | | Wet season ($Y_{max}$ ~7.5 t $ha^{-1}$) | | |
|---|---|---|---|---|---|---|
| | N | P | K | N | P | K |
| (t $ha^{-1}$) | (kg $ha^{-1}$) | | | (kg $ha^{-1}$) | | |
| Low soil fertility | | | | | | |
| 4 | 60–80 | 8–12[a] | 20–40 | 60–80 | 8–12[a] | 20–25 |
| 5 | 90–110 | 15–25 | 50–60 | 90–120 | 15–25 | 50–60 |
| 6 | 120–150 | 25–40 | 80–100 | Yield target not applicable | | |
| 7 | 150–200[b] | 35–60 | 110–140 | | | |
| Medium soil fertility | | | | | | |
| 4 | 0[a] | 8–12[a] | 10–40[a] | 0[a] | 8–12[a] | 10–40[a] |
| 5 | 50–70 | 10–15[a] | 15–50[a] | 50–70 | 10–15[a] | 15–50[a] |
| 6 | 90–110 | 12–18 | 30–60 | 100–120 | 12–18 | 40–60 |
| 7 | 120–150 | 15–30 | 60–80 | Yield target not applicable | | |
| 8 | 160–200[b] | 35–50 | 110–130 | | | |
| High soil fertility | | | | | | |
| 4 | 0[a] | 8–12[a] | 10–40[a] | 0[a] | 8–12[a] | 10–40[a] |
| 5 | 0[a] | 10–15[a] | 15–50[a] | 20–30 | 10–15[a] | 15–50[a] |
| 6 | 50–60 | 12–18[a] | 20–60[a] | 60–80 | 12–18[a] | 20–60[a] |
| 7 | 80–100 | 14–21[a] | 20–70[a] | Yield target not applicable | | |
| 8 | 120–150 | 15–25 | 60–80 | | | |

*Source: QUEFTS model modified for rice. For each yield target, the model was run using the INS, IPS, and IKS assumed for each soil type and using the ranges of recovery efficiencies of N, P, and K specified above.*

[a] *The indigenous supply of P and K is sufficient to achieve this yield level with smaller or no fertilizer application.*

- *For N, this represents a situation where the input from other sources such as biological $N_2$ fixation is large enough to sustain the INS at this level.*
- *For P and K, we recommend applying at least an amount of P and K that is equivalent to the net P and K removal from the field with grain and straw (Sections 3.2 and 3.3) to maintain soil P and K supply. The values given assume a replenishment dose equivalent to a P removal of 2–3 kg P $ha^{-1}$ and a K removal of 3–10 kg K $ha^{-1}$ per ton of grain yield. The smaller value applies to systems in which most of the P and K in straw remains in the field, either incorporated or burned. The larger value applies to systems with a large removal of crop residues.*

[b] *Caution: The N dose recommended is very large and could cause lodging and increased pest incidence.*

- Fertile soil: A soil with moderate inherent fertility and the following characteristics:
  - Medium to heavy soil texture (clay loam to clay).
  - Moderate organic matter status (1–1.5% organic C).
  - Medium CEC (10–20 $cmol_c$ $kg^{-1}$).
  - Moderate available nutrient content (Olsen-P 5–10 mg $kg^{-1}$, exchangeable K 0.15–0.30 $cmol_c$ $kg^{-1}$).
  - Neutral pH after submergence (i.e., 6.5–7).
  - No significant micronutrient deficiencies or toxicities.

Indigenous nutrient supply in a favorable season:

- Unfertilized grain yield ($GY_0$): 4.0 t $ha^{-1}$
- INS: 50 kg N $ha^{-1}$
- IPS: 15 kg P $ha^{-1}$
- IKS: 75 kg K $ha^{-1}$

- Very fertile soil: A soil with high inherent fertility and the following characteristics:
  - Medium to heavy soil texture (CL-C).
  - Moderate-high organic matter status (1.5–2.5% organic C).
  - Large CEC (>20 $cmol_c$ $kg^{-1}$).
  - Large available nutrient content (Olsen-P >10 mg $kg^{-1}$, exchangeable K >0.3 $cmol_c$ $kg^{-1}$).
  - Neutral pH after submergence (i.e., 6.5–7).
  - No significant micronutrient deficiencies or toxicities.

Indigenous nutrient supply in a favorable season:

- Unfertilized grain yield ($GY_0$): >5 t $ha^{-1}$
- INS: 70 kg N $ha^{-1}$
- IPS: 20 kg P $ha^{-1}$
- IKS: 100 kg K $ha^{-1}$

# 5.8 Converting Fertilizer Recommendations into Fertilizer Materials

*Table 45. Conversion factors for nutrient concentrations in fertilizers.*

| From | multiply by | to get / From | multiply by | to get |
|---|---|---|---|---|
| $NO_3$ | 0.226 | N | 4.426 | $NO_3$ |
| $NH_3$ | 0.823 | N | 1.216 | $NH_3$ |
| $NH_4$ | 0.777 | N | 1.288 | $NH_4$ |
| $CO(NH_2)_2$ -urea | 0.467 | N | 2.143 | $CO(NH_2)_2$ -urea |
| $(NH_4)_2SO_4$ | 0.212 | N | 4.716 | $(NH_4)_2SO_4$ |
| $NH_4NO_3$ | 0.350 | N | 2.857 | $NH_4NO_3$ |
| $P_2O_5$ | 0.436 | P | 2.292 | $P_2O_5$ |
| $Ca_3(PO_4)_2$ | 0.458 | $P_2O_5$ | 2.185 | $Ca_3(PO_4)_2$ |
| $K_2O$ | 0.830 | K | 1.205 | $K_2O$ |
| KCl | 0.632 | $K_2O$ | 1.583 | KCl |
| KCl | 0.524 | K | 1.907 | KCl |
| $ZnSO_4 \cdot H_2O$ | 0.364 | Zn | 2.745 | $ZnSO_4 \cdot H_2O$ |
| $ZnSO_4 \cdot 7\ H_2O$ | 0.227 | Zn | 4.398 | $ZnSO_4 \cdot 7\ H_2O$ |
| $SO_2$ | 0.500 | S | 1.998 | $SO_2$ |
| $SO_4$ | 0.334 | S | 2.996 | $SO_4$ |
| $MgSO_4$ | 0.266 | S | 3.754 | $MgSO_4$ |
| $MgSO_4 \cdot H_2O$ | 0.232 | S | 4.316 | $MgSO_4 \cdot H_2O$ |
| $MgSO_4 \cdot 7\ H_2O$ | 0.130 | S | 7.688 | $MgSO_4 \cdot 7\ H_2O$ |
| $(NH_4)_2SO_4$ | 0.243 | S | 4.121 | $(NH_4)_2SO_4$ |
| $SiO_2$ | 0.468 | Si | 2.139 | $SiO_2$ |
| $CaSiO_3$ | 0.242 | Si | 4.135 | $CaSiO_3$ |
| $MgSiO_3$ | 0.280 | Si | 3.574 | $MgSiO_3$ |
| MgO | 0.603 | Mg | 1.658 | MgO |
| MgO | 2.987 | $MgSO_4$ | 0.335 | MgO |
| MgO | 3.434 | $MgSO_4 \cdot H_2O$ | 0.291 | MgO |
| MgO | 6.116 | $MgSO_4 \cdot 7\ H_2O$ | 0.164 | MgO |
| MgO | 2.092 | $MgCO_3$ | 0.478 | MgO |
| CaO | 0.715 | Ca | 1.399 | CaO |
| $CaCO_3$ | 0.560 | CaO | 1.785 | $CaCO_3$ |
| CaO | 0.715 | Ca | 1.399 | CaO |
| $CaCl_2$ | 0.358 | Ca | 2.794 | $CaCl_2$ |

