20 Increasing Rice Productivity through Improved Nutrient Use in Africa

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Introduction

Smallholder farmers in sub-Saharan Africa generally obtain production levels that are far below what would be possible under favourable conditions. The vast majority of farmers hardly use external inputs and they are, therefore, strongly dependent on native soil fertility. Soil fertility, defined as a mixture of soil chemical, physical and biological factors that affect land potential, is inherently low in sub-Saharan Africa, where nutrient-impoverished granites, basement sediments and sands cover about 90% of the land surface (Smaling, 2005). Low soil fertility and the often unfavourable climate create intense pressure on land, even at relatively low population densities.

Since the early 1990s there has been growing concern about the fertility of soils and, consequently, the sustainability of land use in Africa. Many studies suggest that soils are rapidly degrading. For example, Sanchez *et al.* (1997) stated that 'soil fertility depletion in smallholder farms is the fundamental biophysical root cause for declining per capita food production in sub-Saharan Africa'. Soil degradation seems to be more important in the Sudano-Sahelian regions of West Africa and in some East African countries, like Ethiopia, Kenya, Somalia and Sudan. Stoorvogel and Smaling (1990) analysed the nutrient balances of different cropping systems in Africa. The nutrient balances include, on one hand, major nutrient inflows from rainfall, organic manure, mineral fertilizers, symbiotic N-fixation and sedimentation; and, on the other hand, nutrient outflows through harvested produce and losses due to erosion, leaching, etc. They conclude that soil nutrient depletion is quite severe in Africa. Estimates of net losses were of the order of 10 kg N/ha, 4 kg P_2O_5/ha and 19 kg K_2O/ha per year.

However, such nutrient balances cannot be used to indicate sustainability or fertilizer requirements without consideration of the stocks of nutrients in the soil. Haefele *et al.* (2004) developed a nutrient-application strategy for irrigated systems in the Senegal River valley, placing emphasis on N and P and allowing for mining of the soil's K reserves, as they estimated that these K reserves would be sufficient for decades. A second important consideration is that even in resource-limited smallholder agriculture not all fields are continuously mined. Some fields may have very positive nutrient balances, especially those near the homestead (infields), while other more distant ones (outfields) may have negative

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balances. These typical soil-fertility gradients are due to preferential application of scarce nutrients from animal manure and other nutrient resources to infields. This ensures at least good yields in these limited areas and saves labour. Soil-fertility management strategies need to consider such gradients.

This chapter starts with a few key definitions related to nutrient management and a general overview of the quality of soil resources and fertilizer use in Africa. Next, innovations to increase rice productivity through improved nutrient use are discussed for production systems at different stages of intensification in sub-Saharan Africa (see also Saito *et al.*, Chapter 15, this volume), i.e. for rainfed, low-input/subsistence rice systems and for high-input irrigated lowland rice systems. Finally, we discuss challenges and opportunities for managing soil fertility and adapting crop management in general in rice-based systems in Africa.

Definitions

Nutrient resources are allocated by farmers through decisions made at the field and farm scales, and their use is constrained by the other principal resources for agricultural production available at the farm level – land, water, labour and capital. Within a given production system, farmers may manipulate soil fertility in several ways. They may: (i) add nutrients to replenish stocks and flows in the soil; (ii) block nutrient outflows from the field or farm; (iii) recycle nutrients that are not optimally used within the farm; or (iv) increase the efficiency with which nutrients are used by the various production systems (Hilhorst and Muchena, 2000).

The yield a rice farmer will obtain from a particular field will depend on the quantities of nutrients that are taken up by the plant during the growth cycle, either from the soil's indigenous nutrients (natural reserves) or from external inputs, such as mineral fertilizer, and whether this nutrient uptake is balanced. For example, for irrigated rice in Africa it has been shown that a balanced nutrient uptake would mean 14.1 kg N/ha, 6.9 kg P_2O_5/ha and 21.7 kg K_2O/ha for a 1 t/ha increase in yield (Haefele *et al.*, 2003), if yield levels are less than 80% of the maximum yield that is possible given climatic conditions (i.e. of the potential yield). Aiming for a higher yield level is not economical because crop response to nutrients is not linear beyond this point, i.e. greater and greater fertilizer quantities are required to obtain the same absolute increase in yield from higher starting points. A whole range of other factors intervenes as well, most notably variability in weather and choice of crop management practices, such as sowing date, variety, and weed management strategy. Looking beyond a growing season, it is important to know whether application of soil amendments will have a 'lasting' effect, i.e. will contribute to soil organic-matter build up, and eventually to increased soil nutrient-supplying capacity or improved recovery of fertilizer nutrients, or whether it mainly acts as a mineral fertilizer, i.e. giving a one-time boost to crop growth.

Installation of water-harvesting structures or irrigation and drainage infrastructure aim at increasing the yield potential in a given environment and reducing risk, lifting the production system to a higher level and opening up opportunities for intensification and diversification. This may also be possible through the introduction of new production systems, such as minimum tillage and fallow crops.

Rice Soil Resources and Mineral Fertilizer Use in Africa

Rice in Africa is grown in a wide range of agro-ecological zones from the humid forest to desert areas. Within these regional agro-ecological zones, five main systems of rice cultivation are distinguished with respect to water supply, soil hydrology and topography (adapted from Windmeijer *et al.*, 1994):

- **Irrigated** rice systems with relatively good water control, which have anaerobic soils for most of the season – mostly in deltas and flood plains.
- **Lowland rainfed** rice systems with varying degrees of water control, which have aerobic soils for a considerable part of the season – mostly in valley bottoms and flood plains.
- **Rainfed upland** rice systems, which have aerobic soils for most of the season – situated on plateaux and slopes.
- **Deep-water** and **mangrove** systems, rarely having water control, which have anaerobic

soils for most of the season – along river beds and in tidal areas in lagoons, deltas and in coastal areas.

A distribution of soil quality for the total rice area of most African countries is given in Table 20.1. These estimates were achieved by overlaying the rice area map of Africa (IRRI, 2012 unpublished) with the digital version of the *Soil Map of the World* (FAO, 1995) (see Haefele and Hijmans, 2007, for details). Soil-fertility constraints were classified and mapped according to the Fertility Capability Soil Classification (FCC) system (Sanchez and Buol, 1985; Sanchez *et al*., 2003). Four groups of soils were distinguished. The first two groups ('good' and 'poor' soils) do not have major soil chemical constraints, but differ in their degree of weathering and, therefore, their indigenous soil fertility. The third group ('very poor' soils) represents highly weathered soils with very low nutrient availability and a high probability of soil chemical constraints to crop growth (acid, low nutrient reserves, low CEC, Al toxicity, high P fixation). The last group combines the most frequently cited 'problem soils', i.e. acid-sulfate

Table 20.1. Distribution of the total rice area in Africa on four major soil-quality groups (see the definition of the groups in the text). (Data from FAO, 1995; IRRI, 2012.)

