Reference 15 Integrated soil fertility management

Summary

Integrated soil fertility management (ISFM) aims at the optimal and sustainable use of soil nutrient reserves, mineral fertilizers and organic amendments. We explain in this reference how to calculate mineral and organic fertilizer needs to obtain target yields as a function of the soil nutrient-supplying capacity (mainly nitrogen, N; phosphorus, P; potassium, K) and taking into account yield potential (determined by cultivar choice, sowing date and climate). Analysis of soil fertility using laboratory procedures is seldom possible in farmers' fields, and the relation between such analyses and rice growth is often poor, especially for nitrogen. This reference offers another method to determine the soil nutrient-supplying capacity. The rice yield from a mini-plot, with good soil-fertility management but without application of one nutrient (for instance, without N, P or K) is considered as an indicator of the capacity of the soil to supply that 'missing nutrient.'

To increase yield by 1 t/ha, nutrient uptake at maturity needs to increase by 15 kg N/ha, 6 kg P_2O_5/ha and 18 kg K_2O/ha. A well-balanced fertilization thus requires an application of 50 kg N/ha, 30 kg P_2O_5/ha and 60 kg K_2O/ha to increase yield by 1 t/ha, based on a recovery rate of applied fertilizer of 30% for N and K and of 20% for P. The recovery rate is the percentage of fertilizer effectively absorbed by the plant as compared to the quantity applied. These relations are approximate and only valid for yields not exceeding 70 to 80% of the potential yield. For higher yield targets, more nutrients have to be applied to get the same return, and this is not usually cost-effective. Nitrogen losses are irreversible, thus it is very important to increase the recovery rate of this nutrient. The recovery rate of nitrogen is strongly related to crop management. This reference provides instructions to help increase this recovery rate. For P and K, losses are much less (P and K are absorbed by the soil), and the residual effect of the fertilizer applied is often visible several years after application. Organic fertilizer can, to a certain extent, replace mineral fertilizers, but large quantities need to be applied as organic fertilizers have a low nutrient content. However, using both mineral fertilizers and organic amendments often has synergistic effects, increasing the soil's nutrient-supplying capacity in the long term and in some cases increasing the recovery rate of mineral fertilizer nutrients.

Soil fertility depends on the soil's origin (alluvial soils, soils derived from different types of parent rock, etc.), its texture, structure and organic-matter content, and the farmer's soil-fertility management in the past. Dark soils usually have high organic-matter content. Red soils, characteristic of a large part of Sub-Saharan Africa, are in general acidic and poor in organic matter.

Soils differ in their capacity to store nutrients available to plants. Clayey soils have a good capacity to store nutrients and to release them gradually to the plant roots, because they are composed of very fine particles. Sandy soils have a very limited capacity to store nutrients. Thus, the application of large quantities of fertilizer to sandy soils is not advised, because significant losses can be expected.

Organic-matter content is also important. A low organic-matter content has a harmful effect on soil structure and increases erosion risks. Soils with high organic-matter content have a higher waterholding capacity and are an important source of nutrients for the plants. Nutrients easily available to plants are localized either in the soil solution, or are adsorbed (concentrated in the topsoil) by the well-decomposed soil organic matter or the available clay particles. The outside surface of this well-decomposed soil organic matter and of available clay particles together form the *exchange complex*. Nutrients adsorbed by this exchange complex form a reserve of nutrients easily available to plants. This stock is gradually recharged by soil nutrient reserves that are less accessible to plants.

An increase in the organic-matter content cannot be reached within one or two cropping seasons, it is a long-term project. Improving soil texture requires large investments and is in practice impossible.

Soil-fertility management is crucial for maintaining or increasing the yields and incomes of the majority of farmers in Sub-Saharan Africa. How they manage that fertility not only determines the yield during the current season, but it can also have a significant impact on future yields.

