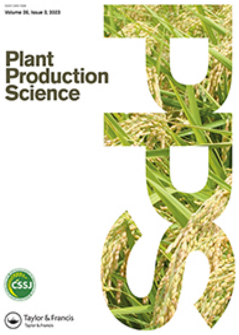

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Status quo and challenges of rice production in sub-Saharan Africa

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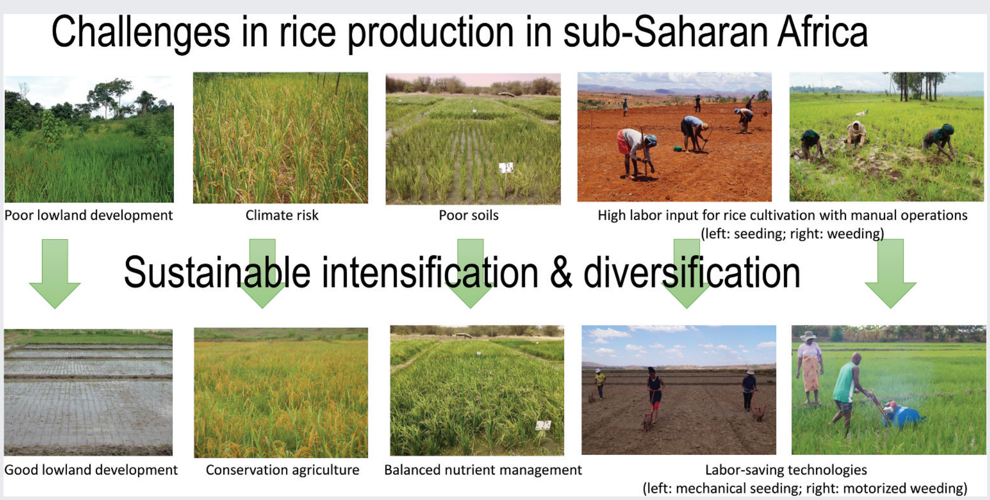
ABSTRACT

Rice production in sub-Saharan Africa (SSA) has increaed ten-fold since 1961, whereas its consumption has exceeded the production and the regional self-sufficiency rate is only 48% in 2020. Increase in rice production has come mainly from increased harvested area. Yield increase has been limited and the current average yield in SSA is around 2 t ha^{-1}. This paper aims to provide the status quo of (i) current rice production and its challenges, (ii) selected achievements in rice agronomy research mainly by the Africa Rice Center and its partners, and (iii) perspectives for future research on rice agronomy in SSA. The major problems confronting rice production include low yield in rainfed environments, accounting for 70% of the total rice harvested area. Rainfed rice yields are strongly affected by climate extremes such as water stresses, soil-related constraints, and sub-optimum natural resource management and crop management practices by smallholder farmers including poor water management, and suboptimal use of fertilizers, herbicides, and machineries. For alleviating these constraints, a wide range of technologies have been developed and introduced over the last three decades. These include water conservation technologies in rainfed and irrigated lowland rice, site-specific nutrient management practices, decision support tools such as crop growth simulation models, and labor-saving technologies. We conclude that further research efforts are needed to develop locally adapted agronomic solutions for sustainable intensification, especially in rainfed rice to enhance the resilience to climate change and increase land and labor productivity and sustainability of rice cultivation in SSA.



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Introduction

Rice (*Oryza* spp.) is one of the most important staple crops for food security and social stability in large parts of sub-Saharan Africa (SSA). Its consumption has been increasing more rapidly than any other staple crop (Arouna et al., 2021). This rapid increase is driven by high population growth, urbanization and changing consumer preferences in the region. Recently reaching

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one billion inhabitants, SSA has had the highest population growth rate in the world with a mean increase of 2.5% per annum between 2007 and 2016 (The World Bank, 2022). During the same period, rice consumption has increased, at a rate of 6% per annum, and is expected to continue to grow in the foreseeable future (FAO, 2022).

In response to its growing demand in SSA, rice production has increased ten-fold since 1961 (FAO, 2022). This has resulted mostly from both an expansion of rice harvested area and, albeit to a lesser extent, an increase in rice production per unit of land (referring to as yield). Between 2000 and 2020, the harvested area increased from 6.9 million ha to 16.6 million ha, whereas the gain in rice yield was limited, increasing from 1.7 to 2.1 t ha^{-1} only (FAO, 2022). Recent yield levels are still much lower than the global average which is around 4.8 t ha^{-1}. Furthermore, on average in SSA countries, actual yields are less than half of the potential yield (Yp) or water-limited yield (Yw) (van Oort et al., 2015), suggesting that doubling rice yield is possible. 'Yp' is defined as the maximum yield that can be obtained from a crop in a given environment, as determined by simulation models with plausible physiological and agronomic assumptions. Under irrigated conditions, potential yield is determined by climate (solar radiation and temperature), varietal characteristics and crop establishment methods including sowing date and density. Under rainfed environments, 'Yw' is affected by water availability (Saito et al., 2013). In 2020, rice consumption in SSA was estimated to be 32.2 million tons of milled rice, which was partially fulfilled by the importation of approximately 15.6 million tons (equivalent to 33% of the world market), indicating that the self-sufficiency rate in SSA is only 48%. The large gap between demand and supply for rice has pointed the attention of African governments and international donors to efforts strengthening the rice sector to achieve self-sufficiency in SSA (Arouna et al., 2021; Saito et al., 2015).

The objectives of this paper are to provide the status quo of (i) rice production and its main challenges, (ii) selected achievements in rice agronomy research mainly by Africa Rice Center (AfricaRice) and its partners, and (iii) perspectives for future research on rice agronomy in SSA. An edited book, published 10 years ago (Wopereis et al., 2013), and a recent special issue in Field Crops Research (Rodenburg & Saito, 2022) provided comprehensive reviews on historical efforts on agronomy research. This paper does not intend to summarize their reviews, but provide complementary information, which were missing in those reviews, and present perspectives for future research, building on these publications. Thus, the main foci in this paper are on (i) climate risks and associated crop management practices in rainfed environments, (ii) soil-related constraints, and (iii) labor issues in rice cultivation. First, we summarize characteristics of rice-growing environments and farmers' rice cultivation practices, and some of the sustainable rice performance indicators (SRP, 2020) such as yield and profit of three rice-growing environments based on recent studies. Second, we discuss climate risks, soil-related constraints and labor issues in rice cultivation. Then, we showcase some of the key technologies developed by Africa Rice Center and partners, addressing various challenges, and we discuss perspectives for future research.

Characteristics of rice-growing environments in SSA

In SSA, rice-growing environments comprise irrigated lowland, rainfed lowland, and rainfed upland, with deepwater and mangrove rice being of minor overall importance. Irrigated lowland, rainfed lowland, rainfed upland, and others account for 22%, 40%, 35%, and 4%, respectively, of the total rice area in SSA (Diagne et al., 2013). Surface-water regimes and water sources (e.g., irrigation, rainfall, water table) distinguish the rice-growing environments. Irrigated lowlands comprise bunded fields with assured irrigation for one or more crops per year. Rainfed lowlands include slightly sloping, unbunded or bunded fields on waterlogged soils, often found in lower parts of the landscape such as lower slopes and valley bottoms of inland valleys. Rainfed uplands refer to level or sloping, unbunded fields on free-draining soils.

On-farm surveys in nineteen SSA countries showed that mean rice yields were 4.0, 2.6, and 1.6 t ha^{-1} in irrigated lowland, rainfed lowland, and rainfed upland, respectively (Tanaka et al., 2017; Table 1). Similarly, three recent studies (Arouna et al., 2021; Dossou-Yovo et al., 2020; Ibrahim et al., 2022) showed higher rice yields from irrigated lowlands (4.1 and 5.0 t ha^{-1}, respectively) than other environments (Table 1). The yields of irrigated lowland rice obtained in these studies are similar to the global average which is around 4.8 t ha^{-1} contradicting the general perception that rice yields in SSA are low. National-level statistics on rice yields, feeding this perception, do however not differentiate rice-growing environments and their share of harvested areas. The low national yield level in SSA is attributed to a relative larger area share of rainfed lowland and upland rice that inherently have lower yields. Boosting rice production in SSA should be possible through the expansion of irrigated rice

Table 1. Selected farmers' rice cultivation practices, yield, and profit in three major rice-growing environments in sub-Saharan African countries.

