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Towards sustainable productivity enhancement of rice-based farming systems in sub-Saharan Africa

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ABSTRACT

In the past 50 years, rice has become an important crop for food security in sub-Saharan Africa. However, rice yields remain relatively low, and large yield gaps exist. This Special Issue brings together agronomy research on rice-based farming systems in sub-Saharan Africa and addresses three main, overarching questions: (1) what has been achieved in the past decades in terms of rice agronomy in sub-Saharan Africa, (2) what is the state-of-the-art regarding development of technologies and (3) what will be likely or required future directions? The broad topics included in this Special Issue are (1) yield trends and yield gap analyses, (2) soil & nutrient, water, weed and integrated crop management practices, (3) cropping systems, (4) genetic improvements, (5) crop simulation modeling, and (6) assessment of farmers' rice cultivation practices and the sustainability of these practices. The papers cover different sub-regions, from the Sahel to the highlands of Madagascar and three major rice growing environments (irrigated lowlands, rainfed lowlands, and rainfed uplands). In this paper we describe the major challenges in the rice production sector in sub-Saharan Africa and historical efforts on agronomy research, and we provide a short introduction and discussion on the papers presented in this Special Issue. This Special Issue arrives at six main recommendations. 1. There is a need to increase research and development efforts focusing on rainfed rice-based systems. 2. More attention needs to be paid to research on the farming system or landscape level, aimed at development of integrated cropping and farming systems and integrated agronomic solutions. 3. Current and future agronomic rice research should thematically center around sustainability, including judicious natural resources management, climate change adaptation and mitigation, and conservation of biodiversity and environments. 4. To operationalize this, sustainability performance indicators need to be developed and used. 5. There is broad consensus regarding the need for more labor-saving technologies, including mechanization options, provided these do not increase the ecological footprint of production systems. 6. Future rice agronomy research work should be interdisciplinary and transdisciplinary, to better address the myriad of challenges of smallholder farmers in Africa. Papers presented in this Special Issue should inform on the state-of-the art in rice agronomy in SSA, and on ways to sustainably enhance rice production and self-sufficiency in this region.

1. Introduction

Rice has become an important crop for food security in sub-Saharan Africa (SSA). It is grown under widely diverse conditions spanning three main rice growing environments, i.e. irrigated lowlands, rainfed lowlands and rainfed uplands (whereby the terms low- or upland refers to soil hydrology rather than elevation). Rice consumption is increasing faster than that of any other staple food in SSA (Seck et al., 2012). This increase is driven by urbanization and related changes in dietary habits, and population growth. Although its production has been increasing, it has not been able to catch up with the demand. Around 40–50% of its consumption in this region is still from imported rice. Rice yield remains relatively low (around 2 t/ha), and its yield gaps are generally large, suggesting that there is large scope for improving local rice production (van Oort et al., 2015). This would require addressing a myriad of locally specific biotic and abiotic stresses and implementation of improved agronomic practices. The scientific and technical challenges this presents, are only overshadowed by the socio-economic ones, as the main stakeholders are smallholder farmers that are often limited by financial resources and information. These challenges are not new. When the

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Africa Rice Center (AfricaRice) officially began operating in 1971, the center was entrusted with attainment of regional self-sufficiency (AfricaRice, 2021). Numerous efforts have been made for improving rice production in Africa since then, but achieving self-sufficiency remains a challenge.

Although it has been frequently indicated that the green revolution bypassed SSA (Pingali, 2012), a recent study shows that on the plot level, mean rice yields of the three main rice growing environments in SSA are in similar ranges as Southeast and South Asia, except for some cases (Tanaka et al., 2017). On a regional level, the overall (weighed) rice production in SSA is however much lower than that of Asia, and this could therefore be attributed to the relatively larger share of the less productive rainfed environments, with 32% of the area under rice classified as rainfed lowland and 28% as rainfed upland (Diagne et al., 2013b), compared to the situation in Asia where rice is predominantly produced in irrigated lowlands. The exception includes Madagascar where rice yield remains low despite its relatively high share of irrigated lowlands (Diagne et al., 2013b).