The soil's nutrient stock can be enriched or depleted through farmers' management practices. For instance, the incorporation of crop residues in the soil and fertilizer application increase nutrients in the soil, while harvesting removes nutrients. This means that there are nutrient cycles in the soil that can be balanced or unbalanced. Without human intervention, these nutrient cycles are generally balanced. But such a situation is exceptional. Human intervention, e.g. introduction of mineral fertilizer or increase of cropping intensity (e.g. two crops per year on the same field instead of one crop) requires changes in soil-fertility management to avoid unbalanced nutrient cycles. Such instability may result in decreasing fertility and lower yields in the long run.

In sub-Saharan Africa, farmers are often obliged to mine their soils: they remove more nutrients than they return. In the uplands, farmers' practice of burning vegetation to facilitate soil preparation for cultivation decreases the carbon ratio in the soil and may result in leaching of significant amounts of other nutrients with the first rains. Farmers are also often obliged to use the same plot for several years without any fertilizer input. With each harvest, nutrients leave the field without being replaced. In order to increase soil fertility, farmers used to leave the plot fallow for some time. Unfortunately, this practice is increasingly being abandoned in Sub-Saharan Africa, where farmers are obliged to intensify their land use, often without compensating for nutrient losses. Without compensation, excessive nutrient exportation from the field may result in an imbalanced nutrition situation in the long term. Lowland soils are in general more robust and fertile than upland soils, but poor soil-fertility management of lowlands may also lead to nutrient-deficiency symptoms in the long term.

It has been estimated that during the last 30 years, an average of 22 kg nitrogen, 2.5 kg phosphorus and 15 kg potassium per hectare has been lost each year on 200 million of hectares of cultivated land in Sub-Saharan Africa (not including South Africa). This negative balance has a depleting effect on soil fertility and results in yield decreases.

Reference 15

Integrated soil fertility management

Nutrient stocks in the soil

Soil nitrogen reserves are localized in the organic matter. These reserves can be significant, but they are not easily available to plants. Nitrogen becomes available after the mineralization (decomposition) of this organic matter by micro-organisms in the soil. The nitrogen available to plants is either localized in the soil solution, or adsorbed on the clay–organic matter exchange complex (Box 15.1).

Phosphorus reserves are mostly found in organic matter and fixed by aluminum and iron oxides in the soil (Box 15.2).

Potassium reserves are largely dependent on the type of soil and on the minerals present. Clayey soils have large reserves of K. Available K is the sum of the soil-solution K and the K adsorbed by the exchange complex. Sandy soils are poorer in K than clayey soils (Box 15.3).

Box 15.1. How to estimate soil nitrogen reserves

For light-textured soils, 1 liter of soil weighs about 1.5 kg. Clayey soils tend to be heavier: about 1.7 kg/L of dry soil.

The volume of 1 ha of soil with a depth of 0.2 m is:

10,000 m^2 × 0.2 m of depth = 2000 m^3 of soil, i.e.

2000 × 1000 L = 2,000,000 L

This equals 2,000,000 × 1.5 kg of soil = 3,000,000 kg. A soil with a good supply of nitrogen contains about 0.1% nitrogen, i.e. 1 ha will contain about 3,000,000 kg × 0.1/100 = 3000 kg of nitrogen. Out of this, 1500 kg (50%) represents the 'dynamic reserve.' Only about 2% of this dynamic reserve is directly available for plants.

Estimation of nitrogen reserve (N) in the root zone (depth: 0.2 m)

N level in soil	% soil N	Available for crop (kg/ha)	Dynamic reserve (kg/ha)	Inert reserve (kg/ha)
Good level	> 0.1	> 30	> 1500	1500
Low level	0.05 – 0.1	15 – 30	750 – 1500	750 – 1500
Very low level	< 0.05	< 15	< 750	< 750

Box 15.2. How to estimate soil phosphorus reserves in the soil

Assuming we use the same soil as in Box 15.1. If soil analytical data indicate a P-Bray content (a proxy for plant-available P) of about 6 mg/kg, a total of 3,000,000 × 6 = 18,000,000 mg of P is available for the crop per hectare, or 18 kg of P per hectare. Total reserves in the soil are much more important. If soil analytical data indicate a P-total of 800 mg/kg, total reserves are about 2400 kg/ha.