	Irrigated lowland	Rainfed lowland	Rainfed upland	Reference
Rice area (ha household^{-1})	1.2	2.3	NA	Arouna et al. (2021)[1]
	1.0	1.3	1.8	Ibrahim et al. (2022)[2]
Certified seed (% of farmers interviewed)	59	33	20	Niang et al. (2017)[3]
	74	4	NA	Arouna et al. (2021)
	87	76	69	Ibrahim et al. (2022)
Construction of field bunds (% of farmers interviewed)	93	27	15	Niang et al. (2017)
	100	77	7	Senthilkumar et al. (2020)[4]
Mechanical tillage (% of farmers interviewed)	83	52	47	Niang et al. (2017)
	0	18	0	Senthilkumar et al. (2020)
Field leveling (% of farmers interviewed)	47	23	19	Niang et al. (2017)
	48	27	0	Senthilkumar et al. (2020)
	70	59	56	Ibrahim et al. (2022)[5]
Transplanting (% of farmers interviewed)	77	28	7	Niang et al. (2017)
	96	43	0	Senthilkumar et al. (2020)
	92	25	NA	Arouna et al. (2021)
N application rate (kg ha^{-1})	83	78	35	Dossou-Yovo et al. (2020)[6]
	19	10	2	Senthilkumar et al. (2020)
	40	19	NA	Arouna et al. (2021)
	104	80	69	Ibrahim et al. (2022)
P application rate (kg ha^{-1})	12	2	2	Senthilkumar et al. (2020)
	5	2	NA	Arouna et al. (2021)
	18	13	9	Ibrahim et al. (2022)
Labor input (person day ha^{-1})	90	89	NA	Arouna et al. (2021)
	116	43	48	Ibrahim et al. (2022)
Herbicide use (% of farmers interviewed)	44	36	24	Rodenburg et al. (2019)[6]
	40	39	NA	Arouna et al. (2021)
Rice yield (t ha^{-1})	4.0	2.6	1.6	Tanaka et al. (2017)[6]
	4.1	1.4	NA	Arouna et al. (2021)
	5.0	3.0	1.8	Ibrahim et al. (2022)
Net profit (USD ha^{-1})	1036	223	NA	Arouna et al. (2021)
	909	526	376	Ibrahim et al. (2022)

Notes: [1] Benin, Cameroon, Cote d'Ivoire, Ghana, Madagascar, Mali, Niger, Nigeria, Senegal, Sierra Leone, Tanzania, and Togo.
[2]Burkina Faso, Ghana, Nigeria, Senegal, and Tanzania. Farmers buying certified seeds with quality control or using self-saved seeds for a maximum of three crop cycles and with quality control (%).
[3]Data from 11 West African countries only (Benin, Burkina Faso, Côte d'Ivoire, Ghana, Guinea, Mali, Niger, Nigeria, Sierra Leone, The Gambia, and Togo).
[4]Data from five East and Southern African countries only (Tanzania, Uganda, Ethiopia, Rwanda, and Madagascar).
[5]Land having been leveled or had soil conservation practices (%).
[6]Benin, Burkina Faso, Cameroon, Chad, Côte d'Ivoire, Democratic Republic of Congo, Ethiopia, Ghana, Guinea, Madagascar, Mali, Niger, Nigeria, Rwanda, Senegal, Sierra Leone, Tanzania, The Gambia, Togo, and Uganda. Tanaka et al. (2017) did not include data from Senegal.

cultivation (Saito et al., 2013), or by improving yields from rainfed rice growing environments.

Irrigated rice cultivation can be characterized by a higher profit associated with higher yield, resulting from higher inputs including seed, chemicals, and machinery for land preparation, lower plot sizes, and better field leveling compared to the other two major rice-growing environments (Table 1). In addition, farmers who grow irrigated lowland rice also often have better access to certified seed and mechanical tillage, conduct better land preparation (bunding, leveling) and transplanting, and apply higher N and P fertilizer application rates. Herbicide application levels are similar in irrigated and rainfed lowland rice, whereas labor inputs were not consistent across the three major rice-growing environments in these studies (Table 1). Apart from traditional equipment, machineries for planting, weeding, and harvesting are still not common except for a few cases such ashand-operated rotary weeders in Madagascar (Rodenburg et al., 2019) and combined harvesters in the Senegal River Valley, in Senegal. In contrast with irrigated and rainfed lowland rice, rainfed upland rice is grown with relative low input levels such as certified seed, fertilizers, and herbicides. Table 1 does not show separate data on the potassium (K) application rate as it is generally highly correlated with application rates of the two most deficient nutrients, nitrogen (N) and phosphorus (P) (Ibrahim et al., 2022; Saito et al., 2019; Vandamme et al., 2018). The inconsistencies in data shown in Table 1 across studies (e.g., labor input) could be due to differences in the target countries and survey sites within a given country.

Reported N fertilizer application rates, especially in irrigated lowland rice, are higher than expected based on national statistics (Table 1). Again, national-level statistics do not differentiate crops and rice-growing environments, and account for their relative shares of harvested areas. For example, when the mineral N application rate was calculated by dividing total N consumption by total arable land area, the N application rate in SSA remained less than 10 kg N ha^{-1} (Tsujimoto et al., 2019). Yet, a relatively higher N application rate to cereals was observed in household surveys in SSA (Holden, 2018) and the N application rates observed in irrigated lowland rice, mainly studies from West Africa (e.g., Dossou-Yovo et al., 2020; Ibrahim et al., 2022), are similar to that in some of Asian countries (IFA, 2022).

Yuan et al. (2021) recently quantified yield gaps and resource-use efficiencies (including water, pesticides, N, labor, energy, and associated global warming potential) across 32 rice cropping systems covering half of the global rice harvested area including SSA. The rice production in SSA is characterized by large yield gaps, low use of chemical inputs (inorganic N fertilizer, pesticides), high risks of soil N mining, and high labor inputs. Relative higher labor inputs in SSA are associated with a relative lower use of machines. Rice production in SSA tended to have a lower global warming potential per area, but a higher yield-scaled global warming potential due to low yields. Hence, rice in SSA would need a larger production area for reaching a given production target, which, ultimately, would lead to a larger environmental impact. Furthermore, rainfed rice environments in SSA tend to have a lower yield stability than those in other regions (Saito et al., 2021; Supplementary Fig.4 in; Yuan et al., 2021).

Constraints to rice production

It has been frequently reported that low rice yields in SSA are caused by a range of biophysical and socioeconomic constraints that impose abiotic and biotic stresses on the rice crop during its growth cycle (Asai et al., 2021; Dossou-Yovo et al., 2020; Ibrahim et al., 2021; Niang et al., 2017, 2018; Saito et al., 2013; Senthilkumar et al., 2020). Although the constraints are site- and rice-growing environment-specific, soil-related constraints including iron toxicity and salinity, extreme temperatures, drought (water scarcity, and poor water management in irrigated and rainfed lowlands), flooding, weeds, diseases, pests, and suboptimal land and crop management interventions are the major factors causing low yields. Production risks arising from these constraints aggravate farmers' resource use inefficiency (Mujawamariya et al., 2017). As mentioned in the introduction section, we do not describe all the constraints to rice production in SSA in this paper but instead will focus on (i) climate risks and associated crop management practices to mitigate them in rainfed environments, (ii) soil-related constraints, and (iii) labor issues in rice cultivation.

Climate risks related to rainfed environments

It is well-recognized that cropping systems with low potential yield (Yp) or water-limited yield (Yw) typically exhibit high year-to-year yield variability (van Ittersum et al., 2013; van Oort et al., 2017; Yuan et al., 2021). This is especially the case for rainfed environments in SSA, which have both drought and flooding risks (Saito et al., 2021; Yuan et al., 2021). The harsh and variable climate generally limits maximum productivity and makes investment in agricultural inputs riskier. Year-to-year variation in Yw in rainfed rice in SSA is much higher than that in simulated Yp in irrigated lowland rice (Saito et al., 2021; van Oort et al., 2017), indicating a higher risk in rainfed rice. Using a 20% threshold, yield loss due to water stress ($Yw/Yp < 0.8$), 24% of all rainfed lowland sites and 76% of all rainfed upland sites in SSA were classified as suffering from drought (van Oort, 2018). With such risk, farmers' agricultural inputs are generally lower in rainfed rice than irrigated lowland rice, as shown in Table 1. Therefore, farmers in rainfed environments tend to be trapped in a vicious cycle of poverty: low investment leading to low productivity, resulting in a small income, and low capital accumulation leading to low investment. There are a few studies showing year-to-year variation in yield based on data from field experiments or surveys, i.e., 4-year field survey/experiment in Benin (Niang et al., 2018) and a 6-year experiment in Côte d'Ivoire (Husson et al. 2022). Both studies clearly showed large yield variation in rainfed environments (1.1 to 2.9 t ha^{-1} in Niang et al., 2018; 0.7 to 2.1 t ha^{-1} in Husson et al., 2022), and indicated a strong association between yield variation and rainfall or soil water conditions. Furthermore, spatial variation in soil water status strongly affects variation in yield response to N fertilizer application (Niang et al., 2018). Together with the evidence from these studies, greater climate variability predicted in future climate scenarios, resulting in increased rainfall extremes, greater risks, and a negative impact on agriculture calls for urgent development of climate change adaptation options in rainfed environments in SSA (Akpoti et al., 2020; Müller et al., 2011).