*Table 45. (... continued).*

| From | multiply by | to get / From | multiply by | to get |
|---|---|---|---|---|
| $CaSO_4$ | 0.294 | Ca | 3.397 | $CaSO_4$ |
| $Ca_3(PO_4)_2$ | 0.388 | Ca | 2.580 | $Ca_3(PO_4)_2$ |
| $FeSO_4$ | 0.368 | Fe | 2.720 | $FeSO_4$ |
| $MnSO_4$ | 0.364 | Mn | 2.748 | $MnSO_4$ |
| $MnCl_2$ | 0.437 | Mn | 2.290 | $MnCl_2$ |
| $MnCO_3$ | 0.478 | Mn | 2.092 | $MnCO_3$ |
| $MnO_2$ | 0.632 | Mn | 1.582 | $MnO_2$ |
| $CuSO_4 \cdot H_2O$ | 0.358 | Cu | 2.795 | $CuSO_4 \cdot H_2O$ |
| $CuSO_4 \cdot 5\ H_2O$ | 0.255 | Cu | 3.939 | $CuSO_4 \cdot 5\ H_2O$ |
| $Na_2B_4O_7 \cdot 5\ H_2O$ | 0.138 | B | 7.246 | $Na_2B_4O_7 \cdot 5\ H_2O$ |
| $Na_2B_4O_7 \cdot 7\ H_2O$ | 0.123 | B | 8.130 | $Na_2B_4O_7 \cdot 7\ H_2O$ |

*Table 46. Molecular weights (g mol$^{-1}$) for nutrients.*

| Nitrogen | |
|---|---|
| N | 14.01 |
| $NH_4^-$ | 18.05 |
| $NO_3^-$ | 62.01 |

| Phosphorus | |
|---|---|
| P | 30.97 |
| $P_2O_5$ | 141.94 |

| Potassium | |
|---|---|
| K | 39.1 |
| $K_2O$ | 94.4 |
| KCl | 74.5 |

| Zinc | |
|---|---|
| Zn | 65.38 |
| ZnO | 81.4 |
| $ZnSO_4 \cdot H_2O$ | 179.5 |

| Sulfur | |
|---|---|
| S | 32.06 |
| $SO_4^{2-}$ | 96.06 |
| $SO_2$ | 64.1 |

| Silicon | |
|---|---|
| Si | 28.09 |
| $SiO_2$ | 60.1 |
| $SiO_3$ | 76.1 |

| Magnesium | |
|---|---|
| Mg | 24.31 |
| MgO | 40.31 |

| Calcium | |
|---|---|
| Ca | 40.08 |
| CaO | 56.08 |
| $CaSO_4$ | 136.14 |

| Iron | |
|---|---|
| Fe | 55.85 |
| $FeSO_4$ | 151.91 |

| Manganese | |
|---|---|
| Mn | 54.94 |
| $MnSO_4$ | 151.0 |

| Copper | |
|---|---|
| Cu | 63.55 |
| $CuSO_4$ | 159.61 |

| Boron | |
|---|---|
| B | 10.81 |
| $B_2O_3$ | 69.6 |
| $Na_2B_4O_7 \cdot 5\ H_2O$ | 227.2 |

*Box 8. Converting fertilizer recommendations into fertilizer materials.*

**Example for 2-ha plot size:**

Fertilizer recommendation (kg $ha^{-1}$):

120-60-50 = 120 kg N, 60 kg $P_2O_5$, and 50 kg $K_2O$ $ha^{-1}$
= 120 kg N, 26 kg P, and 42 kg K $ha^{-1}$

Available fertilizer materials (all in 50-kg bags):

| | |
|---|---|
| Urea | 46% N |
| Single superphosphate (SSP) | 18% $P_2O_5$ |
| Muriate of potash (MOP, KCl-60) | 60% $K_2O$ |
| Diammonium phosphate (DAP) | 18% N, 46% $P_2O_5$ |
| Compound fertilizer (14-14-14) | 14% N, 14% $P_2O_5$, 14% $K_2O$ |

1. Amount of fertilizer needed for 2-ha area using single-nutrient fertilizers

N: 120 kg N $ha^{-1}$ x 2 ha x 100/46 = 120 x 2 x 2.17 = 521 kg urea ***~ 10.5 bags urea***

P: 60 kg $P_2O_5$ $ha^{-1}$ x 2 ha x 100/18 = 60 x 2 x 5.56 = 667 kg SSP ***~ 13.5 bags SSP***

K: 50 kg $K_2O$ $ha^{-1}$ x 2 ha x 100/60 = 50 x 2 x 1.67 = 167 kg MOP ***~ 3.5 bags MOP***

2. Amount of fertilizer needed for 2-ha area using compound fertilizer 14-14-14 as the source of K, 14-14-14 and DAP as sources of P, and 14-14-14, DAP, and urea as sources of N

*a) Use 14-14-14 as K source*

50 kg $K_2O$ $ha^{-1}$ x 2 ha x 100/14 = 50 x 2 x 7.14 **= 714 kg (or ~ 14 bags) 14-14-14**

*b) Calculate P supplied in 14-14-14*

14 bags 14-14-14 = 700 kg 14-14-14 = 700 kg/(100/14)/2
= 49 kg $P_2O_5$ $ha^{-1}$ applied as 14-14-14

60 – 49 = balance of 11 kg $P_2O_5$ $ha^{-1}$ required

*c) Calculate amount of DAP required to supply balance required of 11 kg $P_2O_5$ $ha^{-1}$*

11 kg $P_2O_5$ $ha^{-1}$ x 2 ha x 100/46 = 11 x 2 x 2.17 **= 48 kg (or ~ 1 bag) DAP**

*d) Calculate N inputs from 14-14-14 and DAP*

14 bags 14-14-14 = 700 kg 14-14-14 = 700 kg/(100/14)/2
= 49 kg N $ha^{-1}$ applied as 14-14-14

1 bag DAP = 50 kg DAP = 25 kg/(100/18)/2 = 4.5 kg N $ha^{-1}$ applied as DAP

120 – (49 + 4.5) = balance of 66.5 kg N $ha^{-1}$ required

*e) Calculate amount of urea required to supply balance required of 66.5 kg N $ha^{-1}$*

66.5 kg N $ha^{-1}$ x 2 ha x 100/46.3 = 66.5 x 2 x 2.16 **= 287 kg (or ~ 6 bags) urea**

*Comment:*

*In this example, it is possible to implement the recommendations 'exactly' but in most cases, the inclusion of compound fertilizers results in over- or under-supply of one nutrient. Recommendations using single-nutrient fertilizers are easier to calculate and allow more precise application of each nutrient. Most of the P and K and 58 kg N $ha^{-1}$ is applied ≤2 weeks after planting, which might result in low N recovery efficiency (Figure 8, Section 3.1).*

# 5.9 Soil and Plant Sampling

Diagnosing nutrient deficiency requires complementary efforts in soil and plant analysis, but both are ineffective unless proper protocols are followed. In this section, we describe several standard methods for soil and plant sampling that have been used widely in recent on-station and on-farm research. Many other methods are also in use, but we particularly encourage the use of the detailed harvest sampling procedure in research because it allows us to assess the overall quality of sampling and sample processing.