Estimation of phosphorus reserves (P) in the rooting zone (depth: 0.2 m)

P level in soil	P-Bray		P-total	
	Laboratory data (mg/kg)	Available for crop (kg/ha)	Laboratory data (mg/kg)	Total reserves (kg/ha)
Good	> 25	> 75	> 800	> 2400
Average	6 – 25	18 – 75	200 – 800	600 – 2400
Low	3 – 6	9 – 18	100 – 200	300 – 600
Very low	< 3	< 9	< 100	< 300

Box 15.3. How to estimate the availability of potassium in the soil

Assuming we use the same soil as in Box 15.1. If laboratory data indicate a 0.10 cmol/kg of exchangeable K (a proxy for plant-available K) we first have to convert cmol into grams. This is possible using the atomic weight of K (39): 1 mol of K is equivalent to 39 grams, i.e. 1 cmol is equivalent to 0.39 grams of K. A ratio of 0.10 cmol/kg of exchangeable K represents for this soil a quantity of (3,000,000 × 0.1 × 0.39)/1000 = 117 kg of K/ha. The reserves in K are usually much higher, but can be very variable.

Estimation of potassium (K) available (exchangeable K) in the rooting zone (depth: 0.2 m)

K level in soil	Exchangeable K	
	Laboratory data (cmol/kg)	Available for crop (kg/ha)
Good	> 0.25	> 300
Average	0.10 – 0.25	120 – 300
Low	0.05 – 0.10	60 – 120
Very low	< 0.05	< 60

Mineral fertilizers

Nitrogen fertilizers

Two types of nitrogen fertilizer are commonly used in West Africa: urea containing 46% N and ammonium sulfate containing 20–21% N. Complex fertilizers used for phosphorus fertilization (such as di-ammonimum phosphate, containing 18% N and 46% P_2O_5) also sometimes contain N (*see* under phosphate fertilizers). For nitrogen fertilization, urea is the best type of fertilizer to use. It is not advisable to use fertilizer containing nitrate (NO_3) as a source of nitrogen, because nitrate is easily leached to the bottom of the profile, out of reach of the rice roots.

Example: a bag of 50 kg of urea contains 50 × 0.46 = 23 kg N.

Phosphorus fertilizers

Phosphorus can be applied as rock-phosphate or as mineral fertilizer. Phosphorus application has to be supported by N application. Red soils contain significant amounts of iron oxide. These oxides form a complex with P and fix P so that it is not available to the crop. With such soils, farmers will have to use very large quantities of phosphorus fertilizer for some to be available for the plants.

Single super phosphate (containing 18% P_2O_5) and triple super phosphate (TSP) (containing 46% P_2O_5) can be used. However, di-ammonium phosphate (DAP) or 18-46-0, containing 46% P_2O_5, is also available.

Examples: one 50-kg bag of TSP contains 50 × 0.46 = 23 kg P_2O_5, or 23 × [(2 × 31)/{(2 × 31) + (5 × 16)}] = 10 kg of P. (In this calculation, 16 is the atomic weight of O, and 31 the atomic weight of P). A 50-kg bag of DAP contains 50 × 0.18 = 9 kg N and 50 × 0.46 = 23 kg P_2O_5, or 10 kg of P.

Potassium fertilizers

Potassium sulfate and potassium chloride are the potassium fertilizers used in Sub-Saharan Africa. Nowadays, few farmers still use them, particularly when crop residues remain in the field. Potassium is mainly found in compound fertilizers, such as 10-20-20.