Spatial and temporal impact of flooding on rice has not been quantified yet (van Oort et al., 2019). However, it has been considered that early-season flash flooding and submergence greatly impair rice production in the rainfed lowlands of SSA (Devkota et al., 2022).

Soil-related constraints

Soil fertility is inherently low in SSA and has been considered as one of the major constraints to rice production (Diagne et al., 2013; Haefele et al., 2013; Tsujimoto et al., 2019). Recent studies used digital soil maps for assessing soil-related constraints to rice production at the African continent level (Haefele et al., 2014; Saito et al., 2013; van Oort, 2018). Soil constraints, in general, are more common in rainfed rice than irrigated lowland rice (>75% v. 52% in poor and very poor soils) (Saito et al., 2013), whereas a relative higher percentage of problem soils (mainly saline and sodic soils) is observed in irrigated lowland rice than rainfed rice (18 vs. 2–3%). Haefele et al. (2014) identified drought-prone soils (with low soil water-holding capacity) as a major constraint to rice production in SSA. Quantitative estimates by van Oort (2018) showed that 20–33%, 12%, and 2% of Africa's total rice area, were potentially affected by drought, iron toxicity, and soil salinity/alkalinity, respectively.

A recent study assessed the degrees of variation of 19 soil fertility properties for 2845 soil samples collected from 42 study sites in 20 SSA countries (Johnson et al., 2019). The majority of soil samples were collected from farmers' fields. Soil fertility properties in rice-cultivated fields across SSA varied largely except for pH. In general, soils in rice fields were characterized by low chemical fertility and high deficiencies in total N, available P, and extractable B. Furthermore, Johnson et al. (2021) assessed concentrations of six macronutrients (N, P, K, Ca, Mg, and S) and seven micronutrients (Na, Fe, Mn, B, Cu, Mo, and Zn) in grain and rice straw samples collected at harvest from 1628 farmers' fields in 20 SSA countries. N, P, and K concentrations in rice straw in irrigated lowland fields were higher than in rainfed lowland and upland. From the studied fields, 2%, 16%, and 16% of straw samples were deficient in N, P, and K, respectively. K deficiency occurred in all three major rice-growing environments, whereas P deficiency mainly occurred in rainfed upland rice.

Haefele et al. (2022) assessed soil fertility properties and nutrient concentrations in grain and straw samples in long-term experiments in the Senegal River Valley, Senegal, which included six different fertilizer treatments. The samples were collected in the 2016/17 dry season (after 26 years, implying 52 iterations of continuous rice cropping). In addition to N and P deficiencies, which are typically observed in nutrient omission trials (Saito et al., 2019), likely deficiencies of K, S and Zn are appearing in these experiments and may begin to limit rice yields in intensive irrigated lowlands. Unfortunately, to our knowledge, there are no long-term experiments (>20 years) on rainfed lowland and upland rice in SSA.

The above-mentioned assessment was based on a comparison of soil fertility properties or crop nutrient concentrations observed in the literature. Quantification of relationships between soil fertility properties or plant nutrient concentration and rice productivity remains a challenge (Dossou-Yovo et al., 2020; Niang et al., 2017, 2018; Zingore et al., 2022). In most cases, rice yield was not strongly related to soil fertility properties assessed by soil tests. This also applied to data from nutrient omission trials; rice yields from -N, -P, or -K plots could not be simply estimated by total N, or total/extractable P or K in all three major rice-growing environments (Zingore et al., 2022). Further research is still needed for estimating yield response to indigenous soil nutrient supplies and fertilizers. The alternative is a heavy reliance on data on rice yield from nutrient omission trials (Saito et al., 2019), the establishment and monitoring of which requires substantial investment.

Recently, micronutrient deficiency has been identified as one of the limiting factors for rice yield (Haefele et al., 2022; Johnson et al., 2021; Johnson et al., 2019). But, the results are inconsistent among study sites. Positive impacts of micronutrient fertilizer application on rice yield were observed in Burkina Faso, Mali, and Tanzania, but this was not the case for Niger and Uganda (Awio et al., 2021; Garba et al., 2018; Senthilkumar et al., 2021; van Asten et al., 2004). Thus, a site-specific approach is needed for enhancing rice yield via additional micronutrients.

Labor

As indicated above, farmers' adoption of labor-saving technologies such as chemical inputs and machineries are limited for rice cultivation in SSA. Thus, rice cultivation requires significant manual labor inputs from both male and female farmers in SSA (Arouna et al., 2021; Ibrahim et al., 2022; Yuan et al., 2021). In addition, child labor is common in this region (Bass, 2004). The agricultural workforce contains a larger share of women than men (Palacios-Lopez et al., 2017). However, a recent study, which was conducted in Burkina Faso, Côte d'Ivoire, Madagascar, and Sierra Leone, provided evidence that female farmers do not necessarily spend more time than men in rice cultivation in SSA (Kinkingninhoun et al., 2020).

Land preparation, crop establishment, weeding, bird scaring, and harvesting are major interventions requiring substantial labor inputs for rice cultivation (Paresys et al., 2018; Komatsu et al., 2022). Delayed land preparation and crop establishment due to labor shortage or poor access to machinery tend to result in rice plants having more abiotic (e.g., lower rainfall or temperature at the end of wet season) and biotic stresses (e.g., birds) (Tanaka et al., 2015). Consequently, delayed planted rice tends to have lower yields. Competition from weeds is typically one of the major biophysical constraints, frequently leading to significant yield losses and sometimes to complete crop failure (Rodenburg et al., 2022). Without labor-saving technologies including herbicides or mechanical weeders, weeding is however very labor intensive. In rainfed upland rice, Ogwuike et al. (2014) reported that average yields of 1.2 t ha^{-1} are achieved after one manual weeding intervention requiring 179 h ha^{-1} and each additional weeding intervention, while requiring progressively less labor (130 hours ha^{-1} for second weeding, 125 h ha^{-1} for third weeding), improves yields by 0.5 t ha^{-1}. Weeding proved not only to reduce weed competition, but also decrease bird visits and concomitant rice grain losses from granivorous birds (Rodenburg et al., 2014). This is an important additional reason for farmers to invest in weeding because birds cause substantial damage in SSA. Annual bird damage is found to average 13% of the rice production in irrigated lowland rice. Farmers heavily rely on their traditional bird control techniques, e.g., manual bird scaring, flags, and scarecrows (de Mey et al., 2012).

Based on the above, the introduction of labor-saving technologies (e.g., machineries, herbicides, early maturing varieties) for critical management operations is essential for enhancing yield as well as labor productivity. Furthermore, reducing the labor inputs for rice cultivation could also simply free time and improve farmer health and quality of life, create opportunities for other agricultural or off-farm activities, and free children from labor in favor of schooltime, thus improving their future opportunities (Brosseau et al., 2021; Kinkingninhoun et al., 2020).

Opportunities for increased productivity of rice

This section showcases some of the efforts made by Africa Rice Center and its partners to evaluate or develop technologies for addressing the challenges mentioned in section 3. This section will focus on (i) enhancing rice productivity in rainfed environments, (ii) soil and nutrient management practices, and (iii) labor-saving technologies.

Enhancing rice productivity in rainfed environments

Rainfed lowland rice fields in SSA do not always have bunds and are often not well leveled (Niang et al., 2017). For reducing climate risks due to drought in rainfed lowland rice, water conservation technologies that involve leveled fields and improved bunding have been extensively tested and disseminated in SSA (Dossou-Yovo et al., 2022). Wherever possible, the construction of inlets for irrigation to have supplemental irrigation has been considered as one of the alternative approaches for adapting to climate change, as drought-resistant varieties cannot completely mitigate the risks for yield reduction due to drought (Asai et al., 2021; Grotelüschen et al., 2022; Onaga et al., 2020). For example, in Uganda, Onaga et al. (2020) reported that supplemental irrigation of 20 mm of water using sprinklers every 5 days during windows of dry weather starting from the panicle initiation stage significantly increased rice yield (by 37%), fertilizer use efficiency (by 54%), and profitability of rice cultivation (by 32%). Grotelüschen et al. (2022) quantified the impact of supplemental irrigation on yield in two sites of East Africa using the Agricultural Production Systems Simulator (APSIM) over 30 years of historical weather data. Supplemental irrigation showed average yield gains of > 1.5 and > 0.4 t ha^{-1} in two sites. Reducing production risks could be important to foster intensification, as it would allow and incentivize farmers to invest more inputs (e.g. fertilizer), resulting in further yield increase (Niang et al., 2018). Where supplemental irrigation is not available or expensive, an APSIM model-based approach could deliver recommendations for optimum fertilizer application levels in drought-prone rainfed conditions (Grotelüschen et al., 2022). Models like APSIM or ORYZA2000 or ORYZAv3 can also be used to stimulate yield gain and risk related to sowing windows and variety options (Van Oort & Dingkuhn, 2021). However, such studies have not been undertaken yet in SSA for rainfed rice. The challenge is that such simulations require high-quality input data on soil parameters and local dynamics of soil hydrology (Van Oort & Dingkuhn, 2021). In contrast with rainfed lowland rice, climate change adaptation options such as sowing window, variety choice, and cropping pattern choice were recently evaluated for irrigated rice (van Oort et al., 2019).