## *Soil sampling for nutrient analysis*

### Soil sampling field experiments

This procedure is used for *regular* sampling of soil from small treatment plots (e.g., 20–70 $m^2$) of on-farm or on-station field experiments. It is particularly suitable for monitoring soil changes over time, where sampling a constant soil volume must be emphasized whenever a sample is collected. Sampling is done at tillering (20–40 DAT/DAS), *preferably at* 30 DAT or DAS, when the soil has settled and intensive nutrient uptake by rice begins. If it is necessary to determine the extractable inorganic N in soil, collect a separate soil sample for immediate determination of N on fresh, anaerobic soil.

Refer to Box 9 for step-by-step instructions on soil sampling in field experiments.

### Routine soil sampling in farmers' fields

For *routine* assessment of soil fertility, use samples collected shortly after harvest or before land preparation; the sampling design depends on the objective and prevailing field conditions. Because field sizes and available materials differ, the procedure can only be described in general terms, assuming a relatively small rice field of about 0.1–1 ha located in a flat area.

The main objective of routine sampling for advisory purposes is to obtain one sample representing the average nutrient content for the whole field. Therefore, a stratified random sampling strategy gives the most representative sample covering all parts of the field equally. If a significant slope affects the spatial distribution of soil properties, such as in an upland rice field, use a transect along the main direction of the slope for sampling. If different soil test values are required for different field parts, for example, if a map needs to be produced, use grid sampling to allow interpolation of soil test results.

Refer to Box 10 for step-by-step instructions on routine soil sampling in a farmer's field.

*Box 9. Procedure for regular soil sampling from small treatment plots in field experiments for the purpose of monitoring soil changes over time.*

**Equipment**

Standardized PVC sampling tube (e.g., 7.5 cm in diameter; 25 cm length for sampling 0–20 cm depth or 20 cm length for 0–15 cm depth), knife (to cut soil sample), plunger

Plastic bags or bottles (airtight), waterproof marker pen, labels

Plastic tray, porcelain mortar, 2-mm screen, 0.5-mm screen, desktop fan (if available)

**Timing**

Sampling is done at tillering (20–40 DAT/DAS), *preferably at* 30 DAT or DAS.

*Box 9. (...continued, last).*

**Records**

Mark the location of sample points on a map. If possible, take a global positioning system (GPS) reading for each sample point.

**Procedure**

1 Prelabel each plastic bag or bottle (using a waterproof marker) with essential sample information: site, sampling date, treatment, replication, plot number, sampling depth.

2 Push the sampling tube vertically into the soil until the marker indicating the required depth on the tube is at the same level as the soil surface. Cut the soil column at the bottom end of the tube with a knife and lift the core from the soil (secure the bottom with a free hand to avoid soil loss). Collect *four soil cores* per sampling plot.

3 Push the soil column out of the four sampling tubes (from the same sampling plot) onto a plastic tray using a plunger. Remove visible plant residues, foreign material, and debris, and destroy all aggregates and clods. Mix the soil thoroughly into one composite sample per plot.

5 Flatten the homogenized soil sample in the plastic tray and divide it into four equal portions. Take equal amounts of soil subsamples (at least 500 g of wet soil) from the four portions and place them in the prelabeled plastic containers. Return excess soil to the plot. Work fast to minimize exposure to sunlight and high temperatures.

6 Air-dry samples for 7–14 days at *room temperature* in a room with good air circulation (a fan accelerates drying). Avoid windy, open places with dust blowing around. Regularly break clods into smaller pieces to enhance drying.

7 Crush and sift the samples through a 2-mm screen. Do not use steel or iron tools for crushing if micronutrients (Fe, Zn, Cu) are to be measured. A porcelain mortar is preferable. The entire sample must be sifted.

8 Flatten the sifted soil sample and divide it into four equal parts. Take representative subsamples to constitute an air-dried sifted plot subsample for chemical and physical analysis.

9 For analyses requiring finely sifted soil, take another subsample from the 2-mm bulk sample. Crush this entire subsample and pass it through a 0.5-mm screen.

If it is planned to determine initial extractable and hot-KCl extractable $NH_4$-N, collect one additional fresh soil sample as a composite of two soil cores taken from each sampling plot. Minimize exposure to sunlight and high temperatures. Mix the two cores and place the subsample in a labeled, airtight plastic container. Carry out the KCl extraction as soon as possible. To minimize microbial activity, store samples in a refrigerator if they have to be kept for more than a day.

**Notes**

- The actual sampling depth should refer closely to the depth of the plowed soil layer. Sample 0–20 cm depth on deep soils, but only 0–15 cm on shallower soils with no deep plowing.
- Choose the sampling spots from the first 4–5 rows surrounding the harvest area (which is usually centered within the plot). Do not disturb the harvest area.
- Make sure that the sampling tube is pushed into the soil to the exact and same depth for all samples collected.

To determine the extractable inorganic N in soil, a separate soil sample should be collected for immediate determination of N on fresh, anaerobic soil.

*Box 10. Procedure for obtaining one sample that represents the average nutrient content for a farmer's field.*

**Equipment**

Auger, knife (to cut soil sample), desktop fan (if available)

Waterproof marker pen, labels, bucket

Porcelain mortar, 2-mm screen, 0.5-mm screen

Airtight plastic bags or bottles

**Timing**

Samples are collected shortly after harvest or before land preparation

**Records**

Mark the location of sample points on a map. If possible, take a global positioning system (GPS) reading for each sample point.

**Procedure**

Use an auger that allows the collection of a uniform soil core for the whole plowed soil layer. Conical-shaped augers may lead to biases as *less* soil is sampled from the lower part of the desired sampling depth.

Sample 0–20 cm depth on deep soils, but only 0–15 cm on shallower soils where deep plowing is not practiced. Make sure that the auger is pushed into the soil to the exact and same depth for all samples collected.

1 Prelabel each plastic bag or bottle (using a waterproof marker) with essential sample information: site, sampling date, treatment, replication, plot number, sampling depth.

2 Roughly divide the field into 10–15 equal squares or rectangles. Collect one soil sample per square (randomly located within each square/rectangle).

4 Push the soil column out of the auger into a bucket. Remove visible plant residues, foreign material, and debris, and destroy all aggregates and clods. Mix everything thoroughly into one composite sample per field.

5 Take a subsample of at least 500 g fresh soil.

6 Air-dry samples for 7–14 days at *room temperature* in a room with good air circulation (a fan accelerates drying). Avoid windy, open places with dust blowing around. Regularly break clods into smaller pieces to enhance drying.

7 Crush and sift the samples through a 2-mm screen. Do not use steel or iron tools for crushing if micronutrients (Fe, Zn, Cu) are to be measured. A porcelain mortar is preferable. The entire sample must be sifted.

8 Flatten the sifted soil sample, divide it into four equal parts, and take representative subsamples to constitute an air-dried, sifted field subsample for chemical analysis.

9 For analyses requiring finely sifted soil, take another subsample from the 2-mm bulk sample. Crush this entire subsample and pass it through a 0.5-mm screen.

**Notes**

- ✍ If the spatial distribution of soil properties is significantly affected by the slope, use a transect along the main direction of the slope for sampling.
- ✍ If different soil test values are required for different parts of the field, use grid sampling to allow interpolation of soil test results.