Example: a 50-kg bag of 10-20-20 contains 50 × 0.2 = 10 kg of K_2O or 10 × {2.39 / (2.39 + 16)} = 8.3 kg of K. (In this calculation 39 is the atomic weight of K, and 16 is the atomic weight of O.)

Organic amendments

An interesting option is the introduction of legumes into a crop production system. Legumes are often cultivated in rotation with cereals and are incorporated into the soil when they are still green. In the lowlands, this can be done during the dry season following wet-season rice. The advantage of green manure is that it increases the N content, improves the soil structure and increases the organic-matter content. They also often increase P availability in the soil. *Mucuna pruriens* is a rapidly growing legume, it suppresses weeds and can fix up to 60 kg N/ha per year. Other legumes, such as *Sesbania rostrata*, *Sesbania sesban*, *Tephrosia vogelii* and *Crotalaria* spp., have an N-fixing capacity of 10 to 50 kg N/ha. The N content of this green manure is between 2 and 4.3%. The N content of animal manure is extremely variable and mostly depends on the storage method. In general, the N content is rather low and does not exceed 0.5 to 1%.

The incorporation of crop residues will not always increase N availability. This is often the case when these residues, e.g. rice straw, have a poor N content as compared to their C content. The micro-organisms in the soil fix nitrogen to decompose the residues with large C/N ratios, which means that there is less N available for the plants in the short term. Rice straw is, however, an important source of K (straw has a K content of about 1.5%).

Compost is a mixture of partially decomposed plant material, such as weed and rice straw. Nitrogen content of compost is often between 0.3 and 0.9%.

When comparing the N contents of organic and mineral fertilizers, it is evident that large quantities of organic fertilizer are required to apply 30 or 40 kg N/ha. However, applying both mineral fertilizer and organic amendments often results in synergistic effects, increasing soil nutrient-supplying capacity in the long term, and sometimes even the recovery rate of nutrients applied with mineral fertilizers.

Site-specific integrated soil-fertility management

Integrated soil-fertility management aims at the optimal and sustainable use of nutrient stocks from the soil, mineral fertilizers and organic amendments. A procedure is given below for calculating fertilizer needs to reach target yields as a function of the soil nutrient-supplying capacity and potential yield.

Three steps are necessary:

- Fix a target yield.
- Estimate the capacity of the soil to supply N, P and K.
- Calculate fertilizer requirements.

Fixing a yield target

The potential or maximum yield of a crop (Y_{max}) is determined by the climate (minimum and maximum temperatures and solar radiation), sowing date and the characteristics of the variety chosen by the producer. For a given sowing date, Y_{max} is not constant but fluctuates from year to year because of climatic variability. It is evident that the producer cannot change the weather, but he/she can choose a sowing date that will allow him or her to exploit the weather conditions more productively and to choose a variety adapted to these conditions. Y_{max} can be obtained on experimental plots conducted under optimal growing conditions, where plant growth and development are not limited by factors other than solar radiation and temperature. Y_{max} is the real yield ceiling, limited by climate, sowing date and varietal choice. In practice, this yield cannot be reached in farmers' fields, and it would also not be cost-effective to try to do so. From an economical point of view, the maximum attainable yield,

Y_a is situated in the range of 70 to 80% of Y_{max}. The actual average farmer yield (Y_f) is often much lower because of a range of constraints that interfere with the rice crop, i.e. growth-limiting factors, such as lack of water and nutrient deficiencies, and growth-reducing factors, such as weed pressure, diseases and pests. With optimal management, best farmer yields (Y_{bf}) can be considerably higher than Y_f. Yield gaps between Y_{max}, Y_a , Y_{bf} and Y_f can be very important.