Country	Good soils (%)	Poor soils (%)	Very poor soils (%)	Problem soils (%)
Angola	29	11	59	1
Benin	15	79	5	1
Burkina Faso	44	50	3	3
Burundi	40	5	48	7
Cameroon	30	24	35	11
Central African Republic	5	15	80	0
Chad	35	55	10	0
Côte d'Ivoire	8	26	66	0
Democratic Republic of Congo	7	3	90	0
Egypt	41	0	0	59
Equatorial Guinea	0	32	68	0
Ethiopia	66	8	26	0
The Gambia	51	38	0	11
Ghana	21	51	24	4
Guinea	27	17	51	5
Guinea-Bissau	16	43	21	20
Kenya	30	38	25	7
Liberia	8	19	69	4
Madagascar	7	26	63	4
Malawi	27	27	45	1
Mali	51	19	27	3
Mauritania	57	0	14	29
Mozambique	33	35	23	9
Niger	28	12	52	8
Nigeria	25	46	26	3
Rwanda	58	4	38	0
Senegal	10	44	18	28
Sierra Leone	16	18	63	3
Tanzania	26	18	53	3
Togo	7	92	1	0
Uganda	12	19	63	6
Zambia	30	21	42	7
Others (9 countries)	48	15	25	12
Average	27	28	37	8

soils, peat soils, saline and alkaline soils (Sanchez and Buol, 1985), which are characterized by specific and severe soil chemical constraints. (See Saito *et al.*, Chapter 15, this volume, for more details.)

The results (Table 20.1) show an abundance of very poor rice soils (37%), followed by equal fractions of poor (28%) and good soils (27%). Overall, problem soils are not common and make up 'only' 8% of all rice soils in Africa. However, the distribution of rice soil quality and constraints within countries is far from even. Some countries have a substantial proportion of good rice soils – for example, Burkina Faso, Egypt, Ethiopia, The Gambia, Mali and Mauritania. However, in many more countries more than 50% of the rice is grown on very poor soils – for example, Côte d'Ivoire, Democratic Republic of Congo (DRC), Equatorial Guinea, Guinea, Liberia, Madagascar, Sierra Leone, Tanzania and Uganda. Rice on problem soils is abundant in some countries, including Egypt, Guinea-Bissau, Mauritania and Senegal.

Africa is the continent with the lowest fertilizer use, estimated at 23 kg/ha agricultural land per year for the whole continent and at only 9 kg/ha agricultural land per year in West Africa (CEDEAO, 2006). It can be generally assumed that some of the increase in fertilizer use during the last 30–40 years occurred in rice cultivation, but little data is available on how much inorganic fertilizer is used for rice in Africa. Fertilizer availability is a problem in many places: in many African countries, fertilizer is only available where the supply chain for cash crops like cotton, cocoa or banana is well established. Only in some regions with large irrigation schemes are such supply chains established mainly for rice production. The only countries with fertilizer consumption above 400,000 t/year are Egypt, South Africa, Nigeria and Morocco. The only two countries in Africa with a significant rice area and considerable total fertilizer consumption are Egypt (2.0 million tonnes (Mt) in 2008) and Nigeria (0.5 Mt in 2008), and there are several countries with considerable rice areas and very low total fertilizer consumption (e.g. DRC, Guinea, Madagascar and Tanzania).

Regarding specific cases, relatively high fertilizer use of 75–143 kg N/ha has been reported for intensive irrigated rice cropping in the Sahel (Wopereis *et al.*, 1998; Haefele *et al.*, 2001). Becker *et al.* (2003) found much lower average rates in the humid forest zone (23 kg N/ha) and in the Guinea savannah zone (17 kg N/ha). High fertilizer rates are also common in Egypt and some intensive rice production schemes in East Africa (FAO, 2005). Mineral fertilizer use is not very common in rainfed lowlands (Meertens *et al.*, 1999; Sakurai, 2010; Kamara *et al.*, 2011), and rare in traditional upland rice cultivation (Balasubramanian *et al.*, 2007; Oikeh *et al.*, 2008; Mghase *et al.*, 2010). These differences are mainly determined by fertilizer availability (high in irrigated lowlands, low in rainfed uplands) and production risk (low in irrigated lowlands, high in rainfed uplands).

Innovations for Improving Nutrient Use

In this section, we provide (i) an overview of farmers' practices and constraints related to soil fertility and nutrient use; and (ii) technological options for improving nutrient use in the three major rice-based systems (irrigated lowland, rainfed upland and rainfed lowland), with a focus on West Africa.

Irrigated lowland rice-based systems

Farmers' practices, challenges and opportunities

Wopereis *et al.* (1999) and Donovan *et al.* (1999) conducted surveys in Senegal (Senegal River delta and middle valley), Mali (Office du Niger) and Burkina Faso (Kou Valley) to identify farmers' practices and determinants of rice productivity with a focus on nutrient management. Average farmers' yields ranged between 3.8 t/ha and 7.2 t/ha, resulting in an overall average of 4.5 t/ha. Yields of individual farmers were highly variable, ranging from almost complete crop failure (0.3 t/ha, due to weeds) to very high yields (8.7 t/ha). High average yields and low yield variability were found in relatively old irrigation schemes, e.g. in the Office du Niger. Maximum yields reached by farmers were only 40–60% of ten-year averages of simulated potential yield (limited by climate only). The difference between average farmers' yields and highest farmers' yield was between 0.7 t/ha and 4.1 t/ha, with an average of 2.6 t/ha, indicating considerable scope for improving yields.

Fertilizer use did not follow recommended rates and was quite variable, but quantities were generally high, with average fertilizer N input ranging from 73 kg/ha (Burkina Faso) to 143 kg/ha (Mali), average fertilizer P input from 15 kg/ha (Senegal) to 22 kg/ha (Burkina Faso) and average fertilizer K input from none (Mali, Senegal) to 22 kg/ha (Burkina Faso). Grain yields were highly variable, both within and across sites.

Only a few farmers in Mali and Burkina Faso applied organic inputs (compost, manure). Without exception, farmers applied N fertilizer, and most farmers also applied P fertilizer. Potassium fertilizer use was mainly restricted to sites where use of NPK compound fertilizer was recommended. Nitrogen was always the most limiting nutrient for rice growth. Average N fertilizer recovery was relatively low and in the range 18–50%, i.e. fertilizer N losses ranged from 50% to 82%.

Sustainability issues

The sustainability of intensive irrigated rice cropping in Africa has been studied through long-term fertility experiments (Haefele *et al.*, 2002; Bado *et al.*, 2010). Haefele *et al.* (2002) conclude that intensive irrigated rice cultivation is sustainable if N and P are applied as inorganic fertilizer. Bado *et al.* (2010) found that double cropping of irrigated rice does not decrease soil organic matter and the application of the recommended doses of NPK fertilizer (120 kg N/ha, 26 kg P/ha, 50 kg K/ha) maintained rice yields for 18 years. In arid or semi-arid environments like the Sahel, salinization or alkalinization, sometimes followed by sodification, may affect soil quality, especially if drainage is limited, because the water table rises close to the surface or the irrigation water is rich in dissolved inorganic ions. Reports of micronutrient deficiencies are rare and often concern problem soils (e.g. saline and sodic soils) or organic soils. However, where high yields are achieved regularly and perhaps even twice a year, micronutrient (e.g. Zn, S) deficiencies can appear quickly (van Asten *et al.*, 2004).