Recent yield gap assessments indicate that in addition to a yield gap closure, an increasing cropping intensity (the number of crops grown per 12-month period on the same field) and area expansion are needed to achieve self-sufficiency in this region (van Oort et al., 2015; van Ittersum et al., 2016). To avoid massive area expansion, at the expense of environmental health and biodiversity, the most suitable new land for rice area expansion needs to be carefully identified (e.g. Rodenburg et al., 2014). Thus, key research questions are (1) how to sustainably reduce the rice yield gap and increase cropping intensity, and (2) how to increase rice production area without causing further environmental harm? These should be addressed by multi-disciplinary research. Obviously, agronomic research should play a vital role in delivering locally adapted sustainable intensification options adapted to smallholder farmers (e.g., George, 2014; Kuyah et al., 2021). Together with new rice varieties developed by breeders, it enables to develop suitable cropping systems and calendars for increasing cropping intensity. Agronomists can also contribute to sustainable land management for newly expanded rice areas.

Rice research started in SSA some 100 years ago. In 2021, Africa Rice Center celebrated its 50th anniversary. This is a good moment for stock taking; what has been achieved in the past decades in terms of rice agronomy in SSA, what is the state-of-the-art in rice agronomy research focused on this region, and what will be likely or required future directions? These questions have been addressed in this Special Issue of Field Crops Research. Special attention was given to the acquisition of research or insights from different rice growing environments, and diverse agroecological zones and regions in SSA with a focus on sustainable intensification and diversification. This Special Issue did not include research topics on biotic stresses (e.g. diseases, pests, birds) apart from weeds, as these stresses are not mainly managed agronomically. In the current paper we will briefly describe historical efforts on agronomy research, and introduce and discuss the papers published in this Special Issue.

2. History of rice research in sub-Saharan Africa

The efforts on rice research in SSA have been made by a wide range of research organizations including national agricultural research institutes (NARIs), bilateral organizations and three CGIAR centers (Dalrymple, 1986; Tollens et al., 2013).

Rice research began at a range of NARIs including those of Madagascar and Nigeria in the 1920s (Tollens et al., 2013). Several NARIs (Côte d'Ivoire, Mali, Senegal, Guinea, and Sierra Leone) have long histories of research facilitated by bilateral assistance from France (originally through IRAT, Institut de Recherche Agronomique Tropicale, and later through CIRAD, Centre de coopération internationale en recherche agronomique pour le développement), the UK, and North Korea from the 1960 s (Dalton and Guei, 2003). Starting in the mid-1960s, technical assistance teams from Taiwan, and later from China, played an important role in rice research and development (R&D) (Dalrymple, 1986).

The Africa Rice Center (AfricaRice) was established under the name "West Africa Rice Development Association (WARDA)" by 11 West African countries and officially began operating in 1971. Since 1986, AfricaRice has been one of the 15 international agricultural research centers of CGIAR, a global research partnership for a food-secure future. AfricaRice is also an intergovernmental association of African member countries. Recognizing the strategic importance of rice in Africa and the effective geographic expansion of the organization to Eastern and Southern Africa, its Council of Ministers decided in 2009 to change the organization's name to "Africa Rice Center (AfricaRice)". Today AfricaRice's membership comprises 28 African countries. AfricaRice has had strong partnership with NARIs since its establishment. In the 1970 s and 1980 s, AfricaRice coordinated multi-location trials with a variety of research topics (AfricaRice, 2021). To further strengthen the collaboration between AfricaRice and the NARIs, a Task Force mechanism was introduced in 1991 (Tollens et al., 2013) as an Africa-wide systematic collaborative research effort on critical thematic areas that aims to build the rice research capacity at the regional and national levels, and to reduce the time lag between the development and the release of new rice technologies across the continent, in order to increase their impact. The Task Forces were divided over six themes – (1) breeding; (2) agronomy; (3) postharvest and value addition; (4) policy; (5) gender; (6) mechanization. The Task Forces continued until mid-2000 s, when research funds were limited and in 2010 they were revitalized, and continue until now.