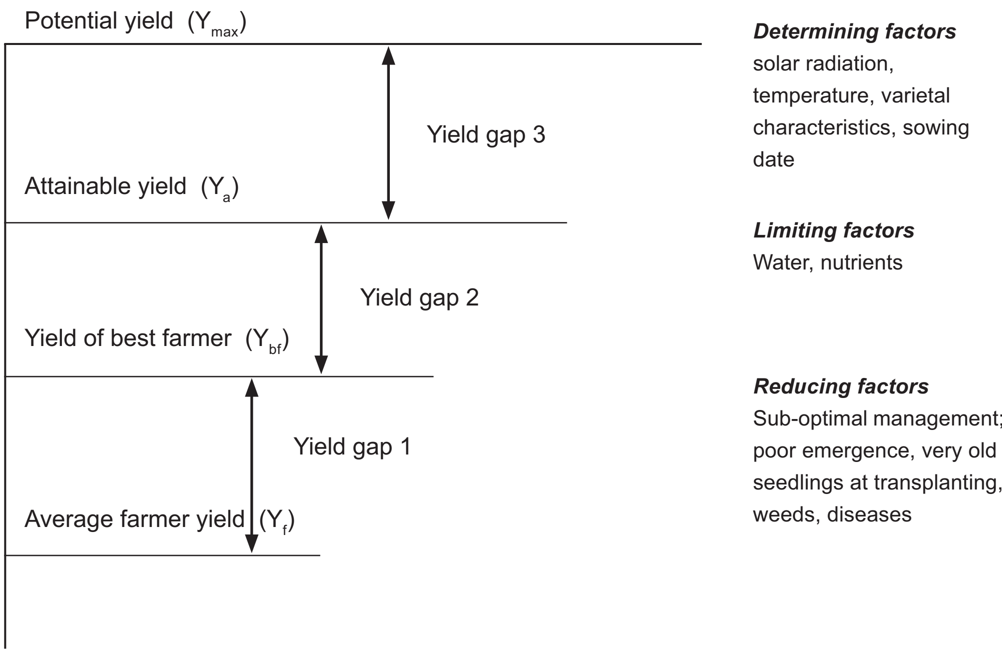

Figure 15.1. Yield gaps between average yield (Y_f) in farmers' fields, the yield of the best farmer (Y_{bf}), attainable yield (Y_a) and potential yield (Y_{max})

Farmers often achieve far less than Y_{max}. It is, however, important to choose a realistic target yield. Yield increases of 0.5 or 1 t/ha compared to previously obtained yields are often possible in farmers' fields. The target yield should not be higher than the attainable yield of 70 to 80% of the potential yield. This is very important as the response of rice to nutrients is not linear from this point onwards, i.e. larger and larger fertilizer quantities are required to obtain the same increase in yield. Targeting high yields is often neither economical nor realistic, especially when water management is not optimal (in such cases, the application of large quantities of fertilizer becomes too risky).

Estimate the capacity of the soil to supply N, P and K

The soil's capacity to supply N, P and K nutrients can be estimated through chemical soil analysis, as indicated in Boxes 15.1 to 15.3. However, the relationship between these analytical data and crop growth is often poor, especially for N. A more direct method is to determine the soil nutrient-supplying capacity through small, well-managed plots in farmers' fields that receive adequate quantities of fertilizer nutrients to reach the target yield, minus one nutrient (for instance, without N, P or K). The yield obtained in these plots is considered an indicator of the soil capacity to supply this 'missing nutrient'. The principle of these small zero-N, zero-P and zero-K plots is explained in Table 15.1.

Figure 15.2 gives an example of the results obtained for these zero-nutrient plots. For the yield target, the soil nutrient-supplying capacity is limiting in the order of N > P > K. For the yield obtained, soil K-supplying capacity is not a limiting factor but N and P are limiting factors, in the order of N > P.

Table 15.1. The principle of zero-N, zero-P and zero-K plots

Mini-plots	N	P	K
Plot 0-N, +P, +K	0	+	+
Plot 0-P, +N, +K	+	0	+
Plot 0-K, +N, +P	+	+	0
Plot +N, +P, +K	+	+	+

0- = nutrient is not applied, it is the 'missing nutrient'; + = nutrient is applied sufficiently so as not to limit crop growth (the exact amount will depend on the growth conditions, one may refer to recommendations currently used by extension staff, or to what is done by the best farmer).