Improving crop management

It is clear that farmers could improve efficiency and profit by improving the recovery rate of applied nutrients, especially N, through better crop management in general, without major increases in investment in fertilizers. The most important constraints that resulted in low N recovery rates were: timing of N fertilizer application that did not coincide with critical growth stages of the rice plant; use of relatively old (>40 days) seedlings at transplanting; unreliable irrigation water supply; weed problems; and late harvesting (Senegal River delta) (Wopereis *et al.*, 1999). Similar results were obtained by Haefele *et al.* (2000, 2001) for the Senegal River delta and Segda *et al.* (2004) for the Bagré irrigation scheme in Burkina Faso.

Discussions with farmers in Burkina Faso and Senegal revealed that they lacked knowledge on (i) optimal timing, dosage and mode of fertilizer application; (ii) optimal sowing dates to avoid yield loss due to cold- or heat-induced sterility; and (iii) the importance of N as the main yield-limiting factor. Other factors included problems with collective and individual planning of the cropping calendar for double cropping of rice (two rice crops in the same field in one year) and the need to attend to rainfed crops outside the scheme.

Working with Senegalese and Mauritanian farmers, improved nutrient management (application of 20 kg P/ha and 150 kg N/ha in three splits at early tillering, panicle initiation and booting) increased yields by about 1 t/ha. Improving weed management (application of 6 l propanil/ha and 2 l 2,4-D-amine/ha at 2–3-leaf stage of weeds) also raised yields by about 1 t/ha over farmers' practice. The combined effect of improved nutrient and weed management was additive: improving both nutrient and weed management raised yields by almost 2 t/ha over average farmers' yields of 3.9 t/ha, i.e. an increase of about 50%. Value–cost ratios were between 2.1 and 4.6 for improved soil fertility and weed management, respectively, resulting in an increase in net revenues of 40–85% compared to farmers' practice. The results of the learning plots were amazingly consistent and were obtained for both smallholder farmers in Senegal (Haefele *et al.*, 2000) and large-scale farmers in Mauritania (Haefele *et al.*, 2001). The yield increases obtained are considerably larger than those obtained for similar work in intensive rice-cropping systems in Asia (Dobermann *et al.*, 2002).

Site- and season-specific mineral fertilizer recommendations

Recommended N rates for lowland rice usually range from 60 kg/ha to 120 kg/ha, applied in 2–3 splits at planting, early tillering and panicle initiation. An additional split at booting can be beneficial in very high-yielding systems (Wopereis-Pura *et al.*, 2002). Upper rates in the wet season under irrigated conditions are 90–120 kg N/ha. Very high N rates up to 150 kg/ha can be recommended in irrigated rice during the dry season, if high solar radiation enables potential grain yields of up to 12 t/ha (Haefele and Wopereis, 2004). Application of urea super granules (USGs) is promoted in some irrigated systems (Fofana *et al.*, 2010). Conditions necessary for USG technology are full water control (aerobic soil phases should be avoided) and (clayey) soils with limited percolation. USGs are pressed into the soft surface soil between four hills, usually in one or two applications. USG technology has been shown to reduce N losses considerably, but its disadvantage is the labour needed for application.

Phosphorus deficiency is common, especially if higher yields are targeted. The incorporation of P fertilizers during land preparation or surface application up to 20 days after transplanting is good practice for flooded rice crops.

Potassium fertilizers should be applied along with N and P on poor soils, if higher yields are targeted, and especially if two (high-yielding) crops are grown per year regularly. The amount of K that needs to be applied also depends on K inputs from the irrigation water and from dust depositions. In West Africa, the dust deposition (dry deposition) is highest at the northern fringes of the Sahel (e.g. in the Senegal River valley and in the Office du Niger, Mali) and decreases towards the south.

Simulation tools can be used to develop site- and season-specific mineral fertilizer recommendations, as demonstrated for irrigated rice in the Office du Niger (Haefele *et al.*, 2003). The dynamic ecophysiological ORYZA_S model provided potential rice yields under irrigation, based on weather conditions, cultivar choice and sowing date. This yield potential was then used in the static FERRIZ model, together with on-farm data on recovery efficiency of applied N, P and K, indigenous soil N, P and K supply, and maximum N, P and K accumulation and dilution in rice dry matter. Resulting outputs were fertilizer rates necessary to obtain different target yields depending on yield potential and soil nutrient supply. Adding current fertilizer and paddy prices into the analyses then allowed an agro-economic evaluation of different fertilizer options. In a last step, the dynamic decision tool RIDEV was used to simulate optimal timing of different management actions, such as fertilizer application, weeding and harvest. This approach showed that (i) current uniform recommendations for the wet season performed well except on low-K soils where the application of K was profitable; and (ii) adjusting fertilizer doses to the lower yield potential in the dry season reduced costs and risk without reducing profit. Based on the analysis, the existing recommendation could be adjusted for the wet and dry seasons, keeping fertilizer costs and risk low, and having net benefits close to optimal.

Based on this experience, Segda *et al.* (2005) used a combination of two simulation models and selected field data to develop alternative fertilizer recommendations (AFR) for irrigated rice in the irrigation scheme of Bagré (Burkina Faso). Existing fertilizer recommendations (EFR) in Bagré were 82 kg N/ha (wet season) or 105 kg N/ha (dry season), plus 31 kg/ha P and 30 kg K/ha, using urea (100–150 kg/ha) and a compound NPK fertilizer (300 kg/ha, containing 12% N, 24% P_2O_5 and 12% K_2O). RIDEV was used to improve timing of sowing to avoid cold-induced sterility and timing of N fertilizer applications (i.e. improved crop management). FERRIZ was used to determine AFR, based on estimations of indigenous nutrient supply for N, P and K, yield potential (Y_{pot}), internal N, P and K efficiency of rice, fertilizer N, P and K recovery fractions, and fertilizer and rice prices. Simulations suggested decreasing P and K doses to 21 kg/ha and 20 kg/ha, respectively, but increasing the N dose to 116 kg/ha in the wet season (Y_{pot} = 8 t/ha) and 139 kg/ha in the dry season (Y_{pot} = 9 t/ha). This translates to substituting two bags (100 kg) of compound NPK fertilizer for two bags of urea per hectare. AFR keeps the P-balance neutral, but a negative K balance was tolerated on the basis of the high soil K supply. Compared to existing recommendations, yield gains of up to 0.5 t/ha were simulated at equal costs. These yield gains were exceeded in farmers' fields during four consecutive growing seasons. AFR increased gross returns above fertilizer costs by an average of about US$160 per season as compared to both farmers' practice and existing recommendations. Although it is unlikely that farmers will follow these recommendations exactly, the basic message from this study – to apply more urea and less compound fertilizer – was adopted quickly by farmers (Segda *et al.*, 2010).