Up to now, there has been a limited number of studies on the evaluation of submergence-tolerant rice varieties that contain the Sub1 gene in SSA. Devkota et al. (2022) assessed the performance of two Sub1 varieties developed for West Africa under transplanted and wet-seeded conditions, in comparison with the predominant local variety (WITA 9). The fields were submerged for 1–2 weeks at 5–7 weeks after seeding. This study showed similar results to those observed in Asia, and the yield of the Sub1 varieties was 1.1–4.5 t ha^{-1} higher than that of the local popular variety WITA 9. Although the yield of the Sub1 varieties was not affected by the establishment method, wet seeding also reduced labor requirements and costs, and increased profitability. Thus, combining Sub1 varieties with wet seeding could provide co-benefits in terms of increased profitability and resilience to flash flooding as well as reducing labor inputs. Further evaluation of such combined packages in actual production environments is warranted.

In rainfed upland rice, Asai et al. (2021) performed a meta-analysis to assess the impact of mineral fertilizer application on upland rice yield and to quantify the effects of soil texture and rainfall on the yield response to mineral fertilizer application. This study clearly showed the importance of rainfall, and higher rainfall is related to greater yield response to fertilizer. The effect of N fertilizer depends on soil type and is poor or negative on soils with a low clay content, especially under low rainfall conditions. The information aids in developing strategies for fertilizer management and other crop management practices. In soils with a high clay content, N fertilizer application is recommended to target higher yield because of the high return and low risk of a negative response, even under low rainfall conditions. Combining such fertilizer recommendations with high-yielding varieties such as upland *indica* materials from Asia could enhance rice productivity further (Futakuchi et al., 2021; Saito et al., 2018). For areas dominated by soils with a low clay content and low and/or variable rainfall, water conservation technologies such as conservation agriculture including mulching, crop diversification options (e.g., rotating upland rice with maize and sorghum), and weather forecasting for fine-tuning fertilizer recommendations could also be considered. Recent studies showed that conservation agriculture practices or mulching only could reduce soil erosion (Rodenburg et al., 2020), improve upland rice yield, and reduce the year-to-year coefficient of variation (Bruelle et al., 2015; Husson et al., 2022; Partey et al., 2016; Totin et al., 2013). However, sometimes, yield increases with conservation agriculture have also been associated with increases, rather than reductions, in yield variability (Rodenburg et al., 2020). Among the above studies, three studies (i.e., Bruelle et al., 2015; Husson et al., 2022; Partey et al., 2016) showed that the yield levels obtained with conservation agriculture, even with inorganic fertilizer application, remained below 2 t ha^{-1}. In such conditions, a substantial increase in rice production is not expected, and more studies are needed for exploring crop diversification options having greater resilience to drought in terms of profit and crop production. Here, supplemental irrigation might be also considered. Again, evaluating various crops is needed for identifying their suitability under supplemental irrigation.

Soil and nutrient management

Djagba et al. (2022) evaluated one of the soil digital soil maps (AfSoilGrids250m, Hengl et al., 2015) to examine if such digital soil information can predict soil fertility properties in rice fields in SSA for its potential use for the development of field-specific nutrient management recommendations. The results showed that at the field scale, the prediction accuracy of AfSoilGrids250m for pH (H_2O), clay and silt contents, total N, and organic carbon were poor (R^2 <0.50). The best predictive performances were obtained when data were aggregated by site and rice growing environment combination, suggesting limitations of the use of soil digital information for field-specific recommendations. In 2021, Hengl et al. (2021) developed new, detailed pan-African maps of soil nutrients at a 30 m resolution. Evaluation of these maps is warranted for their use for field-specific nutrient management recommendations.

Another advancement in the domain of research on soil and plant nutrient analyses for rice in SSA is the application of infrared spectroscopy for estimating soil fertility properties and plant nutrient concentrations. Good prediction models (R^2 >0.75) were obtained for 13 soil fertility properties including pH H_2O, total N, total organic C, clay and silt content, exchangeable Ca, and exchangeable Mg, as well as 7 nutrients concentrations in rice plants, i.e. N, P, K, Ca, Mg, Mn, and Cu (Johnson et al., 2021). These studies clearly show that diffuse reflectance spectroscopy can offer an efficient, rapid, and environmental-friendly alternative to conventional wet chemistry methods for assessing soil fertility properties and nutrient concentrations in rice plants in SSA.

Chivenge et al (2021, 2022). reported progress in research and development of site-specific nutrient management (SSNM). RiceAdvice was developed as an SSNM tool for rice in SSA, and its impact was evaluated (Arouna et al., 2021; Zossou et al., 2021). The yield gain obtained following RiceAdvice fertilizer recommendations was limited, and yields were generally still far from their potential. Emphasis is needed for integrating SSNM approach with other good agricultural practices such as land preparation, variety choice, crop establishment, and weed management. Furthermore, SSNM work for rice in SSA still focuses on irrigated rice or favorable rainfed lowland rice, i.e. where yield loss due to water stress is limited. Here, weather forecasting can be used for considering seasonal variation. Real-time adjustment of nutrient management based on weather data and crop growth could help improving farmers' decision-making. For improving nutrient use efficiency, fertilizer application methods such as application to nursery beds in transplanted rice and micro-dose placement in dry-seeded, dibbled rice were tested (Vandamme et al., 2016, 2018). But these studies focused on P only. Further studies should consider other nutrient elements.

Senthilkumar (2022) reviewed the literature on crop and nutrient management approaches and innovations for rice in SSA. Out of 84 studies that dealt with nutrient management, only six studies were done on organic amendments (including green manures) and only four included micronutrients. With soaring inorganic fertilizer prices in SSA (Awio et al., 2022), future research should focus more on the use of renewable and locally available resources (e.g. rice husks, organic matter from crop residues or household waste). For example, Tippe et al. (2020) concluded that rice husks, widely and often freely available from local rice mills, could supplement part of the inorganic fertilizers required in both rainfed upland and lowland. What would be necessary is to quantify their availability and impact on a much larger scale and identify target domains for scaling. Yield responses to organic resources require evaluation and linking such observations with digital soil maps would be warranted to examine and understand site-specificity of gains from organic soil amendments. Furthermore, long-term soil health monitoring is needed to make sure that recommended fertilizer management practices would not have a negative impact on future environmental sustainability.

Labor-saving technology

Agronomists or crop scientists can play major roles in the above two topics, i.e. enhancing rice productivity in rainfed environments and improving soil and nutrient management practices. When it comes to testing labor-saving technologies, collaboration should be sought with mechanization experts and private companies (e.g., manufacturers, dealers, and service providers) with an interest in developing and upscaling technologies. Social scientists need to come to the table to gain (and apply) knowledge on gender and power dynamics and other socio-economic factors underlying needs and adoption of such technologies by farm actors. Agronomists or crop scientists would focus on on-station and on-farm field evaluation of these technologies before introducing them to farmers. Such evaluations could help further improving technologies as well. Social scientists could also play an important role in quantifying the impact of labor-saving technologies, on different user groups, in terms of labor savings and spin-offs thereof. It has been observed that the rate of women adopting labor-saving technology is low because its design is generally based on factors important to men (Vemireddy & Choudhary, 2021) and women in rural Africa are often faced with limited access to such technologies and training on their use (Achandi et al., 2018).

Apart from testing of herbicides as part of integrated good agricultural practices, there were limited studies assessing the effect of labor-saving technologies on labor inputs for rice cultivation in SSA (Senthilkumar, 2022). Rodenburg et al. (2015) assessed potential time savings from mechanical weeders and herbicides, and Amponsah et al. (2017) evaluated the performance of combined harvesters. Johnson et al. (2019) worked with farmers to evaluate mechanical weeders. Labor-saving technologies for land preparation and crop establishment have so far not been considered for rice production in SSA. This does not mean that research on mechanization was not a high priority in rice agronomy research for AfricaRice and its partners (Rickman et al., 2013). There are several potential reasons for a limited publication record. First, mechanization specialists often focused on post-harvest technologies rather than rice production technologies. Consequently, the collaboration between mechanization experts and agronomists has been limited. Second, there is a scarcity of mechanization experts with academic backgrounds or interests. The focus of mechanization experts has been on the development side, rather than the experimental research and publication side. Information derived from factorial experimental research across environments and contexts would however be especially helpful for potential users who want to know more about benefits, costs, technical requirements and how to handle the machineries (Mujawamariya & Kalema, 2017).