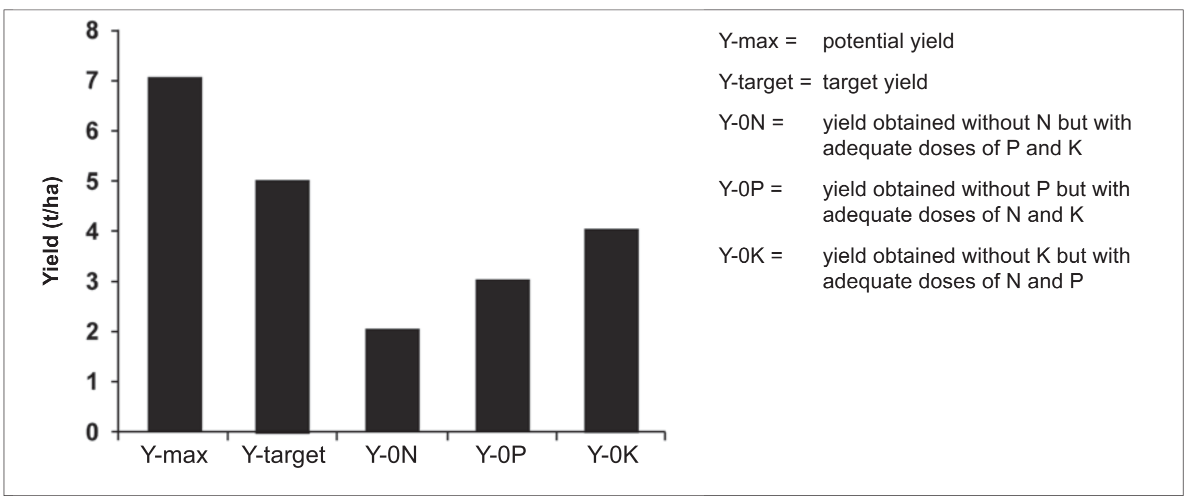

Figure 15.2. Example of yields obtained in zero-nutrient plots, potential yield and target yield

Calculating fertilizer requirements

Nitrogen, P and K rates for rice straw and rice grains are indicated in Table 15.2. Nutrients leave the plot at harvest with the rice grains. Straw is often burned or incorporated into the soil. Using straw has little effect on the soil capacity to supply P or N, but it increases K supply. If the straw is not returned to the field, significant quantities of K are lost to the system.

Table 15.2. N, P and K concentrations in rice grains and straw (%)

	N	P_2O_5	K_2O
Grain	1.0	0.4	0.3
Straw	0.5	0.2	1.5

Field research in Asia and West Africa has shown that for a yield increase of 1 t/ha and balanced N, P and K nutrition, rice consumes:

- 15 kg N/ha.
- 6 kg P_2O_5/ha.
- 18 kg K_2O/ha.

Nitrogen

The recovery rate of N in a farmer's field is on average about 30%. This means that about 70% of N-fertilizer is lost because of many constraints, such as late urea application, weed pressure and seedlings that are too old at transplanting. To obtain a balanced consumption of 15 kg N/ha for a yield increase of 1 t/ha, one has to apply 50 kg N/ha, thus a little more than two bags of urea per hectare. Better field management can increase the recovery rate and diminish fertilizer losses (*see* Box 15.4). In the example of Figure 15.2, the yield of the 0-N plot is 2 t/ha. To obtain the target yield of 5 t/ha, one should apply 150 kg N/ha.

It is better not to apply more than 50 kg N/ha at one time. The best times for N application in rice cropping are at the start of tillering (once rice seedlings have recovered from transplanting shock), at panicle initiation and at heading.