Organic inputs

In lowland rice-based systems, the aquatic fern *Azolla* (a genus of seven species in the family *Salviniaceae*) has been used as a green manure for rice in northern Vietnam, and central to southern China for centuries (Watanabe and Van Hove, 1996). Given its high N content, *Azolla* boosts growth directly, i.e. it acts as a substitute for mineral fertilizer. Depending on the ecological conditions, a 4–10-week old 'crop' of *Azolla* can accumulate an average of 70 kg N/ha (range 20–146 kg N/ha), of which about 80% is derived from atmospheric nitrogen (Roger and Ladha, 1992). Accordingly, Watanabe *et al.* (1989) estimated that the use of *Azolla* can replace 30–60 kg of mineral N fertilizer depending on frequency and time of incorporation. Experiences in Senegal (Diara *et al.*, 1987; Van Hove and Diara, 1987; Van Hove, 1989) and Egypt (Yanni *et al.*, 1994) show that its adoption is blocked by two main factors: (i) high labour cost needed for incorporation of *Azolla*, and (ii) contamination of irrigation and drainage canals with *Azolla*.

Rainfed upland rice-based systems

Farmers' practices, challenges and opportunities

Upland rice production in Africa is dominated by subsistence-oriented farm households, which do not use external inputs mainly due to high production risk and poverty. However, in Uganda upland rice is grown by farmers for income generation (Oonyu, 2011). But even there, most farmers do not apply inorganic fertilizer due to the high price of fertilizer and considerable production risks (Kijima *et al.*, 2011; Miyamoto *et al.*, 2012). Upland rice yields average about 1 t/ha, but there are large differences between farms, mostly because of differences in the quality of the land, rainfall patterns, and in crop management practices. Up to 2 t/ha can be obtained under favourable conditions – high soil fertility, good hydrological conditions, or following long fallows or appropriate previous crops in rotation systems (Sokei *et al.*, 2010; Kijima *et al.*, 2011; Miyamoto *et al.*, 2012). Upland rice is grown as a sole crop or mixed with other crops such as maize and beans both in slash-and-burn systems and in intensified systems, where upland rice is rotated with other crops on permanently cultivated lands. In slash-and-burn systems, increased cropping intensity (reduced fallow period and increased cropping period) have aggravated weed pressure and led to a general decline in land quality through soil nutrient depletion. Expansion of slash-and-burn upland rice-based systems should generally not be encouraged because of the fragility of these agroecosystems.

Many upland soils have low N availability and are highly P-fixing (Becker and Johnson, 2001; Sahrawat *et al.*, 2003). Becker and Johnson (2001) analysed cropping intensity effects on upland rice yield and sustainability in four agroecological zones (Guinea savannah, derived savannah, bimodal forest, monomodal forest) in Côte d'Ivoire. Increased cropping intensity was associated with yield reduction. Cropping intensification-induced yield loss was about 25% (a drop from an average 1.5 t/ha to 1.1 t/ha) and was mainly related to increased weed infestation and declining soil quality. Miyamoto *et al.* (2012) report that in intensified systems in Uganda, continuous rice cropping reduced rice yield, compared with rotation systems.

Use of organic fertilizer such as farmyard manure and cow dung is still limited except in a few countries, such as Madagascar and Uganda. In Namulonge (central Uganda), Miyamoto *et al.* (2012) report that 19% of farmers use chicken manure.

Organic inputs

As most farmers cannot afford mineral fertilizer, organic inputs have been considered as potential options for sustainable production in intensified upland rice-based systems. Promising alternative cropping systems include the use of weed-suppressing and multi-purpose legumes as short-term fallow crops. Some 54 legumes were evaluated as dry-season fallow crops in the mid-1990s in four agroecological zones (Guinea savannah, derived savannah, bimodal forest, monomodal forest) in Côte d'Ivoire (Becker and Johnson, 1998, 1999). Legumes were introduced into the upland rice crop one month before harvesting, and allowed to grow until the end of the dry season, when their N accumulation and weed suppression were evaluated. Fallow vegetation was cleared according to the practice of local farmers, and upland rice was seeded to evaluate the effect of the previous legume crop on weed growth and rice yield. Biomass accumulation at the end of the dry season was generally greater in legume fallows than in natural fallows (control), and several legume species suppressed weed growth. Nitrogen accumulation by legumes ranged from 1 kg/ha to 270 kg/ha, with 30–90% of the accumulated N derived from the atmosphere. Across sites, *Mucuna* spp., *Canavalia* spp. and *Stylosanthes guianensis* showed consistently high N accumulation. Rice yields following legume fallows were on average 0.2 t/ha greater than those following a natural weedy fallow. On average across four sites, *Tephrosia villosa* and *Stylosanthes guianensis* fallows increased yields by 0.5 t/ha and 0.4 t/ha, respectively, in comparison with a natural fallow. Furthermore, to increase benefits from the systems, the effects of timing of legume establishment in relation to rice and fallow-residue management (removing, burning, mulching or incorporating) prior to the rice crop on rice and weed growth were determined (Becker and Johnson, 1999; Akanvou *et al*., 2000; Saito *et al*., 2010). Timing of legume establishment in upland rice depended on legume, rice variety and their crop densities, and environmental conditions. Incorporating or mulching of fallow residues provided no significant yield advantage compared to burning. Africa Rice Center (AfricaRice) also conducted on-farm participatory legume evaluation and selected legumes were grown by farmers. Through this work, researchers learned that solutions such as improved fallows must consider the biophysical and socio-economic specifics of prevailing systems in order to be successful. However, adoption rates by farmers have been very low because of:

- Lack of seed availability and poor seed quality
- Insufficient adaptability of most of the legumes to diverse site conditions
- High variability in the performance of legumes (especially in marginal environments)
- High cost of land and labour.

Some of these constraints to green-manure adaptation, especially the high costs for land and labour, can be overcome by integrating grain legumes into rice-based systems, as these can provide (at least in part) the benefits of green manure (e.g. biological N fixation and weed suppression), while also giving harvestable product with market value or for home consumption (for this reason, they are known as 'dual-purpose legumes'). This can be achieved using different approaches:

- Intercropping upland rice with grain legumes like cowpea or soybean
- Developing upland rice–grain legume rotations
- Integrating early maturing legumes as pre- or post-rice crops into the existing upland or lowland monocrop rice systems.

Oikeh *et al*. (2008) compared dual-purpose soybean and upland rice rotation with continuous upland rice cropping in the Guinea savannah of Benin. Rice yield following soybean was 0.7 t/ha higher than in continuous rice cropping. However, in local farmers' practice, the aboveground biomass of legumes (except for litter that falls before harvest) is often entirely removed from the field for use as animal fodder. This practice will further contribute to negative N balances and might even accelerate soil fertility degradation.

Variable performance of legumes in diverse conditions may also be related to P deficiency in the uplands, because most legumes have considerable P requirements. Somado *et al*. (2003, 2011) suggest integrated approaches including application of rock phosphate (which is a relatively cheap source of P) to legumes and rice cultivation following legumes for enhancing both N and P use.