## NOTES:

- Sampling soil to measure the dynamics of soil mineral N availability and soil microbial properties requires a large number of samples per area due to extreme microvariability of properties to be measured (particularly during early growth stages and after fertilizer application). About 30–40 soil samples must be collected to obtain a representative composite sample for a 0.25-ha field.

## Plant sampling for diagnosis of nutritional disorders

Interpreting deficiency symptoms becomes difficult when two or more nutrients are deficient, and when deficiency symptoms resemble those of pest and disease attack. For this reason, it is important to corroborate soil and, particularly, plant analysis with the analysis of leaf deficiency symptoms.

Critical levels have been identified for several nutrients (Section 5.3) but these values can vary according to climatic conditions, varieties, and growth stages. Thus, critical values should only be used with great caution.

Diagnostic sampling is carried out to determine the cause of deficiency symptoms and poor plant vigor. The following guidelines apply:

- Timing: Take samples when the plants show first symptoms of a nutritional disorder. Plants that have endured prolonged deficiency often develop unusual nutritional spectra and may be affected by secondary problems such as diseases. Many nutritional disorders in rice, particularly those of Zn, P deficiency, and Fe toxicity, are usually diagnosed best 2–4 weeks after planting.
- Location: Collect samples from areas where symptoms have been detected. Samples must reflect the variation in symptoms observed. If symptoms are patchy, take samples from severely deficient, moderately deficient, and slightly deficient plants of the same physiological age. Only one composite sample is required if the crop is uniformly affected. Ideally, submit paired samples representing normal and deficient plants for analysis.
- Plant part: The whole shoot, the leaf blades, or the Y leaf (the most recently fully developed leaf blade) are often used for tissue analysis in rice. Critical levels have been established for these parts. The following guidelines apply:
  - At early growth stages when plants are small (up to midtillering), sample whole plants (shoots) for nutrient analysis.
  - During late vegetative growth and the reproductive phase (until flowering), sample Y leaves for nutrient analysis.
  - To diagnose K deficiency, sample leaf sheaths because under K stress, K content in leaf blades tends to be maintained at the expense of leaf sheath K.
  - Mineral content in the grain is not suitable for diagnosis.
- Number of samples: For a precision of ±10%, randomly collect about 10–20 samples per field.
- Sampling and sample processing:
  1. Cut the plant part to be sampled. If whole shoots are sampled, rinse the basal parts with distilled water. If leaves or shoots are dusty, rinse the sample with distilled water (this can also be done in the laboratory before drying). To minimize contamination, do not collect samples shortly after pesticides have been sprayed.
  2. Place the sample in a clean paper bag and note the date, location, and any other important information on the bag.
  3. Dry the samples at 70°C until a constant weight is obtained (48–72 hours). Do not pack too many samples in the drying oven – good air circulation is needed for rapid and

even drying. When drying is complete, record the dry weight immediately after removal from the drying oven (to avoid rehydration).

4 Cut and grind the samples to <1 mm. Keep the samples in glass bottles with tight stoppers or in envelopes in a polyethylene bag. Store in a cool, dark place. Ensure that all samples are properly labeled. For longer storage, redry samples regularly to avoid growth of fungi.

5 Analyze samples for nutrient content. Before weighing samples for chemical analysis, redry the ground tissue at 70°C for several hours.

## *Plant sampling to determine grain and straw yield, yield components, and nutrient uptake*

A set number of hills (called *hill sample*) are collected at *physiological maturity* (PM), either in single treatment plots of a field experiment or in designated sampling plots (about 6 x 6 $m^2$) located within a larger farmer's field. This 'hill sample' is used for obtaining the harvest index (based on grain and straw yield in this sample), yield components, and nutrient uptake with grain and straw. PM is the point at which grain filling ends, typically several days before harvestable maturity.

Samples for determining yield components and total nutrient uptake are taken at PM to avoid loss of plant tissues to rapid weathering of straw that occurs in tropical climates. Therefore, make sure that sampling at PM is *not* delayed.

- For direct-seeded rice, two 0.25-$m^2$ quadrat samples are collected at PM to determine yield components and nutrient uptake.
- In transplanted rice, 12 hills are collected.

At full, *harvestable maturity* (HM), *plot grain yield* is measured from a 4–6-$m^2$ harvest area, centered within the treatment plot to be sampled. HM is determined by grain moisture, which is generally 18–23% at the time of harvest.

Using the harvest index obtained from the *hill sample*, the plot straw yield is estimated from the plot grain yield. Nutrient uptake in grain and straw is then calculated from NPK concentrations measured in the hill sample and the plot grain and straw yields.

Refer to Box 11 for step-by-step instructions on plant sampling.

### *NOTES:*

- For the same variety, sampling at PM may occur 3–5 days later in well-fertilized plots compared with unfertilized plots where the grain-filling duration is shorter.
- In experiments with larger plot sizes (>100 $m^2$), collect samples from two separate 6 x 6-$m^2$ sampling areas within each plot (both 12-hill sample and harvest area).
- All calculations should be done in an automated spreadsheet template containing all equations needed.
- Estimate grain yield from yield components and compare with actual grain yield measured in the 4–6-$m^2$ harvest area. Typically, GY estimated from yield components is about 10–15% greater than grain yield from the large grain-yield harvest area, but both should be highly correlated.
- When only grain yield, straw yield, and total nutrient uptake have to be measured, simplify the procedure by not measuring yield components and 1,000-grain weight. A *hill sample* is taken at physiological maturity, but this sample will only be used to determine grain:grain+straw ratio, or harvest index, and the nutrient contents in grain and straw. The harvest index and nutrient concentrations measured from this sample are then used to estimate straw yield and total nutrient uptake with grain and straw based on the grain yield

*Box 11. Procedure for measuring yield components and nutrient concentrations at physiological maturity.*

**Equipment**

Sharp knife, wooden or metal sampling frame (quadrat, 50 x 50 $cm^2$), large brown paper (or cloth) bags

Tap water, labels, waterproof marker pen, balance, drying oven

**Timing**

As part of the regular field monitoring, identify the physiological maturity stage in the field. PM is visually identified when grains on the lower portion of secondary and tertiary panicles reach the hard dough stage and begin to lose their green color.

**Records**

Mark the location of sample points on a map. If possible, take a global positioning system (GPS) reading for each sample point.

**Procedure: Collecting yield component samples**

- For transplanted rice (TPR) ('12-hill' sample):
  1. Obtain an estimate of the hill density (hill number $m^{-2}$) of the sampling plot. The number of hills ($TNH_{12}$) to be collected is roughly equal to one-half the hill density. For example, if hill density is 40 hills $m^{-2}$, 20 hills are needed.
  2. Collect plant samples around the grain yield harvest area. For example, if 20 hills are needed, choose five adjacent hills from each of the four sides of the grain yield harvest area.

     Alternatively, collect six adjacent hills from each of the longer sides of the grain yield harvest area, and four adjacent hills from each of the shorter sides.
  3. Cut all plants at the soil surface. Make sure that no leaves or stems (including dead tillers) are lost. Try to take these samples without smearing soil on the leaves or stems. Proceed to step 4.