For smaller quantities, it is advised to make two applications of 50% each at the start of tillering and at panicle initiation. For larger quantities, it is advised to apply in three splits: at the start of tillering (40%), at panicle initiation (40%) and at heading (20%). Avoid applying fertilizer in deep water (> 5 cm) or in weed-infested plots.

Box 15.4. Increasing the recovery rate of nitrogen

A number of good crop management practices help limit losses of N applied with mineral fertilizers:

- Using good-quality seed (Reference 9).
- Transplanting seedlings at the right age (References 13 and 16).
- Using a plant spacing that is adequate for the variety used, usually 0.2 × 0.2 m.
- Removing weeds before fertilizer application.
- Using pest and disease control.
- Harvesting on time, at maturity.
- Applying N when the crop most needs it: at tillering, panicle initiation and, if required, at heading; for small N doses, apply at tillering and panicle initiation.
- Using N in two splits of 50% each, at the start of tillering and at panicle initiation, or in three splits of 40%, 40% and 20%, respectively, at the start of tillering, at panicle initiation and at heading.
- Using a good application method:
  - Lower the water level to a strict minimum (about 3 cm);
  - Broadcast in a homogeneous way (without incorporation);
  - Prevent field from drying out immediately after application;
  - Irrigate again 4 to 5 days later.

To maximize fertilizer uptake by crops, fertilizer should be applied in a homogeneous way, when needed, after weeding and after reducing the plot water-level. Never use fertilizer when the sky is threatening, during rain or immediately after rain. If these crop management practices are followed, N losses can be minimized and the N-recovery rate by the crop will increase.

Phosphorus

The recovery rate of phosphorus is on average about 20%. Nevertheless, the phosphorus not absorbed by the crop remains available for the next year. In the first year, for a yield increase of 1 t/ha, about 30 kg P_2O_5/ha will be required. Figure 15.2 shows that the yield of the 0-P plot is 3 t/ha. The target yield of 5 t/ha can be obtained with an application of 60 kg P_2O_5/ha. Phosphorus application is preferably done basally. If not, it should be applied very early to stimulate tillering.

Potassium

The recovery rate of K is on average about 30%. As for phosphorus, the potassium not absorbed during the campaign is (normally) available the next year. To cover the K requirement in the first year, to obtain a yield increase of 1 t/ha, one should apply 60 kg K_2O/ha. The example of Figure 15.2 indicates that the yield of the 0-K plot is 4 t/ha. To reach the target yield of 5 t/ha, an application of 60 kg K_2O/ha is required.

Potassium can be applied as basal fertilizer or as top-dressing. Small quantities of K can be used at transplanting or as basal fertilizer. It is advisable to apply larger quantities (> 50 kg K_2O/ha) as basal fertilizer (50%) and at panicle initiation (50%).

Avoid soil nutrient mining!

The small zero-N, zero-P and zero-K plots are good soil-fertility indicators. It is advisable to use them each year, but not in the same spot. Good management of these mini-plots is essential to ensure that the yields obtained actually express the capacity of the soil to supply the 'missing nutrient.' These well-managed mini-plots can become a means of evaluating the evolution of soil fertility in farmers' fields over time.

Careful! Even if the yields of the small zero-nutrient plots do not indicate the need to apply fertilizer, it is possible that a maintenance application is necessary to prevent soil fertility from being mined over time. Table 15.2 could help estimate the requirements for a maintenance application. For instance, considering Figure 15.2, a target yield of 4 instead of 5 t/ha does not require K application. However, the soil loses a considerable quantity of K, especially when straw is exported from the plot. A grain yield of 4 t/ha is usually equivalent to a straw yield of 4 t/ha. Which means that, with each harvest, the soil loses (Table 15.2) (4000 × 0.015) + (4000 × 0.003) = 72 kg K_2O/ha.

Combining organic amendments and mineral fertilizers is often the best strategy for maintaining or even increasing soil fertility.

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