Within the One CGIAR, Excellence in Agronomy (EiA) for Sustainable Intensification and Climate Change Adaptation Initiative, which started in 2022, a strategic project on mechanization was initiated, which brings mechanization experts across different CGIAR centers together. The project explores appropriate mechanization options that can make an impact on improved efficiency of resources (i.e., land, water, nutrient, labor, and capital) and increase productivity at the field and farm level in a given location. Furthermore, it is essential to explore different mechanization service provision models that could help farmers implementing timely land preparation (e.g., two-wheel tractors), crop establishment (e.g., seeders and transplanters) and other rice cultivation practices such as motorized weeders for weeding and reapers for harvesting.

Conclusion and perspectives for future research

This review shows that significant efforts in agronomic research for development have been undertaken to address the challenges in rice cultivation in sub-Saharan Africa (SSA). Despite these efforts and achievements, however, considerable yield gaps in researcher-managed trials as well as farmers' fields persist. Further improving rice yield and closing the rice yield gaps across environments, is an essential objective for achieving food security and rice self-sufficiency. Sustainable intensification in rainfed lowlands and uplands offers substantial room for increasing rice production because total rainfed rice represents > 70% of the total rice harvested area in SSA. Agronomists and crop scientists should demonstrate how much the yield gap could realistically be closed with integrated crop management practices. We summarized the

Table 2. Suggested research priority areas and their detailed research agenda for rice agronomy in sub-Saharan Africa.

Priority area	Research theme	Short-term research topic	Strategic research topic (requires several years or more)
Enhancing rice productivity in rainfed environments	Integration of water conservation technologies and good agricultural practices	• Ex-ante assessment for identifying target domains for rainfed lowland rice at regional level (e.g. identify climate vulnerable regions) • Identify climate change adaptation options using crop simulation models for climate change adaptation (e.g. shifting planting dates, improved water conservation technologies management, introduction of submergence tolerant varieties) • Integrate existing water conservation technologies, good agricultural practices, and promising climate change adaptation options (above-mentioned) and its testing	• Improvement of crop simulation models (Van Oort & Dingkuhn, 2021) • Remote sensing for acquiring input data on soil parameters and local dynamics of soil hydrology for crop simulation modeling (Van Oort & Dingkuhn, 2021) • Assessment of environmental sustainability and resilience to climate change of integrated practices via long-term trials (Saito et al., 2021) • Feasibility studies on use of seasonal weather forecasting for decision support for rice cultivation (Niang et al., 2018)
	Supplemental irrigation in rainfed lowland and upland rice	• Identify target sites for introducing supplemental irrigation via ex-ante assessment (e.g. groundwater assessment, assessment of potential gain through supplemental irrigation using crop simulation models) • Identify locally available and affordable irrigation methods • Introduce and test supplemental irrigation with farmers	• Remote sensing for water resource assessment at different scale levels
	Intensification for rainfed upland rice cultivation	• Identify target sites for intensification of rainfed upland rice (e.g. less drought-prone environments, good input-responsiveness) • Identify climate change adaptation options using crop simulation models for climate change adaptation (e.g. shifting planting dates) • Test upland *indica* materials from Asia as well as other varieties and integrated good agricultural practices, and assessment of their sustainability	• Testing of weather forecasting for in-season adjustment in agricultural practices
	Diversification options in drought-prone environments for upland rice	• Identify drought-prone environments for rainfed upland rice cultivation • Develop an inventory of farm diversification options and their testing	• Assessment of environmental sustainability and resilience to climate change of farm diversification options via long-term trials
Soil and nutrient management	Improving soil and nutrient management practices	• Integrate SSNM approach with other good agricultural practices such as land preparation, variety choice, and crop establishment	• Assessment of soil digital maps for examining their usefulness for field-specific nutrient management recommendations • Quantification of relationships between soil fertility properties or plant nutrient concentration and rice productivity through the use of advanced analytical approaches (infrared or X-ray fluorescence spectra and machine learning algorithms) (Breure et al., 2022; Leenen et al., 2019; Miao et al., 2023) • Testing of renewable and locally available resources (e.g. recycling of organic matter) and assessment of their impact on environmental sustainability • Feasibility study on agronomic fortification for improving grain nutrient concentrations in different rice-growing environments
Labor-saving technology	Mechanization options	• Identify appropriate intervention sites and appropriate agricultural machinery inventories through demand mapping • Quantify the technical efficiency of different small and medium-scale machines in target locations • Quantify the labor-saving potential and economic feasibility of machine use on profitability	• Identification and development of local capacity for fabrication and sustained production of identified machineries to meet the demand • Introduction, testing and validation of service provision models for small and medium-scale machineries for different field operations
	Labor-saving crop management options, cropping systems, and crop protection	• Develop an inventory of promising labor-saving technologies and their testing • Appropriate and safe use of labor-saving chemical options for weed pest and disease control • Test preventative weed, pest, and disease control methods helps to manage conditions to avoid their build-up and can include resistant varieties, crop rotation, intercropping, sanitation, ecological engineering, and others	• Development of integrated weed, pest, and disease management strategies for different rice-growing environments (Rodenburg et al., 2022)

suggested research priority areas on a selected number of themes (Table 2). Collaboration needs to be strengthened among scientists from different disciplines. Breeders, soil scientists, crop modelers, remote sensing and GIS specialists, mechanization specialists, social scientists, and agronomists/crop scientists would play important roles in these priority areas. We believe that such collaborative efforts will deliver locally-adapted agronomic solutions for sustainable intensification especially in rainfed rice to enhance the resilience to climate change and increase land and labor productivity and sustainability of rice cultivation in SSA. In addition to such research efforts, enabling environments are essential for success in SSA, such as farmers' (particularly women) access to agro-input and machineries, training, extension systems, markets, and financial services. Engagement with public and private stakeholders is also needed for enhancing farmers' adoption of agronomic solutions.

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References

Achandi, E. L., Mujawamariya, G., Agboh-Noameshie, A. R., Gebremariam, S., Rahalivavololona, N., & Rodenburg, J. (2018). Women's access to agricultural technologies in rice production and processing hubs: A comparative analysis of Ethiopia, Madagascar and Tanzania. *Journal of Rural Studies*, *60*, 188–198. https://doi.org/10.1016/j.jrurstud.2018.03.011

Akpoti, K., Kabo-Bah, A. T., Dossou-Yovo, E. R., Groen, T. A., & Zwart, S. J. (2020). Mapping suitability for rice production in inland valley landscapes in Benin and Togo using environmental niche modeling. *Science of the Total Environment*, *709*, 136165. https://doi.org/10.1016/j.scitotenv.2019.136165

Amponsah, S. K., Addo, A., Dzisi, K. A., Moreira, J., & Ndindeng, S. A. (2017). Performance evaluation and field characterization of the Sifang mini rice combine harvester. *Applied Engineering in Agriculture*, *33*(4), 479–489. https://doi.org/10.13031/aea.11876

Arouna, A., Devkota, K. P., Yergo, W. G., Saito, K., Frimpong, B. N., Adegbola, P. Y., Depieu, M. E., Kenyi, D. M., Ibro, G., Fall, A. A., & Usman, S. (2021). Assessing rice production sustainability performance indicators and their gaps in twelve sub-Saharan African countries. *Field Crops Research*, *271*, 108263. https://doi.org/10.1016/j.fcr.2021.108263

Arouna, A., Fatognon, I. A., Saito, K., & Futakuchi, K. (2021). Moving toward rice self-sufficiency in sub-Saharan Africa by 2030: Lessons learned from 10 years of the Coalition for African rice development. *World Development Perspectives*, *21*, 100291. https://doi.org/10.1016/j.wdp.2021.100291

Arouna, A., Yergo, W. G., Michler, J. D., & Saito, K. (2021). One size does not fit all: Experimental evidence on the digital delivery of personalized extension advice in Nigeria. *American Journal of Agricultural Economics*, *103*(2), 596–619. https://doi.org/10.1111/ajae.12151

Asai, H., Saito, K., & Kawamura, K. (2021). Application of a Bayesian approach to quantify the impact of nitrogen fertilizer on upland rice yield in sub-Saharan Africa. *Field Crops Research*, *272*, 108284. https://doi.org/10.1016/j.fcr.2021.108284

Awio, T., Senthilkumar, K., Dimkpa, C. O., Otim-Nape, G. W., Kempen, B., Struik, P. C., & Jan Stomph, T. (2021). Micronutrients in East African lowlands: Are they needed to intensify rice production? *Field Crops Research*, *270*, 108219. https://doi.org/10.1016/j.fcr.2021.108219

Awio, T., Senthilkumar, K., Dimkpa, C. O., Otim-Nape, G. W., Struik, P. C., & Stomph, T. (2022). Yields and yield gaps in lowland rice systems and options to improve smallholder production. *Agronomy*, *12*(3), 552. https://doi.org/10.3390/agronomy12030552

Bass, L. E. (2004). *Child labor in sub-Saharan Africa*. Lynne Rienner Publishers.