- For direct-seeded rice (DSR) (0.5-$m^2$ sample):
  1. Collect plant samples from two 0.25-$m^2$ quadrats in the sampling zone surrounding the grain yield harvest area. Carefully place a wooden or metal sampling frame (50 x 50 $cm^2$) over the canopy. Make sure that only plants with their full stems within the 0.25-$m^2$ quadrat are collected. Pull out any weeds growing within the quadrat.
  2. Cut all plants within each quadrat at the soil surface. Make sure that no leaves or stems (including dead tillers) are lost. Try to take these samples without smearing soil on the leaves or stems.
  3. Pool the plant material from both 0.25-$m^2$ quadrats into *one composite 0.5-$m^2$ sample per sampling plot.*

- For both transplanted and direct-seeded rice:
  4. Carefully place the sample collected from Step 3 *head down* in large paper bags or cloth bags (to minimize loss of grain). Label the bag with essential site information: site, farm number, year, crop, growth stage, treatment, sampling date, and sampling plot number. Process the sample as soon as possible after sampling so

*Box 11. (... continued).*

that deterioration of the sample is minimized. If there is any soil on the stems, carefully rinse adhering soil off with clean tap water.

5 Count the number of all panicles in the 0.5-m² ($PAN_{0.5}$) or 12-hill sample ($PAN_{12}$) and calculate *panicles m⁻²* (PAN) as follows:

*Direct-seeded rice:* $PAN = PAN_{0.5} \times 2$

*Transplanted rice:* $PAN = (PAN_{12} \times HD)/TNH_{12}$

where $TNH_{12}$ is the total number of hills taken and HD is the average hill density equal to Nht (Box 12, Step 1) divided by the sampling area.

6 Strip all spikelets from the panicles. Strip *both* filled and unfilled spikelets and place them in a prelabeled paper bag. Place the remaining straw in another paper bag that has been labeled accordingly.

**Procedure: Processing the grain sample**

1 Oven-dry the whole sample at 70ºC for three days to reduce moisture content. After this initial drying, record the weight (g) of each sample ($SpW_{0.5}$ or $SpW_{12}$)

2 Immediately (do not let the grain rehydrate!) remove a subsample (30–40 g) and record subsample weight ($SpW_{SS}$).

3 Separate and count the total number of filled ($FSpNo_{SS}$) and unfilled spikelets ($UFSpNo_{SS}$) in the subsample.

4 Place filled and unfilled spikelets in separate, prelabeled bags and again oven-dry as before to attain complete oven-dryness.

5 To avoid rehydration, immediately weigh and record oven-dry weight of filled ($FSpODW_{SS}$) and unfilled spikelets ($UFSpODW_{SS}$) in each subsample. Save these subsamples for grinding and nutrient analyses. Calculate the oven-dry weight of filled spikelets for the 0.5-m² (or 12-hill) sample (*FSpODW*) as follows:

*DSR:* $FSpODW_{0.5} = FSpODW_{SS}/SpW_{SS} \times SpW_{0.5}$

*TPR:* $FSpODW_{12} = FSpODW_{SS}/SpW_{SS} \times SpW_{12}$

6 Calculate total spikelets per panicle (*SpPan*), filled spikelets per panicle (*FSpPan*), filled spikelet percentage (*FSpPct*), and 1,000-filled-grain weight based on yield components ($TGODW_{COYOD}$) using the following equations:

$$FSpPct = \left(\frac{FSpODW_{SS}}{(FSpODW_{SS} + UFSpODW_{SS})}\right)100$$

$$TGODW_{COYOD} = \left(\frac{FSpODW_{SS}}{FSpNo_{SS}}\right)1{,}000$$

$$FSpPan = \frac{FSpNo_{0.5}}{PAN_{0.5}}$$

$$SpPan = \left(\frac{FSpPan}{FSpPct}\right)100$$

*Box 11. (... continued, last).*

**Procedure: Processing of the straw sample**

1 Weigh and record the total fresh straw weight ($StFW_{0.5}$ or $StFW_{12}$) after removing all spikelets as described under Step 6.

2 To avoid moisture loss, take a representative straw subsample of 200–250 g *immediately* after weighing the total fresh weight. Record fresh weight of the subsample ($StFW_{SS}$).

Depending on the availability of oven-drying space, you can also dry the entire 0.5-$m^2$ straw sample at 70ºC to constant weight. Bend or cut straw samples in half so they will fit into the paper bags.

3 Oven-dry the straw subsamples at 70ºC to constant weight. Avoid overpacking samples in the oven – good air circulation is needed for rapid and even drying.

4 Record the final oven-dry weight of the subsample ($StODW_{SS}$). Calculate the oven-dry weight of the 0.5-$m^2$ (or 12-hill) sample (*StODW*) using

*DSR:* $StODW_{0.5} = (StODW_{SS}/StFW_{SS}) \times StFW_{0.5}$

*TPR:* $StODW_{12} = (StODW_{SS}/StFW_{SS}) \times StFW_{12}$

Save this subsample for grinding and nutrient analysis.

5 Calculate the grain:straw ratio (*GSR*) using

$GSR = FSpODW_{0.5}/StODW_{0.5}$ , *or*

$GSR = FSpODW_{12}/StODW_{12}$

6 Grind the samples of grain (from Step 5 in ‘Processing the grain sample’ procedure) and straw (from Step 4 above) and analyze their nutrient content. Calculate nutrient uptake with grain and straw using the grain yield and straw yield values obtained from Steps 8 and 9 in ‘Procedure for measuring grain yield at harvestable maturity from the 4–6-$m^2$ harvest area’ (Box 12).

measured at full maturity using a 4–6-$m^2$ harvest area.

✍ For simplified routine monitoring in farmers’ fields (no determination of yield components), obtaining a representative sample for the whole field is important. If growth is homogeneous and the field is small (<0.5 ha), collect samples as described earlier from three sampling plots (6 x 6 $m^2$ with a harvest area of 4–6 $m^2$ in each plot) randomly located within the field. An alternative strategy is to collect samples from about 10–20 different locations within the field following a stratified random sampling strategy (particularly if growth is more heterogeneous). At each location, collect a sample of 10–12 hills (or 0.25-$m^2$ sampling quadrats in DSR) within a 1 x 1-m area. Pool all subsamples into one composite sample per field and process to determine grain and straw yield and nutrient uptake. If only grain yield is measured, cut plants below the panicle. If grain and straw measurements are required, cut plants at the soil surface. In larger fields (>0.5 ha), collect samples from more locations (20–30).

## *Further reading*

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*Box 12. Procedure for measuring grain yield at harvestable maturity from the 4–6-m² harvest area.*

**Equipment**

Large brown paper (or cloth) bags, labels, waterproof marker pen, moisture meter, balance, blower, drying oven

**Timing**

Harvestable maturity (HM) is determined by grain moisture, which is generally 18–23% at the time of harvest.

**Records**

Mark the location of sample points on a map. Take a global positioning system (GPS) reading for each sample point.

**Procedure**

1 At HM, plot grain yield is measured from a 4–6-m² harvest area centered within the treatment lot to be sampled. If there are damaged hills (insects, diseases), estimate the pest damage, but *do not replace* the damaged hills with undamaged hills from outside the harvest area. Count the number of damaged hills (*Nhd*), undamaged hills (*Nhu*), and missing hills (*Nhm*) in the harvest area. Record the total number of hills in the grain-yield harvest area (*Nht*) as

$$Nht = Nhu + Nhd + Nhm$$

2 Cut all panicles and place them in bags labeled with site, date, treatment, replication, and plot number.

3 Thresh and clean the spikelets from each plot.

4 Dry these samples to reduce moisture content to 10–16%.

5 Remove unfilled spikelets using a blower.

6 Measure the weight of the filled spikelets for the whole plot sample (*PlotGY*, g) and *immediately* measure the grain moisture content ($MC_{PlotGY}$) with a moisture meter.