In uplands in Madagascar, conservation agriculture has been tested by collaboration works among Centre National de la Recherche Appliquée au Développement Rural (FOFIFA), Université d'Antananarivo and Centre de coopération internationale en recherche agronomique pour le développement (CIRAD). Improved fallow systems using *Stylosanthes guianensis*, combined with mulching as residue management in a zero-tillage system has been introduced to farmers.

Potential use of mineral fertilizer in the uplands

Across Africa, transition from traditional slash-and-burn to intensified upland rice-based systems is occurring, or will occur, depending on the population density and land pressure. Such a transition requires mineral fertilizer application to upland rice for improved and sustainable productivity, ideally with organic inputs as described above. Knowledge of rainfall distribution and general soil fertility will help determine where small quantities of mineral fertilizer can make a difference. Data from Sokei *et al.* (2010) on trials in four countries in West Africa showed a positive relationship between rainfall during the period from around flowering to before maturity and yield increase due to fertilizer application. Thus, fertilizer application is more effective in high-rainfall conditions, whereas fertilizer application is less beneficial in drought-prone systems, or alternative fertilizer application methods are needed in such conditions. This indicates that in areas with large year-to-year variation in rainfall pattern, such as West Africa, site- and season-specific fertilizer recommendations would benefit tremendously from a weather-forecasting system. The positioning of the rice field on the toposequence can also affect soil fertility and hydrological conditions, and thus fertilizer strategies. Touré *et al.* (2009) demonstrated that in the top-most positions, water availability limited rice growth and its response to fertilizer application, whereas in relatively favourable uplands and hydromorphic areas in the middle positions, the response to fertilizer application was high. Farmers in central Benin distinguish soil types in their fields on the basis of water availability – such knowledge could be used for nutrient management recommendations (Takemura *et al.*, unpublished). Distance to markets, distance from village to fields, and farmers' socio-economic status should be taken into account for developing site-specific nutrient recommendations. Adesina (1996), for example, reports that fertilizer use is extremely low to zero for fields far from the village.

Rainfed lowland rice-based systems

Farmers' practices, challenges and opportunities

In general, soils in rainfed lowlands in sub-Saharan Africa are relatively less fragile and better able to support continuous cultivation than those in the uplands. Rainfed lowlands have considerable potential for intensification. Rainfed rice is mainly grown once a year in West Africa and, following the rice, vegetables or legumes are grown in relatively favourable conditions, where residual water or supplementary irrigation is available for these crops (Adigbo *et al.*, 2007; Balasubramanian *et al.*, 2007). In high-rainfall areas in Uganda, double rice cropping is common practice. In West Africa, rainfed lowland rice is often grown without any bunds or proper land levelling. In such (less-favourable) environments, farmers often do not use external inputs mainly because of the high production risk and poverty (Adesina, 1996; Becker and Johnson, 2001; Kijima *et al.*, 2010). Erenstein (2006) reports that fertilizer use was associated with market access and agroecological zone in West Africa. Rice yields in lowlands are generally low, averaging only 2–3 t/ha, although yields obtained by individual farmers may reach 6 t/ha (Becker and Johnson, 2001; Kijima *et al.*, 2010). The difference between the highest farmers' yield and average yield indicates that there is considerable potential for improvement. Major constraints related to soils in this system are N and P deficiency and Fe toxicity. Direct and indirect effects of Fe toxicity in inland valleys can lead to 40–45% rice yield reductions in lowlands, depending on the extent of the problem, water, soil and crop management (e.g. cultivar choice), as well as on the availability of other soil nutrients (Becker and Asch, 2005; Audebert and Fofana, 2009).

Improving crop management

Improved water control is a first step towards improving the productivity of rainfed lowlands.

Bunding and levelling facilitate water management and generally increase nutrient-use efficiencies, particularly in well-drained fields. Water management and regular drainage will also avoid problems with Fe toxicity in inland valley lowlands. Becker and Johnson (2001) report that mineral fertilizer N application significantly increases rice yields (18% on average across sites) in bunded fields only.

Site- and field-specific fertilizer management recommendations

As described for upland rice systems, the combination of rainfall distribution and general soil fertility, distance to markets, distance from village to fields, the positioning of the rice field in the toposequence, farmers' knowledge of their field characteristics and farmers' socio-economic conditions should be taken into account for developing site-specific nutrient recommendations. Given the diversity and dynamics of farmer reality and growing conditions in rainfed lowland systems, on-farm testing in the target environments is crucial for identifying agronomic practices that should result in reduced economic risk and increased fertilizer adoption by farmers (Posner and Crawford, 1992). In the upper positions of the toposequence drought might limit rice growth, and in the bottom the risk from submergence is high. Therefore, fertilizer-use efficiency in both situations can be limited. Nitrogen fertilizer application is more effective in middle parts on the toposequence than in drought-prone upper positions (Touré *et al.*, 2009). Organic inputs are most useful in upper parts because they help to increase the soil water retention, while soils at the bottom usually have a higher organic-matter content naturally. Furthermore, mobile nutrients like N and K are transported down the toposequence, thereby minimizing the need to apply N and K fertilizer in the bottom parts (Bognonkpe and Becker, 2009). The toposequence and related transport processes are also the reason for the widespread occurrence of Fe toxicity at the edges of inland valleys, where the Fe-rich groundwater surfaces. From numerous studies, Becker and Asch (2005) identified three environmental and soil conditions that are typically associated with the occurrence of Fe toxicity, and proposed different management options for each condition.

In rainfed lowland rice systems with favourable water availability (e.g. inland valleys with suitable topography), introduction of post-rice grain legumes or vegetables to the areas where their cultivation is not common practice will allow diversification and enhance organic inputs. That will raise productivity and profitability, and may also have beneficial effects on the rice crop grown in the wet season. Carsky and Ajayi (1992) report on efforts to introduce legumes into the inland valley rice-based cropping systems in West Africa.

Getting It Together

The review of principles and technologies to improve nutrient use in rice presented in this chapter shows that there is a wealth of knowledge available across rice environments. There is an urgent need to capture the basic principles of nutrient management (e.g. the importance of the soil nutrient-supplying capacity, the role of mineral fertilizers and their importance to plant growth, the role of organic inputs, the importance of N in lowland systems and of P and N in upland systems, and the fact that K usually only becomes important at higher yield levels and if most straw is exported from the field) in formats that can be widely distributed to farmers and other rice-development stakeholders, for example via videos. AfricaRice has produced a video on nutrient management in lowland systems that has been translated into 30 African local languages and has been widely distributed (see Van Mele *et al.*, Chapter 30, this volume).

Farmers' fields are generally highly heterogeneous in terms of growth conditions for the rice crop, and that complexity increases from the irrigated systems to the rainfed upland and lowland systems. Moreover, rice may be just one component of a farm, especially in rainfed systems. Going beyond conveying 'best-bet principles for nutrient management' often requires in-depth knowledge of these complex systems. Stratification of soils or fields in types that are likely to be responsive or non-responsive to mineral fertilizer is one important element of site-specific nutrient management in rainfed systems. Knowledge of seasonal differences in rainfall in rainfed systems, and of temperature and solar radiation in irrigated systems allows for the development of season-specific nutrient management recommendations. Moreover, recommendations should always be placed in the general crop and production system context, because so many other yield-limiting or yield-reducing factors may mask nutrient uptake in Africa.