Breure, T. S., Haefele, S. M., Hannam, J. A., Corstanje, R., Webster, R., Moreno-Rojas, S., & Milne, A. E. (2022). A loss function to evaluate agricultural decision-making under uncertainty: A case study of soil spectroscopy. *Precision Agriculture*, *23*(4), 1333–1353. https://doi.org/10.1007/s11119-022-09887-2

Brosseau, A., Saito, K., van Oort, P. A. J., Diagne, M., Valbuena, D., & Groot, J. C. J. (2021). Exploring opportunities of diversification of smallholders' rice-based farming systems in the Senegal River Valley. *Agricultural Systems*, *193*, 103211. https://doi.org/10.1016/j.agsy.2021.103211

Bruelle, G., Naudin, K., Scopel, E., Domas, R., Rabeharisoa, L., & Tittonell, P. (2015). Short-to mid-term impact of conservation agriculture on yield variability of upland rice: Evidence from farmer's fields in Madagascar. *Experimental Agriculture*, *51*(1), 66–84. https://doi.org/10.1017/S0014479714000155

Chivenge, P., Saito, K., Bunquin, M. A., Sharma, S., & Dobermann, A. (2021). Nutrient management tailored to smallholder agriculture enhances productivity and sustainability. *Global Food Security*, *30*, 100570. https://doi.org/10.1016/j.gfs.2021.100570

Chivenge, P., Zingore, S., Ezui, K. S., Njoroge, S., Bunquin, M. A., Dobermann, A., & Saito, K. (2022). Progress in research on site-specific nutrient management for smallholder farmers in sub-Saharan Africa. *Field Crops Research*, *281*, 108503. https://doi.org/10.1016/j.fcr.2022.108503

de Mey, Y., Demont, M., & Diagne, M. (2012). Estimating bird damage to rice in Africa: Evidence from the Senegal river valley. *Journal of Agricultural Economics*, *63*(1), 175–200. https://doi.org/10.1111/j.1477-9552.2011.00323.x

Devkota, K. P., Futakuchi, K., Mel, V. C., & Humphreys, E. (2022). Does wet seeding combined with Sub1 varieties increase yield in submergence prone lowlands of West Africa? *Field Crops Research*, *276*, 108375. https://doi.org/10.1016/j.fcr.2021.108375

Diagne, A., Alia, D. Y., Amovin-Assagba, E., Wopereis, M. C. S., Saito, K., & Nakelse, T. (2013). Farmer perceptions of the biophysical constraints to rice production in sub-Saharan Africa, and potential impact of research. In M. C. S. Wopereis, D. E. Johnson, N. Ahmadi, E. Tollens, & A. Jalloh (Eds.), *Realizing Africa's rice promise* (pp. 46–68). CAB International. https://doi.org/10.1079/9781845938123.0046

Diagne, A., Amovin-Assagba, E., Futakuchi, K., & Wopereis, M. C. S. (2013). Estimation of cultivated area, number of farming households and yield for major rice-growing environments in Africa. In M. C. S. Wopereis, D. E. Johnson, N. Ahmadi, E. Tollens, & A. Jalloh (Eds.), *Realizing Africa's rice promise* (pp. 35–45). CAB International. https://doi.org/10.1079/9781845938123.0035

Djagba, J. F., Johnson, J.-M., & Saito, K. (2022). Can soil fertility properties in rice fields in sub-Saharan Africa be predicted by digital soil information? A case study of AfSoilGrids250m. *Geoderma Regional*, *30*, e00563. https://doi.org/10.1016/j.geodrs.2022.e00563

Dossou-Yovo, E. R., Devkota, K. P., Akpoti, K., Danvi, A., Duku, C., & Zwart, S. J. (2022). Thirty years of water management research for rice in sub-Saharan Africa: Achievement and perspectives. *Field Crops Research*, *283*, 108548. https://doi.org/10.1016/j.fcr.2022.108548

Dossou-Yovo, E. R., Vandamme, E., Dieng, I., Johnson, J.-M., & Saito, K. (2020). Decomposing rice yield gaps into efficiency, resource and technology yield gaps in sub-Saharan Africa. *Field Crops Research*, *258*, 107963. https://doi.org/10.1016/j.fcr.2020.107963

FAO. (2022, December 15). *FAOSTAT database*. https://www.fao.org/faostat/en/#home

Futakuchi, K., Senthilkumar, K., Arouna, A., Vandamme, E., Diagne, M., Zhao, D., Manneh, B., & Saito, K. (2021). History and progress in genetic improvement for enhancing rice yield in sub-Saharan Africa. *Field Crops Research*, *267*, 108159. https://doi.org/10.1016/j.fcr.2021.108159

Garba, M., Dicko, M., Kamissoko, N., Maman, N., & Wortmann, C. (2018). Fertilizer use efficiency and profitability of irrigated rice in Mali and Niger. *Agronomy Journal*, *110*(5), 1951–1959. https://doi.org/10.2134/agronj2017.09.0512

Grotelüschen, K., Gaydon, D. S., Senthilkumar, K., Langensiepen, M., & Becker, M. (2022). Model-based evaluation of rainfed lowland rice responses to N fertiliser in variable hydro-edaphic wetlands of East Africa. *Field Crops Research*, *285*, 108602. https://doi.org/10.1016/j.fcr.2022.108602

Haefele, S. M., Nelson, A., & Hijmans, R. J. (2014). Soil quality and constraints in global rice production. *Geoderma*, *235*, 250–259. https://doi.org/10.1016/j.geoderma.2014.07.019

Haefele, S. M., Saito, K., Ndiaye, K. M., Mussgnug, F., Nelson, A., & Wopereis, M. S. C. (2013). Increasing rice productivity through improved nutrient use in Africa. In M. C. S. Wopereis, D. E. Johnson, N. Ahmadi, E. Tollens, & A. Jalloh (Eds.), *Realizing Africa's rice promise* (pp. 250–264). CAB International. https://doi.org/10.1079/9781845938123.0250

Haefele, S. M., Thomas, C., & Saito, K. (2022). Long-term fertility experiments for irrigated rice in the West African Sahel: Effect on macro- and micronutrient concentrations in plant and soil. *Field Crops Research*, *275*, 108357. https://doi.org/10.1016/j.fcr.2021.108357

Hengl, T., Heuvelink, G. B. M., Kempen, B., Leenaars, J. G. B., Walsh, M. G., Shepherd, K. D., Sila, A., MacMillan, R. A., Mendes de Jesus, J., Tamene, L., & Tondoh, J. E. (2015). Mapping soil properties of Africa at 250 m resolution: Random forests significantly improve current predictions. *PLoS One*, *10*(6), 1–26. https://doi.org/10.1371/journal.pone.0125814

Hengl, T., Miller, M. A. E., Krizan, J., Shepherd, K. D., Sila, A., Kilibarda, M., Antonijevic, O., Glusica, L., Dobermann, A., Haefele, S. M., McGrath, S. P., Acquah, G. E., Collinson, J., Parente, L., Sheykhmousa, M., Saito, K., Johnson, J.-M., Chamberlin, J. ... Crouch, J. (2021). African soil properties and nutrients mapped at 30 m spatial resolution using two-scale ensemble machine learning. *Scientific Reports*, *11*(1), 1–18. https://doi.org/10.1038/s41598-021-85639-y

Holden, S. T. (2018). Fertilizer and sustainable intensification in Sub-Saharan Africa. *Global Food Security*, *18*, 20–26. https://doi.org/10.1016/j.gfs.2018.07.001

Husson, O., Tano, B. F., & Saito, K. (2022). Designing low-input upland rice-based cropping systems with conservation agriculture for climate change adaptation: A six-year experiment in M'bé, Bouaké, Côte d'Ivoire. *Field Crops Research*, *277*, 108418. https://doi.org/10.1016/j.fcr.2021.108418

Ibrahim, A., Saito, K., Bado, V. B., & Wopereis, M. C. S. (2021). Thirty years of agronomy research for development in irrigated rice-based cropping systems in the West African Sahel: Achievements and perspectives. *Field Crops Research*, *266*, 108149. https://doi.org/10.1016/j.fcr.2021.108149

Ibrahim, A., Saito, K., Johnson, J.-M., Diagne, M., Ahouanton, K., Djagba, J. F., Frewer, F., Bamishaye, O. S., & Housessou, M. (2022). Seizing opportunity towards sustainable rice cultivation in sub-Saharan Africa. *Environmental and Sustainability Indicators*, *15*, 100189. https://doi.org/10.1016/j.indic.2022.100189

IFA. (2022). *Fertilizer use by crop and country for the 2017-2018 period. International Fertilizer Association (IFA)*. Author.