7 Correct the plot grain yield to 14% moisture content using

$$PlotGY_{14} = PlotGY \times [(100 - MC_{PlotGY})/86]$$

8 Calculate grain yield adjusted to 14% and 3% moisture content (in kg ha$^{-1}$) from plot grain yield and harvested area ($HA_{GY}$, m$^2$):

$$GY_{14} = (PlotGY_{14}/1{,}000) \times (10{,}000/HA_{GY})$$

$$GY_3 = GY_{14} \times 0.887$$

9 Calculate straw yield (in kg ha$^{-1}$):

$$StY_{OD} = GY_3/GSR$$

10 Measure 1,000-grain oven-dry weight in a grain subsample ($TGODW_{GY3}$) as follows:

(a) Oven-dry a representative 100-g grain subsample ($GY_{SS1}$) to constant weight at 70ºC.

(b) Dry, weigh, and record the oven-dry weight of a 30–35-g subsample ($GYODW_{SS2}$).

(c) Count the number of grains in the subsample ($GYNO_{SS2}$).

(d) Calculate $TGODW_{GY3}$:

$$TGODW_{GY3} = (GYODW_{SS2}/GYNO_{SS2}) \times 1{,}000$$

(e) Compare $TGODW_{GY3}$ with $TGODW_{COYOD}$ measured at physiological maturity in the 0.5-m² or 12-hill sample.

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# *Appendices*

# A1 Glossary & Abbreviations

**AE** see *agronomic efficiency.*

**Agronomic efficiency (AE)** Agronomic efficiency of an added nutrient. Grain yield increase per unit nutrient added. Expressed in kg $kg^{-1}$.

**Apex** The tip of a shoot or root.

**Auxin** Compound regulating plant growth.

**Cation exchange capacity (CEC)** The sum of exchangeable cations that can be adsorbed by a soil, soil constituent, or other material at a particular soil pH. Expressed in centimoles of positive charge per unit exchanger, $cmol_c$ $kg^{-1}$.

**CEC** see *cation exchange capacity*.

**$CEC_{clay}$** Cation exchange capacity of clay fraction. Expressed in $cmol_c$ $kg^{-1}$. Assuming an average CEC of the soil organic matter of 350 $cmol_c$ $kg^{-1}$ C, $CEC_{clay}$ can be estimated as follows:

$$CEC_{clay} = (CEC - 0.35 \times OC) \times 100/C$$

where OC = soil organic C content (g $kg^{-1}$) and C = soil clay content (%).

**Chlorophyll** Green pigment in plants required for photosynthesis.

**Chlorosis** Abnormal yellowing of plant tissue or whole leaves.

**DAS** Days after sowing a rice crop, used mainly for direct-seeded rice.

**DAT** Days after transplanting of rice seedlings.

**DSR** Direct-seeded rice.

**DTPA** Diethylenetrinitrilopentaacetic acid. Chelating agent for micronutrients.

**Dolomite** A mixture of calcium carbonate and magnesium carbonate.

**EDTA** Ethylenediamine tetraacetic acid. Chelating agent for micronutrients.

**ECEC** see *effective CEC.*

**Effective CEC (ECEC)** Sum of exchangeable Na + K + Ca + Mg + acidity. Expressed in $cmol_c$ $kg^{-1}$.

**Electrical conductivity (EC)** The electrolytic conductivity of an extract from saturated soil or a soil-water suspension at 25°C. Expressed in dS $m^{-1}$ (formerly mmhos $cm^{-1}$).

**Enzyme** An organic compound catalyzing a specific reaction in the cell.

**ESP** see *exchangeable sodium percentage*.

**Ethylenediamine tetraacetic acid** see *EDTA*.

**Exchangeable sodium percentage (ESP)** The fraction of the CEC of a soil occupied by Na ions (ESP = exchangeable Na x 100/CEC). Expressed as % of CEC.

**FK** Total amount of fertilizer K applied. Expressed in kg $ha^{-1}$.

**FN** Total amount of fertilizer N applied. Expressed in kg $ha^{-1}$.

**FP** Total amount of fertilizer P applied. Expressed in kg $ha^{-1}$.

**Grain yield (GY)** Cleaned (only filled spikelets) grain adjusted to 14% moisture content. Expressed in kg $ha^{-1}$ or t $ha^{-1}$.

**Harvest index (HI)** Grain dry matter/(grain + straw dry matter).

**HI** see *harvest index*.

**IE** see *internal nutrient efficiency*.

**IKS** see *indigenous K supply.*

**Indigenous nutrient supply** The cumulative amount of a nutrient, originating from all indigenous sources, that circulates through the soil solution surrounding the entire root system, during one complete crop cycle. For practical purposes, the potential indigenous nutrient supply is defined as the amount of each nutrient taken up by the crop from indigenous sources when all other nutrients are amply supplied and other limitations to growth are removed. Expressed in kg $ha^{-1}$ per crop. See also *indigenous N supply*, *indigenous P supply*, and *indigenous K supply*.

**Indigenous K supply (IKS)** Total K uptake in a K omission plot (0 K plot). Expressed in kg K $ha^{-1}$.

**Indigenous N supply (INS)** Total N uptake in an N omission plot (0 N plot). Expressed in kg N $ha^{-1}$.

**Indigenous P supply (IPS)** Total P uptake in a P omission plot (0 P plot). Expressed in kg P $ha^{-1}$.

**INS** see *indigenous N supply.*

**Internal nutrient efficiency (IE)** Kilograms of grain produced per kilogram of nutrient taken up with straw and grain. Also referred to as utilization efficiency. Expressed in kg $kg^{-1}$.

**IPS** see *indigenous P supply.*

**Interveinal** The area between leaf veins.

**Leaf blade** The broad, flat part of the leaf that provides most of the photosynthetic surface area.

**Lime** A soil amendment containing calcium carbonate ($CaCO_3$), magnesium carbonate ($MgCO_3$), and other materials. Used to neutralize soil acidity, and furnish Ca and Mg for plant growth.

**Meristem** Tissue of rapidly dividing cells, generally at the apex of shoot and root.

**Micronutrient** Nutrient required in very small amounts. Examples include Zn, B, Mo, Cu, Fe, and Mn.

**Mottle** An uneven, blotchy discoloration.

**Necrosis** Abnormal death of leaves or other plant tissue (not the entire plant) with a brownish color.

**Nutrient-limited yield** In irrigated rice, grain yield limited only by the supply of nutrients, assuming that water and pests are not limiting growth. Expressed in kg $ha^{-1}$.

**Partial factor productivity (PFP)** Grain yield per unit fertilizer nutrient applied. Expressed in kg $kg^{-1}$.

**PE** see *physiological efficiency*.

**Phloem** Specialized plant tissue mainly for transporting organic substances within the plant.

**Physiological efficiency (PE)** Physiological efficiency of applied nutrient = grain yield increase per unit nutrient taken up from applied fertilizer. Expressed in kg $kg^{-1}$.

**PI** Panicle initiation.

**Potential yield ($Y_{max}$)** Grain yield limited only by climate and genotype, assuming that no other factors limit growth. Also referred to as maximum yield. Expressed in kg $ha^{-1}$.