A second important feature to consider is the heterogeneity in farmers' access to resources. Options to improve nutrient use and agricultural productivity need to take into account socio-economic factors such as household wealth, family structure, production orientation (subsistence, market), main source of income, and main types of constraints faced by farmers.

Conclusions, Looking Ahead

Mineral fertilizers will continue to play a key role in boosting rice productivity given the current very low level of fertilizer use in Africa. Where possible their use should be combined with organic inputs. Mineral fertilizers are the most direct supply for plant nutrients, while organic inputs help to maintain or rebuild the soil organic-matter reserve. Another, more practical, reason for advocating the combined use of organic inputs and mineral fertilizers is that 'very often neither of them is widely available or affordable in sufficient quantities' (Vanlauwe and Giller, 2006).

The most pressing challenge for rice-based systems is to ensure that knowledge of basic principles of integrated nutrient management for rice (rather than 'blanket fertilizer recommendations') is communicated to those that are most in need – Africa's rice farmers. This may be done through video or other means, such as rural radio station broadcasts, distribution of simple cropping calendar posters in village meetings and new information technology tools like mobile phones.

The capacity on the African continent to work on soil nutrient management in general is in desperate need of rebuilding, in both research and extension communities, after decades of under-investment in agriculture. There is a particular need to train a new generation of hands-on rice experts, through season-long training in rice management. AfricaRice has built a new training facility near its regional station in Senegal for this purpose. Japan International Cooperation Agency (JICA) has also established training facilities for rice in several countries in sub-Saharan Africa to rebuild rice extension capacity.

To date, blanket fertilizer recommendations are all that are available to most rice farmers in Asia and Africa, despite the fact that optimal amounts and sources of nutrients to meet the needs of the crop and optimize crop production can vary considerably, even across short distances within and among fields (Haefele and Wopereis, 2005). Major factors affecting the actual fertilizer needs include indigenous fertility of the site, season, variety used, residue management, type of fertilizer available, cropping system, nutrient inputs from irrigation water, atmospheric depositions, and yield target. But rice farmers who want to adjust the general recommendation to their specific conditions or needs have to depend on their own experience for the most part. To address this situation, AfricaRice and the International Rice Research Institute (IRRI) are in the process of developing a nutrient management tool that will allow individual rice farmers to manage their fields with greater precision. This approach relies on the scientific principles determined during 15 years of site-specific nutrient management (SSNM) research across Asia and Africa (Dobermann *et al.*, 2002; Haefele *et al.*, 2003b; Buresh *et al.*, 2010). Based on 15–20 simple questions about a specific field, the nutrient manager will provide farmers with a balanced fertilizer recommendation that aims to increase their profits in a sustainable manner. The nutrient manager is being tested for irrigated and favourable rainfed lowland rice systems in Senegal, Mali, Ghana and Nigeria. A mobile-phone version of the nutrient manager is already available in the Philippines.

Finally, there is also a need to address the challenges that lie ahead in terms of nutrient-management research: (i) for the new varieties that AfricaRice and partners are currently developing for different growth environments (see Kumashiro *et al.*, Chapter 5, this volume); (ii) for new production systems that are likely to become prominent in the near future, such as highly mechanized, direct-seeded rice systems and new crop rotations, such as rice–cotton or irrigated rice–wheat systems; and (iii) to anticipate the consequences of increasing water scarcity for irrigated rice-based systems due to climate change and increased demand for water for agricultural, industrial or urban use.

References

Adesina, A.A. (1996) Factors affecting the adoption of fertilizers by rice farmers in Côte d'Ivoire. *Nutrient Cycling in Agroecosystems* 46, 29–39.

Adigbo, S.O., Okeleye, K.A. and Adigbo, V.B. (2007) Performance of upland rice fitted into lowland rice–vegtable/cowpea sequence in rainfed inland valley. *Agronomy Journal* 99, 377–383.

Akanvou, R., Becker, M., Chano, M., Johnson, D.E., Gbaka-Tcheche, H. and Toure, A. (2000) Fallow residue management effects on upland rice in three agroecological zones of West Africa. *Biology and Fertility of Soils* 31, 501–507.

Audebert, A. and Fofana, M. (2009) Rice yield gap due to iron toxicity in West Africa. *Journal of Agronomy and Crop Science* 195, 66–76.

Bado, V.B., Aw, A. and Ndiaye, M. (2010) Long-term effect of continuous cropping of irrigated rice on soil and yield trends in the Sahel of West Africa. *Nutrient Cycling in Agroecosystems* 88, 133–141.

Balasubramanian, V., Sie, M., Hijmans, R.J. and Otsuka, K. (2007) Increasing rice production in sub-Saharan Africa: challenges and opportunities. *Advances in Agronomy* 94, 55–133.

Becker, M. and Asch, F. (2005) Iron toxicity in rice – conditions and management concepts. *Journal of Plant Nutrition and Soil Science* 168, 558–573.

Becker, M. and Johnson, D.E. (1998) Legumes as dry season fallow in upland rice-based systems of West Africa. *Biology and Fertility of Soils* 27, 358–367.

Becker, M. and Johnson, D.E. (1999) The role of legume fallows in intensified upland rice-based systems of West Africa. *Nutrient Cycling in Agroecosystems* 53, 71–81.

Becker, M. and Johnson, D.E. (2001) Cropping intensity effects on upland rice yield and sustainability in West Africa. *Nutrient Cycling in Agroecosystems* 59, 107–117.

Becker, M., Johnson, D.E., Wopereis, M.C.S. and Sow, A. (2003) Rice yield gaps in irrigated systems along an agro-ecological gradient in West Africa. *Journal of Plant Nutrition and Soil Science* 166, 61–67.

Bognonkpe, J.P. and Becker, M. (2009) Land use and dynamics of water and native soil N in inland valleys of Côte d'Ivoire. *European Journal of Scientific Research* 3, 342–356.

Buresh, R.J., Pampolino, M.F. and Witt, C. (2010) Field-specific potassium and phosphorus balances and fertilizer requirements for irrigated rice-based cropping systems. *Plant and Soil* 335, 35–64.

Carsky, R.J. and Ajayi, E.O. (1992) Fitting soil-improving legumes into inland valley rice-based cropping systems in West Africa. In: Mulongoy, M., Gueye, M. and Spencer, D.S.C. (eds) *Biological Nitrogen Fixation and Sustainability of Tropical Agriculture*. International Institute of Tropical Agriculture, Ibadan, Nigeria, pp. 395–404.

CEDEAO (2006) Stratégie Régionale de Promotion des Engrais en Afrique de l'Ouest. Pepared at the Sommet Africain sur les Engrais, Abuja, Nigeria, 9–13 June. Economic Community of West African States, Abuja, Nigeria.