Johnson, J.-M., Rodenburg, J., Tanaka, A., Senthilkumar, K., Ahouanton, K., Diang, I., Akakpo, C., Segda, Z., Yameogo, L. P., Gbakatchetche, H., Bam, R. K., Bakare, O. S., Gasore, E. R., Ablede, K. A., & Saito, K. (2019). farmers' perceptions on mechanical weeders for rice production in Sub-Saharan Africa. *Experimental Agriculture*, *55*(1), 117–131. https://doi.org/10.1017/S001447971700059X

Johnson, J.-M., Senthilkumar, K., Sila, A., Shepherd, K. D., & Saito, K. (2021). Application of infrared spectroscopy for estimation of concentrations of macro- and micro-nutrients in rice in sub-Saharan Africa. *Field Crops*

Research, *270*, 108222. https://doi.org/10.1016/j.fcr.2021.108222

Johnson, J. -M., Sila, A., Senthilkumar, K., Vandamme, E., Shepherd, K. D., & Saito, K. (2019). Near-infrared, mid-infrared or combined diffuse reflectance spectroscopy for assessing soil fertility in rice fields in sub-Saharan Africa. *Geoderma*, *354*, 113840. https://doi.org/10.1016/j.geoderma.2019.06.043

Kinkingninhoun, F. M., Komatsu, S., Mujawamariya, G., & Saito, K. (2020). Men and women in rice farming in Africa: A cross-country investigation of labor and its determinants. *Frontiers in Sustainable Food Systems*, *4*, 117. https://doi.org/10.3389/fsufs.2020.00117

Komatsu, S., Saito, K., & Sakurai, T. (2022). Changes in production, yields, and the cropped area of lowland rice over the last 20 years and factors affecting their variations in Côte d' Ivoire. *Field Crops Research*, *277*, 108424. https://doi.org/10.1016/j.fcr.2021.108424

Leenen, M., Welp, G., Gebbers, R., & Pätzold, S. (2019). Rapid determination of lime requirement by mid-infrared spectroscopy: A promising approach for precision agriculture. *Journal of Plant Nutrition and Soil Science*, *182*(6), 953–963. https://doi.org/10.1002/jpln.201800670

Miao, X., Miao, Y., Liu, Y., Tao, S., Zheng, H., Wang, J., Wang, W., & Tang, Q. (2023). Measurement of nitrogen content in rice plant using near infrared spectroscopy combined with different PLS algorithms. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, *284*, 121733. https://doi.org/10.1016/j.saa.2022.121733

Mujawamariya, G., & Kalema, E. P. (2017). Limited usage of mechanical equipment in small-scale rice farming: A cause for concern. *Journal of Agriculture and Environment for International Development*, *111*, 5–21. https://doi.org/10.12895/jaeid.20171.493

Mujawamariya, G., Kinkingninhoun, F. M., & Karimov, A. (2017). Integrating quantified risk in efficiency analysis: Evidence from rice production in East and Southern Africa. *Agricultural Economics Research, Policy and Practice in Southern Africa*, *56*(4), 383–401. https://doi.org/10.1080/03031853.2017.1387580

Müller, C., Cramer, W., Hare, W. L., & Lotze-Campen, H. (2011). Climate change risks for African agriculture. *Proceedings of the National Academy of Sciences*, *108*, 4313–4315.

Niang, A., Becker, M., Ewert, F., Dieng, I., Gaiser, T., Tanaka, A., Senthilkumar, K., Rodenburg, J., Johnson, J. -M., Akakpo, C., Sedga, Z., Gbakatcetche, H., Jaiteh, F., Bam, R. K., Dogbe, W., Sékou, K., Kamissoko, N., Mossi, I. M. , and Saito, K. (2017). Variability of yields and its determinants in rice production systems of West Africa. *Field Crops Research*, *207*, 1–12. https://doi.org/10.1016/j.fcr.2017.02.014

Niang, A., Becker, M., Ewert, F., Tanaka, A., Dieng, I., & Saito, K. (2018). Yield variation of rainfed rice as affected by field water availability and N fertilizer use in central Benin. *Nutrient Cycling in Agroecosystems*, *110*(2), 293–305. https://doi.org/10.1007/s10705-017-9898-y

Ogwuike, P., Rodenburg, J., Diagne, A., Agboh-Noameshie, A. R., & Amovin-Assagba, E. (2014). Weed management in upland rice in sub-Saharan Africa: Impact on labor and crop productivity. *Food Security*, *6*(3), 327–337. https://doi.org/10.1007/s12571-014-0351-7

Onaga, G., Kikafunda, J., Bigirwa, G., Asea, G., & Mwamburi, L. A. (2020). Rice response to nitrogen and supplemental irrigation under low phosphorus and potassium in upland production systems in East Africa. In Sutton, M. A., Mason, K. E., Bleeker, A., Hicks, W. K., Masso, C., Reis, S., M. Bekunda (Ed.), *Just enough nitrogen. Perspectives on how to get there for regions with too much and too little nitrogen (Proceedings of the 6th International Nitrogen Conference)*. Chapter 15. Springer.

Palacios-Lopez, A., Christiaensen, L., & Kilic, T. (2017). How much of the labor in African agriculture is provided by women? *Food Policy*, *67*, 52–63. https://doi.org/10.1016/j.foodpol.2016.09.017

Paresys, L., Saito, K., Malézieux, E., Dogliotti, S., Huat, J., Kropff, M. J., & Rossing, W. A. H. (2018). Feeding the world while decreasing farmers' poverty? A yield and labour productivity gaps analysis on rice fields in two villages of Benin. *The European Journal of Agronomy*, *93*, 95–112. https://doi.org/10.1016/j.eja.2017.10.009

Partey, S. T., Saito, K., Preziosi, R. F., & Robson, G. D. (2016). Biochar use in a legume–rice rotation system: Effects on soil fertility and crop performance. *Achieves of Agronomy and Soil Science*, *62*(2), 199–215. https://doi.org/10.1080/03650340.2015.1040399

Rickman, J., Moreira, J., Gummert, M., & Wopereis, M. S. C. (2013). Mechanizing Africa's Rice Sector. In M. C. S. Wopereis, D. E. Johnson, N. Ahmadi, E. Tollens, & A. Jalloh (Eds.), *Realizing Africa's rice promise* (pp. 332–342). CAB International. https://doi.org/10.1079/9781845938123.0332

Rodenburg, J., Demont, M., Sow, A., & Dieng, I. (2014). Bird, weed and interaction effects on yield of irrigated lowland rice. *Crop Protection*, *66*, 46–52. https://doi.org/10.1016/j.cropro.2014.08.015

Rodenburg, J., Johnson, J. -M., Dieng, I., Senthilkumar, K., Vandamme, E., Akakpo, C., Allarangaye, M. D., Baggie, I., Bakare, S. O., Bam, R. K., Bassoro, I., Abera, B. B., Cisse, M., Dogbe, W., Gbakatchetche, H., Jaiteh, F., Kajiru, G. J., Kalisa, A. , and Saito, K. (2019). Status quo of chemical weed control in rice in sub-Saharan Africa. *Food Security*, *11*(1), 69–92. https://doi.org/10.1007/s12571-018-0878-0

Rodenburg, J., Randrianjafizanaka, M. T., Büchi, L., Dieng, I., Andrianaivo, A. P., Ravaomanarivo, L. H. R., & Autfray, P. (2020). Mixed outcomes from conservation practices on soils and Striga-affected yields of a low-input, rice–maize system in Madagascar. *Agronomy for Sustainable Development*, *40*(1), 8. https://doi.org/10.1007/s13593-020-0612-0

Rodenburg, J., & Saito, K. (2022). Towards sustainable productivity enhancement of rice-based farming systems in sub-Saharan Africa – introduction to this Special Issue. *Field Crops Research*, *287*, 108670. https://doi.org/10.1016/j.fcr.2022.108670

Rodenburg, J., Saito, K., Irakiza, R., Makokha, D. W., Onyuka, E. A., & Senthilkumar, K. (2015). Labor-saving weed technologies for lowland rice farmers in sub-Saharan Africa. *Weed Technology*, *29*(4), 751–757. https://doi.org/10.1614/WT-D-15-00016.1

Rodenburg, J., Tippe, D. E., Toure, A., Irakiza, R., Kayeke, J., & Bastiaans, L. (2022). From rice-like plants to plants liking rice: A review of research on weeds and their management in African rice systems. *Field Crops Research*, *276*, 108397. https://doi.org/10.1016/j.fcr.2021.108397

Saito, K., Asai, H., Zhao, D., Laborte, A. G., & Greiner, C. (2018). Progress in varietal improvement for increasing upland rice productivity in the tropics. *Plant Production Science*, *21*(3), 145–158. https://doi.org/10.1080/1343943X.2018.1459751

Saito, K., Dieng, I., Toure, A. A., Somado, E. A., & Wopereis, M. C. S. (2015). Rice yield growth analysis for 24 African countries over 1960-2012. *Global Food Security*, *5*, 62–69. https://doi.org/10.1016/j.gfs.2014.10.006

Saito, K., Nelson, A., Zwart, S. J., Niang, A., Sow, A., Yoshida, H., & Wopereis, M. C. S. (2013). Towards a better understanding of biophysical determinants of yield gaps and the potential for expansion of the rice area in Africa. In M. C. S. Wopereis, D. E. Johnson, N. Ahmadi, E. Tollens, & A. Jalloh (Eds.), *Realizing Africa's rice promise* (pp. 188–203). CAB International. https://doi.org/10.1079/9781845938123.0188