Until late 1980s, the agronomic research had focused on introduction and validation of component technologies including herbicides, fertilizers, and green manures in three rice growing environments (irrigated lowland, mangrove rice, and floating rice). Since early 1990, the focus shifted to systems approaches, with special attention to upland-lowland continuum research in Cote d'Ivoire and the Sahel irrigated rice research in Senegal. Various studies on characterization of rice growing environments and inland valleys, and quantification of yield gaps were carried out by researchers of different disciplines including agronomists, crop modelers, crop physiologists, geographers, and hydrologists. Based on the findings from those studies, integrated crop management options, improved cropping systems, and a framework of participatory learning and action research were developed in the 1990 s and early 2000. In the 2000s, with the success of the development of New Rice for Africa (NERICA) varieties (Tollens et al., 2013), the research shifted to agronomic characterization of the NERICA varieties, and development of crop management practices for NERICAs. In the 2010s, research activities were mainly carried out following AfricaRice's strategic plan for 2011–2020 having two agronomy-related priority areas ("improving rural livelihoods by closing yield gaps through sustainable intensification and diversification of rice-based systems" and "achieving socially acceptable expansion of rice-producing areas, while addressing environmental concerns"). With advances in ICT technology in the 2010s, agronomists started with the development of IoT-based decision support tools for crop management practices (e.g. RiceAdvice). Yield-enhancing innovations were still the major focus area, but the number of studies focusing on other dimensions (e.g., gender, labor, mechanization, water-saving, crop diversification options) were increasing from then onwards. In addition, researchers were becoming increasingly aware of the need to develop scalable technologies and to disseminate them among smallholder farmers.

The International Institute for Tropical Agriculture (IITA) and the International Rice Research Institute (IRRI) have contributed to rice research in Africa since the 1970s. IITA had a rice breeding program until late the 1980s, and then the program was transferred to AfricaRice. Natural resource management and farming systems research related to rice lasted until the 1990s. IRRI has significantly contributed to seed distribution to AfricaRice/IITA since the 1970s, and was directly involved in some projects in Madagascar in the 1990 s. Furthermore, IRRI expanded research activities in Eastern and Southern Africa in the 2010s. In the framework of the CGIAR Research Program on rice, AfricaRice and IRRI had strong collaborations on various research areas in the 2010s (GRISP, 2016). A bibliographic search in Web of Science was conducted before the launch of this Special Issue to shed light on the scientific output from the above-mentioned research efforts (Table 1). The trend in publications on rice agronomy in Africa per year over the past 50 years (until the launch of the Special Issue) is shown in Fig. 1. Publications rapidly increased in the last two decades.

3. Special Issue papers

In this Special Issue, we present 19 papers focusing on, or cross-cutting, 11 different research topics, i.e. (1) trend analysis, (2) crop simulation modeling, (3) yield gap analysis, (4) genetic improvement, (5) soil and nutrient management, (6) weed management, (7) mechanization, (8) water management, (9) integrated crop management, (10) cropping systems and (11) assessment of sustainability performance indicators. Table 2 shows the distribution of Special Issue papers over these research topics and compared to the seminal rice book "Realizing Africa's Rice Promise" edited by Wopereis et al., published in 2013. Below we introduce and discuss these papers along these research topics.

3.1. Trend analysis

Rice production trend at SSA level was analyzed by Seck et al. (2013). The period 2007–2012 was characterized by a steep increase in mean rice yields of 108 kg/ha/year, possibly due to the food crisis. About 71% of production increase after the food crisis could be attributed to yield increase and 29% to harvest area expansion. However, further growth of both yield and area expansion was deemed necessary to reduce reliance on imports and achieve self-sufficiency (Seck et al., 2013). In this Special Issue, Komatsu et al. (2022) showed production trend using data collected through farm surveys in 2000 and 2020 around the city of Bouake in Côte d'Ivoire, one of the main rice producing countries of West Africa (Diagne et al., 2013b). Over the last two

Table 1
Literature research on rice agronomy in Africa in Web of Science (accessed: 26 October 2020, before the launch of this Special Issue).