Diara, H.F., Van Brandt, H., Diop, A.M. and Van Hove, C. (1987) *Azolla* and its use in rice culture in West Africa. In: *Azolla Utilization – Proceedings of Workshop on Azolla Use*. Fujian, China, 1985. International Rice Research Institute, Los Baños, Philippines, pp. 147–152.

Dobermann, A., Witt, C., Dawe, D., Gines, G.C., Nagarajan, R., Satawathananont, S., Son, T.T., Tan, P.S., Wang, G.H., Chien, N.V., Thoa, V.T.K., Phung, C.V., Stalin, P., Muthukrishnan, P., Ravi, V., Babu, M., Chatuporn, S., Kongchum, M., Sun, Q., Fu, R., Simbahan, G.C. and Adviento, M.A.A. (2002) Site-specific nutrient management for intensive rice cropping systems in Asia. *Field Crops Research* 74, 37–66.

Donovan, C., Wopereis, M.C.S., Guindo, D. and Nébié, B. (1999) Soil fertility management in irrigated rice systems in the Sahel and savanna regions of West Africa. Part II. Profitability and risk analysis. *Field Crops Research* 61, 147–162.

Erenstein, O. (2006) Intensification or extensification? Factors affecting technology use in peri-urban lowlands along an agro-ecological gradient in West Africa. *Agricultural Systems* 90, 132–158.

FAO (1995) *The Digital Soil Map of the World*, Version 3.5, 1:5,000,000 scale. Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO (2005) *Fertilizer Use by Crop in Egypt*. Food and Agriculture Organization of the United Nations, Rome, Italy.

Fofana, B., Bandaogo, A., Sanou, S., Youl, S. and Mando, A. (2010) Improving rice productivity in Africa through deep placement of urea supergranules. Presentation at the 3rd International Rice Congress, Hanoi, Vietnam, 8–12 November.

Haefele, S.M. and Hijmans, R.J. (2007) Soil quality in rice-based rainfed lowlands of Asia: characterization and distribution. In: Aggarwal, P.K., Ladha, J.K., Singh, R.K., Devakumar, C. and Hardy, B. (eds) *Science, Technology, and Trade for Peace and Prosperity*. Proceedings of the 26th International Rice Research Conference, New Delhi, India, 9–12 October 2006. International Rice Research Institute, Los Baños, Philippines, and Indian Council of Agricultural Research and National Academy of Agricultural Sciences, New Delhi, India, pp. 297–308.

Haefele, S.M. and Wopereis, M.C.S. (2004) Combining field and simulation studies to improve fertilizer recommendations for irrigated rice in the Senegal River valley. In: Doberman, A., Witt, C. and Dawe, D. (eds) *Increasing Productivity of Intensive Rice Systems Through Site-specific Nutrient Management*. Science Publishers, Enfield, New Hampshire and International Rice Research Institute, Los Baños, Philippines, pp. 265–286.

Haefele, S.M. and Wopereis, M.C.S. (2005) Spatial variability of indigenous supplies for N, P and K and its impact on fertilizer strategies for irrigated rice in West Africa. *Plant and Soil* 274, 57–72.

Haefele, S.M., Johnson, D.E., Diallo, S., Wopereis, M.C.S. and Janin, I. (2000) Improved soil fertility and weed management is profitable for irrigated rice farmers in Sahelian West Africa. *Field Crops Research* 66, 101–113.

Haefele, S.M., Wopereis, M.C.S., Donovan, C. and Maubuisson, J. (2001) Improving the productivity and profitability of irrigated rice production in Mauritania. *European Journal of Agronomy* 14, 181–196.

Haefele, S.M., Wopereis, M.C.S. and Wiechmann, H. (2002) Long-term fertility experiments for irrigated rice in the West African Sahel: agronomic results. *Field Crops Research* 78, 119–131.

Haefele, S.M., Wopereis, M.C.S., Ndiaye, M.K., Barro, S.E. and Ould Isselmou, M. (2003) Internal nutrient efficiencies, fertilizer recovery rates and indigenous nutrient supply of irrigated lowland rice in Sahelian West Africa. *Field Crops Research* 80, 19–32.

Haefele, S.M., Wopereis, M.C.S., Schloebohm, A. and Wiechmann, H. (2004) Long-term fertility experiments for irrigated rice in the West African Sahel: effect on soil characteristics. *Field Crops Research* 85, 61–77.

Hilhorst, T. and Muchena, F. (2000) *Nutrients on the Move: Soil fertility dynamics in African farming systems*. International Institute for Environment and Development, London.

IRRI (2012) Rice Area Database of the World. Unpublished. International Rice Research Institute, Los Baños, Philippines.

Kamara, A.Y., Ekeleme, F., Omoigui, L.O. and Chikoye, D. (2011) Influence of nitrogen fertilization on yield and yield components of rain-fed lowland NERICA® rice in the northern Guinea savanna of Nigeria. *African Journal of Agricultural Research* 6, 3092–3097.

Kijima, Y., Ito, Y. and Otsuka, K. (2010) An Empirical Analysis of Expanding Rice Production in Sub-Saharan Africa. On the Possibility of a Lowland Rice Green Revolution in Sub-Saharan Africa: Evidence from the Sustainable Irrigated Agricultural Development (SIAD) Project in Eastern Uganda. *JICA Research Institute Working Paper* No. 25. Japan International Cooperation Agency, Tokyo, Japan.

Kijima, Y., Otsuka, K. and Sserunkuuma, D. (2011) An inquiry into constraints on a green revolution in sub-Saharan Africa: the case of NERICA rice in Uganda. *World Development* 39, 77–86.

Meertens, H.C.C., Ndege, L.J. and Lupeja, P.M. (1999) The cultivation of rainfed lowland rice in Sukumaland, Tanzania. *Agriculture, Ecosystems & Environment* 76, 31–45.

Mghase, J.J., Shiwachi, H., Nakasone, K. and Takahashi, H. (2010) Agronomic and socio-economic constraints to high yield of upland rice in Tanzania. *African Journal of Agricultural Research* 5, 150–158.

Miyamoto, K., Maruyama, A., Haneishi, Y., Matsumoto, S., Tsuboi, T., Asea, G., Okello, S., Takagaki, M. and Kikuchi, M. (2012) NERICA cultivation and its yield determinants: the case of upland rice farmers in Namulonge, central Uganda. *Journal of Agricultural Science* 4, 120–135.

Oikeh, S.O., Nwilene, F., Diatta, S., Osiname, O., Touré, A. and Okeleye, K.A. (2008) Responses of upland NERICA rice to nitrogen and phosphorus in forest agroecosystems. *Agronomy Journal* 100, 735–741.

Oonyu, J. (2011) Upland rice growing: a potential solution to declining crop yields and the degradation of the Doho wetlands, Butaleja district – Uganda. *African Journal of Agricultural Research* 6, 2774–2783.

Posner, J.L. and Crawford, E.W. (1992) Improving fertilizer recommendations for subsistance farmers in West Africa: the use of agro-economic analysis of on-farm trials. *Nutrient Cycling in Agroecosystems* 32, 333–342.