**PFP** see *partial factor productivity*.

**RE** see *recovery efficiency*.

**Recovery efficiency (RE)** Apparent recovery efficiency of an added nutrient = increase in nutrient uptake per unit nutrient added. Also sometimes referred to as uptake efficiency. Expressed in kg $kg^{-1}$.

**Senescence** The process leading to the death of a plant part (e.g., leaf) or the whole plant as the plant reaches maturity.

**Sodium adsorption ratio (SAR)** The relationship between soluble Na and soluble divalent cations. It is used to predict the ESP of soil equilibrated with a given solution:

$$SAR = Na/(Ca + Mg)^{1/2}$$

where Na, Ca, and Mg are the concentrations of Na, Ca, and Mg, respectively, in water, soil solution, or soil extract, expressed in mol $L^{-1}$.

**Soil and Plant Analysis Division** see *SPAD*.

**SPAD** Soil and Plant Analysis Division. Chlorophyll meter reading (dimensionless) used to quantify leaf N status.

**Spikelet** Plant structure bearing the grains in a rice panicle.

**Thousand-grain weight (TGW)** Weight of 1,000 oven-dried grains. Expressed in g.

**TPR** Transplanted rice

**TGW** see *Thousand-grain weight*.

**UK** Total K uptake with grain and straw. Expressed in kg $ha^{-1}$.

**UN** Total N uptake with grain and straw. Expressed in kg $ha^{-1}$.

**UP** Total P uptake with grain and straw. Expressed in kg $ha^{-1}$.

**Uptake efficiency** see *recovery efficiency*.

**Utilization efficiency** see *internal nutrient efficiency*.

**Withertip** Death of the leaf, beginning at the tip, usually in young leaves.

**WSR** Wet-seeded rice.

**Xylem** Specialized plant tissue for transporting water and inorganic substances (nutrients) from roots to leaves.

**Y leaf** The uppermost fully expanded leaf on a rice plant.

# A2 Measurement Units & Useful Numbers

## *Fertilizer rates*

All estimates of fertilizer rates are given on an elemental basis. To convert elemental nutrients into fertilizer nutrients, or *vice versa*, refer to Table 45 in Section 5.8.

## *Grain yields*

Grain yield values used in this book refer to cleaned grain (i.e., only filled spikelets) adjusted to 14% moisture content ($GY_{14}$). To convert $GY_{14}$ to oven-dry grain yield ($GY_3$, ~3% moisture content), use the following equation:

$$GY_{14} \times 86/97 = GY_3$$

## *Growth stages*

Rice has three maturity classes according to its crop growth stages:

| | Maturity class | | |
|---|---|---|---|
| | Very early | Early | Medium |
| *Transplanted rice (days after transplanting, DAT, 14-d-old seedlings)* | | | |
| Midtillering (MT) | 18 | 20 | 27 |
| Panicle initiation (PI) | 35 | 40 | 55 |
| Flowering (F) | 60 | 65 | 80 |
| Maturity (M) | 90 | 95 | 120 |
| *Direct-seeded rice (days after sowing, DAS)* | | | |
| Midtillering (MT) | 25 | 27 | 35 |
| Panicle initiation (PI) | 50 | 55 | 70 |
| Flowering (F) | 73 | 78 | 93 |
| Maturity (M) | 103 | 108 | 123 |

## *Nutrient input from crop residues*

If all cut straw is removed from the field, the amount of crop residues (kg dry matter $ha^{-1}$) can be estimated from stubble length using the following equation:

*Crop residues (kg $ha^{-1}$) = straw yield (kg $ha^{-1}$) x length of stubble (cm)/plant height at harvest (cm)*

The nutrient input from straw and stubble remaining in the field (i.e., gross input, assuming no losses, and straw is incorporated) can be estimated as follows:

*Nutrient input (kg $ha^{-1}$) = crop residues (kg dry matter $ha^{-1}$) x nutrient concentration in straw (%)/100*

## *Nutrient input from water*

The nutrient input from irrigation or rainwater can be estimated as follows:

*Nutrient input (kg ha$^{-1}$) = water input (mm ha$^{-1}$) x nutrient concentration (mg L$^{-1}$)/100*

For example, 1,000 mm of irrigation water or rainwater with a nutrient concentration of 1 mg K L$^{-1}$ adds 10 kg K ha$^{-1}$ to a rice field. Supplementary irrigation water use is typically in the range of 500–1,000 mm for a dry-season crop, and 0–500 mm for a wet-season crop.

## *Nutrient uptake*

All estimates of crop nutrient removal are given on an elemental basis. All plant nutrient concentrations are given as % or mg kg$^{-1}$ on a dry matter basis. To calculate nutrient uptake with grain and straw, use the following equation:

*Nutrient uptake (kg ha$^{-1}$) = $(GY_3 \times N_{Gr})/100 + (SY_3 \times N_{St})/100$*

where $GY_3$ = oven-dry grain (kg ha$^{-1}$); $SY_3$ = oven-dry straw (kg ha$^{-1}$); $N_{Gr}$ = nutrient concentration in grain (%); and $N_{St}$ = nutrient concentration in straw (%).

## *Soil nutrients*

The following units are used for soil nutrient availability and their conversions:

| SI units | non-SI units |
|---|---|
| mg kg$^{-1}$ | ppm |
| g kg$^{-1}$ (= % x 10) | % |
| $cmol_c$ kg$^{-1}$ | meq 100 g$^{-1}$ |

To convert soil nutrient contents from $cmol_c$ kg$^{-1}$ to mg kg$^{-1}$, use the following equation:

*mg kg$^{-1}$ = $cmol_c$ kg$^{-1}$ M/z x 10*

where M = molar mass in g mol$^{-1}$ (K: 39.10; Ca: 40.08; Mg: 24.30; Mn: 54.94; Al: 26.91) and z is the positive charge of the cation (K: 1; Ca, Mg, Mn: 2; Al: 3).

To convert mass-based soil nutrient contents (mg kg$^{-1}$) to volume-based field values (kg ha$^{-1}$), use the following equation:

*kg nutrient ha$^{-1}$ = mg kg$^{-1}$ soil x soil depth (m) x bulk density (g cm$^{-3}$) x 10*

Most rice soils have an effective rooting depth of 0.2 m and an average bulk density of about 1.25 g cm$^{-3}$ so that a rough estimate can be made as

*kg nutrient ha$^{-1}$ = mg nutrient kg$^{-1}$ soil x 2.5*

## *Straw yield*

For modern rice varieties with a harvest index (HI) close to 0.5, straw yield ($SY_3$, oven-dry, approximately 3% moisture content) can be estimated as

*$SY_3$ (kg ha$^{-1}$) = $GY_3/0.5 - GY_3$*

where $GY_3$ = grain yield adjusted to oven-dry grain (3% moisture content, kg ha$^{-1}$).

## *Roots*

The ratio of root dry weight to total dry weight ranges from ~0.2 at the seedling stage to ~0.1 at heading. For modern rice varieties with a harvest index close to 0.5, the approximate dry weight of roots remaining in the field at harvest can be estimated as follows:

*Root dry weight (kg ha$^{-1}$) = ($GY_3$ + $SY_3$) x 0.11*

where $GY_3$ = oven-dry grain (kg ha$^{-1}$) and $SY_3$ = oven-dry straw (kg ha$^{-1}$).