Saito, K., Six, J., Komatsu, S., Snapp, S., Rosenstock, T., Arouna, A., Cole, S., Taulya, G., & Vanlauwe, B. (2021). Agronomic gain: Definition, approach and applications. *Field Crops Research*, *270*, 108193. https://doi.org/10.1016/j.fcr.2021.108193

Saito, K., Vandamme, E., Johnson, J. -M., Tanaka, A., Senthilkumar, K., Dieng, I., Akakpo, C., Segda, Z., Bassoro, I., Lamare, D., Gbakatchetche, H., Bayuh, B. A., Jaiteh, F., Bam, R. K., Dogbe, W., Sékou, K., Rabeson, R., Kamissoko, N. , and Wopereis, M. C. S. (2019). Yield-limiting macronutrients for rice in sub-Saharan Africa. *Geoderma*, *338*, 546–554. https://doi.org/10.1016/j.geoderma.2018.11.036

Senthilkumar, K. (2022). Closing rice yield gaps in Africa requires integration of good agricultural practices. *Field Crops Research*, *285*, 108591. https://doi.org/10.1016/j.fcr.2022.108591

Senthilkumar, K., Rodenburg, J., Dieng, I., Vandamme, E., Sillo, F. S., Johnson, J. -M., Rajaona, A., Ramarolahy, J. A., Gasore, R., Bayuh, B. A., Kajiru, G. J., Mghase, J., Lamo, J., Rabeson, R., & Saito, K. (2020). Quantifying rice yield gaps and their causes in Eastern and Southern Africa. *Journal of Agronomy and Crop Science*, *206*(4), 478–490. https://doi.org/10.1111/jac.12417

Senthilkumar, K., Sillo, F. S., Dieng, I., Rodenburg, J., Saito, K., Dimkpa, C., & Bindraban, P. S. (2021). Rice yield and economic response to micronutrient application in Tanzania. *Field Crops Research*, *270*, 108201. https://doi.org/10.1016/j.fcr.2021.108201

SRP. (2020). *SRP Performance Indicators for Sustainable Rice Cultivation. Version 2.1*. https://sustainablerice.org/wp-content/uploads/2022/12/103-SRP-Standard-Version-2.1.pdf

Tanaka, A., Diagne, M., & Saito, K. (2015). Causes of yield stagnation in irrigated lowland rice production system in the Senegal River Valley. *Field Crops Research*, *176*, 99–107. https://doi.org/10.1016/j.fcr.2015.02.020

Tanaka, A., Johnson, J. -M., Senthilkumar, K., Akakpo, C., Segda, Z., Yameogo, L., Bassoro, I., Lamare, D., Allarangaye, M. D., Gbakatchetche, H., Bayuh, B. A., Jaiteh, F., Bam, R. K., Dogbe, W., Sékou, K., Kamissoko, N., Mossi, I. M., Bakare, O. S. , and Saito, K. (2017). On-farm rice yield and its association with biophysical factors in sub-Saharan Africa. *The European Journal of Agronomy*, *85*, 1–11. https://doi.org/10.1016/j.eja.2016.12.010

Tippe, D. E., Bastiaans, L., van Ast, A., Dieng, I., Cissoko, M., Kayeke, J., Makokha, D. W., & Rodenburg, J. (2020). Fertilisers differentially affect facultative and obligate parasitic weeds of rice and only occasionally improve yields in infested fields. *Field Crops Research*, *254*, 107845. https://doi.org/10.1016/j.fcr.2020.107845

Totin, E., Stroosnijder, L., & Agbossou, E. (2013). Mulching upland rice for efficient water management: A collaborative approach in Benin. *Agricultural Water Management*, *125*, 71–80. https://doi.org/10.1016/j.agwat.2013.04.012

Tsujimoto, Y., Rakotoson, T., Tanaka, A., & Saito, K. (2019). Challenges and opportunities for improving N use efficiency for rice production in Sub-Saharan Africa. *Plant Production Science*, *22*(4), 413–427. https://doi.org/10.1080/1343943X.2019.1617638

van Asten, P. J. A., Barro, S. E., Wopereis, M. C. S., & Defoer, T. (2004). Using farmer knowledge to combat low productive spots in rice fields of a Sahelian irrigation scheme. *Land Degradation & Development*, *15*(4), 383–396. https://doi.org/10.1002/ldr.619

Vandamme, E., Ahouanton, K., Mwakasege, L., Mujuni, S., Lupembe, A., Mujawamariya, G., Kamanda, J., Senthilkumar, K., & Saito, K. (2018). Phosphorus micro-dosing as an entry point towards sustainable intensification in rice systems in sub-Saharan Africa. *Field Crops Research*, *222*, 39–49. https://doi.org/10.1016/j.fcr.2018.02.016

Vandamme, E., Saito, K., Rose, T., Ahouanton, K., & Matthias, W. (2016). Strategic phosphorus (P) application to the nursery bed increases seedling growth and yield of transplanted rice in low P supply. *Field Crops Research*, *186*, 10–17. https://doi.org/10.1016/j.fcr.2015.11.003

van Ittersum, M. K., Cassman, K. G., Grassini, P., Wolf, J., Tittonell, P., & Hochman, Z. (2013). Yield gap analysis with local to global relevance – a review. *Field Crops Research*, *143*, 4–17. https://doi.org/10.1016/j.fcr.2012.09.009

van Oort, P. A. J. (2018). Mapping abiotic stresses for rice in Africa: Drought, cold, iron toxicity, salinity and sodicity. *Field Crops Research*, *219*, 55–75. https://doi.org/10.1016/j.fcr.2018.01.016

Van Oort, P. A. J., & Dingkuhn, M. (2021). Feet in the water and hands on the keyboard: A critical retrospective of crop modelling at AfricaRice. *Field Crops Research*, *263*, 108074. https://doi.org/10.1016/j.fcr.2021.108074

van Oort, P. A. J., Saito, K., Dieng, I., Grassini, P., Cassman, K. G., & van Ittersum, M. K. (2017). Can yield gap analysis be used to inform R&D prioritisation? *Global Food Security*, *12*, 109–118. https://doi.org/10.1016/j.gfs.2016.09.005

van Oort, P. A. J., Saito, K., & Drame, K. N. (2019). Exploring Adaptation options to Climate Change for irrigated Rice in Africa. Africa Rice Center Report. https://www.africarice.org/_files/ugd/0839e4_ab50f2a4e287478a9100db2fe3fb7ba5.pdf

van Oort, P. A. J., Saito, K., Tanaka, A., Amovin-Assagba, E., Van Bussel, L. G. J., van Wart, J., de Groote, H., van Ittersum, M. K., Cassman, K. G., & Wopereis, M. C. S. (2015). Assessment of rice self-sufficiency in eight African countries in 2025. *Global Food Security*, *5*, 39–49. https://doi.org/10.1016/j.gfs.2015.01.002

Vemireddy, V., & Choudhary, A. (2021). Labor-saving technologies designed for women can reduce their drudgery. *CGIAR GENDER PLATFORM Evidence Explainer*. CGIAR GENDER Platform. https://hdl.handle.net/10568/114807

Wopereis, M., Johnson, D. E., Ahmadi, N., Tollens, E., & Jalloh, A. (2013). *Realizing Africa's Rice Promise*. CAB International. https://doi.org/10.1079/9781845938123.0000

The World Bank. (2022 December 15). *World Bank Open Data*. Retrieved March 12, 2022 https://data.worldbank.org/indicator/SP.POP.GROW?locations=ZG

Yuan, S., Linquist, B. A., Wilson, L. T., Cassman, K. G., Stuart, A. M., Pede, V., Miro, B., Saito, K., Agustiani, N., Aristya, V. E., Krisnadi, L. Y., Zanon, A. J., Heinemann, A. B., Carracelas, G., Subash, N., Brahmanand, P. S., Li, T., Peng, S., & Grassini, P. (2021). Sustainable intensification for a larger global rice bowl. *Nature Communications*, *12*(1), 7163. https://doi.org/10.1038/s41467-021-27424-z

Zingore, S., Adolwa, I., Njoroge, S., Johnson, J. -M., Saito, K., Phillips, S., Kihara, J., Mutegi, J., Murell, S., Dutta, S., Chivenge, P., Chakraborty, T., Oberthur, S., Sileshi, G. W., & Sileshi, G. W. (2022). Novel insights into factors associated with yield response and nutrient use efficiency of maize and rice in sub-Saharan Africa: A review. *Agriculture for Sustainable Development*, *42*(5), 1–20. https://doi.org/10.1007/s13593-022-00821-4

Zossou, E., Saito, K., Imorou, A. A., Ahouanton, K., & Tarfa, B. D. (2021). Participatory diagnostic for scaling a decision support tool for rice crop management in northern Nigeria. *Development in Practices*, *13*(1), 11–26. https://doi.org/10.1080/09614524.2020.1770699