Roger, P.A. and Ladha, J.K. (1992) Biological N_2 fixation in wetland rice fields: estimation and contribution to nitrogen balance. *Plant and Soil* 141, 41–55.

Sahrawat, K.L., Jones, M.P., Diatta, S. and Sika, M. (2003) Long-term phosphorus fertilizer effects on phosphorus uptake, efficiency, and recovery by dryland rice on an Ultisol. *Communications in Soil Science and Plant Analysis* 14, 999–1011.

Saito, K., Azoma, K. and Oikeh, S.O. (2010) Combined effects of *Stylosanthes guianensis* fallow and tillage management on upland rice yield, weeds and soils in southern Benin. *Soil & Tillage Research* 107, 57–63.

Sakurai, T. (2010) Expansion, intensification, and sustainability of rice production in West Africa: the case of rainfed lowland rice in Côte d'Ivoire and Ghana. *International Cooperation in Agriculture* 8, 202–214.

Sanchez, P.A. and Buol, S.W. (1985) Agronomic taxonomy for wetland soils. In: *Wetland Soils: Characterization, classification, and utilization*. Proceedings of a workshop held 26 March to 5 April 1984. International Rice Research Institute, Los Baños, Philippines, pp. 207–229.

Sanchez, P.A., Shepherd, K.D., Soule, M.J., Place, F.M., Buresh, R.J., Izac, A.N., Mokwunye, A.U., Kwesiga, F.R., Ndiritu, C.G. and Woomer, P.L. (1997) Soil fertility replenishment in Africa: an investment in natural resource capital. In: Buresh, R., Sánchez, P.A. and Calhoun, F.C. (eds) *Replenishing Soil Fertility in Africa*. Soil Science Society of America, Madison, Wisconsin.

Sanchez, P.A., Palm, C.A. and Buol, S.W. (2003) Fertility capability soil classification: a tool to help assess soil quality in the tropics. *Geoderma* 114, 157–185.

Segda, Z., Haefele, S.M., Wopereis, M.C.S., Sedogo, M.P. and Guinko, S. (2004) Agro-economic characterization of rice production in a typical irrigation scheme in Burkina Faso. *Agronomy Journal* 96, 1314–1322.

Segda, Z., Haefele, S.M., Wopereis, M.C.S., Sedogo, M.P. and Guinko, S. (2005) Combining field and simulation studies to improve fertilizer recommendations for irrigated rice in Burkina Faso. *Agronomy Journal* 97, 1429–1437.

Segda, Z., Mando, A., Haefele, S.M., Sedogo, M.P., Guinko, S. and Wopereis, M.C.S. (2010) Closing yield gaps through partnerships and good agronomy in Africa. Presentation at the 3rd International Rice Congress, Hanoi, Vietnam, 8–12 November.

Smaling, E.M.A. (2005) Harvest for the world. Presentation at ITC, Enschede, Netherlands, 2 November.

Sokei, Y., Akintayo, I., Doumbia, Y., Gibba, A., Keita, S. and Assigbe, P. (2010) Growth and yield performance of upland NERICA varieties in West Africa. *Japanese Journal of Crop Science* 79(Extra issue 2), 2–3.

Somado, E.A., Becker, M., Kuehne, R.F., Sahrawat, K.L. and Vlek, P.L.G. (2003) Combined effects of legume with rock phosphate on rice in West Africa. *Agronomy Journal* 95, 1170–1178.

Somado, E.A., Kiepe, P. and Niang, A. (2011) Alleviating phosphorus deficiency in rice-based systems in humid Africa. In: Yanagihara, S. (ed.) Next Challenges in Rice Development for Africa: Workshop for New Collaboration between JIRCAS and AfricaRice. *JIRCAS Working Report* 70. Japan International Research Center for Agricultural Sciences, Tsukuba, Japan, pp. 29–35.

Stoorvogel, J. and Smaling, E.M.A. (1990) *Assessment of Soil Nutrient Depletion in Sub-Saharan Africa*. Winand Staring Centre, Wageningen, Netherlands.

Touré, A., Becker, M., Johnson, D.E., Koné, B., Kossou, D.K. and Kiepe, P. (2009) Response of lowland rice to agronomic management under different hydrological regimes in an inland valley of Ivory Coast. *Field Crops Research* 114, 304–310.

van Asten, P.J.A., Barro, S.E., Wopereis, M.C.S. and Defoer, T. (2004) Using farmer knowledge to combat low productive spots in rice fields of a Sahelian irrigation scheme. *Land Degradation & Development* 15, 383–396.

Van Hove, C. (1989) *Azolla. Ses emplois multiples. Son intérêt en Afrique*. Food and Agriculture Organization of the United Nations, Rome, Italy.

Van Hove, C. and Diara, H.F. (1987) *Azolla* introduction in African agriculture: progress and problems. *International Rice Commission Newsletter* 36, 1–4.

Vanlauwe, B. and Giller, K.E. (2006) Popular myths around soil fertility management in sub-Saharan Africa. *Agriculture, Ecosystems and Environment* 116, 34–46.

Watanabe, I. and Van Hove, C. (1996) Phylogenetic, molecular and breeding aspects of *Azolla–Anabaena* symbiosis. In: Camus, J.M., Gibby, M. and Johns, R.J. (eds) *Pteridology in Perspective*. Royal Botanic Gardens, Kew, London, pp. 611–619.

Watanabe, I., Ventura, W., Mascarina, G. and Eskew, D.L. (1989) Fate of *Azolla* and urea nitrogen applied to wetland rice. *Biology and Fertility of Soils* 8, 102–110.

Windmeijer, P.N., Duivenbooden, N.V. and Andriesse, W. (eds) (1994) *Characterization of Rice-growing Agro-ecosystems in West Africa: Semi-detailed characterization of inland valleys in Côte d'Ivoire*. Winand Staring Centre (SC-DLO) and Wageningen Agricultural University, Wageningen, Netherlands.

Wopereis, M.C.S., Donovan, C., Nébié, B., Guindo, D., Ndiaye, M.K. and Häfele, S.M. (1998) Nitrogen management, soil nitrogen supply and farmers' yields in Sahelian rice based irrigation systems. *Advances in GeoEcology* 31, 1261–1266.
Wopereis, M.C.S., Donovan, C., Nebié, B., Guindo, D. and N'Diaye, M.K. (1999) Soil fertility management in irrigated rice systems in the Sahel and savanna regions of West Africa. Part I. Agronomic analysis. *Field Crops Research* 61, 125–145.
Wopereis-Pura, M.M., Watanabe, H., Moreira, J. and Wopereis, M.C.S. (2002) Effect of late nitrogen application on rice yield, grain quality and profitability in the Senegal River valley. *European Journal of Agronomy* 17, 191–198.
Yanni, Y.G., Shalaan, S.N. and El-Haddad, M. (1994) Potential role of *Azolla* as green manure for rice in Nile delta under different levels of inorganic fertilization. In: Hegazi, N.A., Fayez, M. and Monib, M. (eds) *Nitrogen Fixation with Non-legumes*. The American University in Cairo Press, Cairo, Egypt, pp. 127–132.