## *Unfilled spikelets*

The average nutrient uptake in unfilled spikelets is 2–4 kg N ha$^{-1}$, 0.4–0.8 kg P ha$^{-1}$, and 3–6 kg K ha$^{-1}$. Unfilled spikelets contain:

- 2–6% of the total N uptake (average 3.5%)
- 2–6% of the total P uptake (average 3.5%)
- 2–10% of the total K uptake (average 4.5%)
- ~7% of the total Si uptake

## *Local measurement units*

| | |
|---|---|
| *Bangladesh*<br>1 bushel = 0.73 maund = 29.17 seers = 60 lb<br>1 maund = 82.29 lb = 37.32 kg<br>1 seer = 2.05 lb = 0.93 kg<br>1 kg = 2.2046 lb = 1.07 seer<br>1 bushel per acre = 67.253 kg per ha<br>1 ha = 2.4711 acres; 1 acre = 0.4047 ha<br>1 lakh = 100,000<br>1 crore = 10,000,000 | *Myanmar*<br>100 measures rough rice = 1 basket<br>1 basket rough rice = 46 lb = 20.86 kg<br>1 basket milled rice = 75 lb = 34.02 kg<br>1 bag milled rice = 225 lb = 102.06 kg<br>1 pyi milled rice = 4.69 lb = 2.13 kg<br>1 maund = 0.037 mt; 1 mt = 26.792 |
| *Cambodia*<br>1 picul = 68 kg<br>1 mt = 14.7059 picul | *Malaysia*<br>1 picul brown rice = 133.33 lb = 60.48 kg<br>1 gantang rough rice = 5.60 lb = 2.54 kg<br>1 kati = 0.60478 kg |
| *China*<br>1 dou milled rice = 10 liters milled rice = 5 kg<br>1 dan milled rice = 100 liters milled rice = 50 kg<br>20 dan (picul) = 1 mt<br>1 jin (catty) = 0.5 kg = 1.1023 lb<br>1 mu = 0.067 ha; 15 mu = 1.0 ha<br>1 jin/mu = 7.5 kg/ha | *Pakistan*<br>1 kg = 2.2046 lb = 1.07 seer<br>1 quintal = 100 kg = 1.9684 cwt = 2.679 maunds<br>1 metric ton = 0.9842 long ton = 26.79 maunds<br>100 kg per ha = 1.4869 bushels per acre<br>1 bushel = 0.73 maund = 29.17 seers = 60 lb<br>Before 1980: 1 maund = 37.324 kg<br>After 1980: 1 maund = 40 kg |
| *India*<br>1 quintal = 100 kg<br>1 maund = 37.32 kg = 82.29 lb<br>1 Madras measure rice = 54 oz = 3.375 lb<br>1 acre = 0.4047 ha<br>In Gujarat: 4/7 bigha = 1 acre<br>In Rajasthan: 2 1/2 bighas = 1 acre<br>In West Bengal: 3 bighas = 1 acre<br>1 lakh = 100,000<br>1 crore = 10,000,000 | *Nepal*<br>1 seer = 0.80 kg (Hills); 1 seer = 0.93 kg (Terai)<br>1 mana = 0.3 kg rough rice<br>1 mana = 0.454 kg rice<br>1 maund = 37.32 kg rough rice (Terai)<br>1 khet = 1.3 ha<br>1 bigha = 0.67 ha (Terai)<br>1 matomuri = 0.13 ha = 0.25 ropani<br>1 ropani = 0.05 ha (Hills) = 4 muris<br>1 muri = 0.013 ha |
| *Indonesia*<br>1 liter rice = 0.8 kg<br>1 gantang rice = 8.58 liters = 0.0069 mt<br>1 mt rice = 145.69 gantang<br>Dry stalk rough rice (padi) to milled rice = 52%<br>Gabah kering (dry rough rice) to milled rice = 68%<br>Dry stalk rough rice (padi) to rough rice = 76.47% | *Philippines*<br>1 cavan rough/milled rice = 50 kg<br>1 ganta milled rice = 2.24 kg<br>Before 1973:<br>1 ganta = 3 liters<br>1 cavan rough rice = 44 kg<br>1 cavan milled rice = 56 kg |
| *Japan*<br>Rough rice x 0.728 = milled rice<br>Brown rice x 0.91 = milled rice<br>1 koku rough rice = 187.5 kg<br>1 sho milled rice = 1.425 kg<br>1 kan = 3.75 kg<br>1 tan = 0.1 cho = 0.09917 ha<br>1 cho = 10 tan = 2.4507 acres = 0.9917 ha<br>1 ha = 10.0833 tan = 1.0083 cho | *Sri Lanka*<br>1 bushel rough rice = 46 lb = 20.86 kg<br>1 bushel rough rice = 30.69 lb milled rice = 14 kg milled rice<br>1 bushel milled rice = 64 lb = 32 measures of rice<br>1 measure milled rice = 2 lb = 0.907 kg |
| *Korea (Republic of)*<br>1 seok milled rice = 144 kg<br>1 seok brown rice = 155 kg<br>1 seok rough rice = 100 kg<br>100 liters milled rice = 79.8264 kg<br>1 danbo = 0.1 jeongbo = 0.0992 ha<br>1 ha = 1.0083 jeongbo | *Thailand*<br>1 picul = 60 kg<br>1 kwein = 2,000 liters<br>1 ban = 1,000 liters<br>1 sat = 20 liters<br>1 thanan = 1 liter<br>1 kwein rough rice = 1 mt rough rice<br>1 rai = 0.16 ha = 0.395 acre |

# A3 Sources of Information

## *Publications*

The book is not referenced; instead, it lists useful publications at the end of each chapter. Some general references used throughout the book are listed below:

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## *Web sites*

URLs of relevant organizations are listed below:

| | |
|---|---|
| http://www.riceweb.org | IRRI/CIAT/WARDA, basic information on rice, databases, glossary |
| http://www.cigar.org/irri | IRRI's homepage, research facts, online reports |
| http://ricelib.irri.cgiar.org | IRRI library site, online catalog, electronic journals, links to other libraries worldwide |
| http://www.riceworld.org | IRRI Riceworld Museum |
| http://www.ppi-far.com | PPI/PPIC homepage, general information on nutrients |
| http://www.eseap.org | Information on nutrient management in Southeast Asia |
| http://nal.usda.gov/ag98 | AGRICOLA literature database and search site |
| http://apps.fao.org | FAOSTAT, production statistics, fertilizer use, databases |

# Other educational material by PPI

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- Field Handbook: Oil Palm Series Volume 1 – Nursery (109 p.)
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- Pocket Guide: Oil Palm Series Volume 4 – Immature (154 p.)
- Pocket Guide: Oil Palm Series Volume 5 – Mature (154 p.)
- Pocket Guide: Oil Palm Series Volume 6 – Immature (154 p.)
- Pocket Guide: Oil Palm Series Volume 7 – Nutrient Deficiency Symptoms and Disorders in Oil Palm (*Elaeis guineensis* Jacq.) (31 p.)
- Soil Fertility Management Slide Set (120 slides)
- International Soil Fertility Manual

### *In Spanish:*

- Guía de Bolsillo – Síntomas de Deficiencias de Nutrientes y Desórdenes en Palma Aceitera (*Elaeis guineensis* Jacq.) (31 p.)

### *In Bahasa Indonesia:*

- Buku Petunjuk: Oil Palm Series Volume 7 – Gejala Defisiensi Hara dan Kelainan pada Tanaman Kelapa Sawit (*Elaeis guineensis* Jacq.) (31 p.)
- Buku Saku: SebarFos – Proyek Pembangunan Pertanian Lahan Kering 1997–2000

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# Rice

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