Search #	Search term	Number of records	Research papers
#1	Africa OR sub-Saharan Africa	323,902	242,074
#2	All African country names (Algeria, Benin, … Zambia, Zimbabwe)	568,118	443,893
#3	#1 OR #2	800,917	604,948
#4	Rice OR "Oryza sativa" OR "Oryza glaberrima"	174,309	147,723
#5	Crop OR "crop management" OR agronom* OR agricultur*	652,782	511,962
#6	Weed OR soil OR yield OR water	4,899,214	4,151,898
#7	#5 OR #6	5,224,374	4,387,142
#8	#3 AND #4	5239	4612
#9	#4 AND #7	82,983	73,244
#10	#3 AND #4 AND #7	3,362	3010
#11	#10 (research articles) excl. medical, chemical, physics, economics and microbiological sci.		1873
#12	#11 limit to agronomy, plant science, agriculture interdisciplinary, soil science		1179, excluding conference proceedings: 1148
#13	Rice OR "Oryza sativa" OR "O. sativa" OR "Oryza glaberrima" OR "O. glaberrima" in Title	89,752	74,044
	#12 AND #13		663

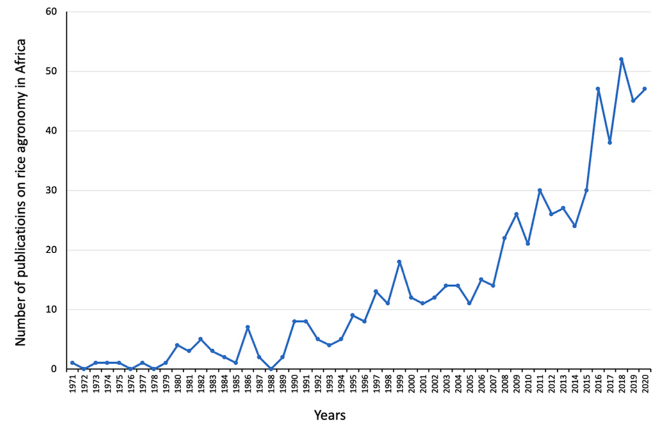

Fig. 1. Publications on rice agronomy in Africa per year over the past 50 years based on literature research on rice agronomy in Africa in Web of Science in Table 1 (until 26 October 2020).

Table 2
Comparison between book chapters in Wopereis et al. (2013) and papers in this Special Issue for research topics.

Research topics	Chapters of "Realizing Africa's Rice Promise"	This Special Issue
1. Trend analysis	Seck et al. (2013)	Komatsu et al. (2022);Saito et al. (2021)
2. Crop simulation modeling	Saito et al. (2013);Tollens et al. (2013)	van Oort and Dingkuhn (2021);Grotelüschen et al. (2022)
3. Yield gap analysis	Saito et al. (2013);Tollens et al. (2013); (2013a; Diagne et al., 2013b)	Ibrahim et al. (2021); Komatsu et al. (2022); Saito et al. (2021);Senthilkumar (2022);van Oort and Dingkuhn (2021)
4. Genetic improvement	Dramé et al. (2013); El-Namaky and Demont (2013);Kumashiro et al. (2013);Sanni et al. (2013);Tollens et al. (2013)	Futakuchi et al. (2021); Ibrahim and Saito (2022)
5. Soil and nutrient management	Haefele et al. (2013); Tollens et al. (2013)	Ibrahim et al. (2021); Ibrahim and Saito (2022); Asai et al. (2021);Johnson et al. (2021);Rakotoson et al. (2022);Haefele et al. (2022);Chivenge et al. (2022);Senthilkumar (2022);Grotelüschen et al. (2022);Husson et al. (2022); Rodenburg et al. (2022a)
6. Weed management	Rodenburg and Johnson (2013);Tollens et al. (2013)	Rodenburg et al. (2022b); Senthilkumar (2022); Ibrahim et al. (2021)
7. Mechanization	Rickman et al. (2013)	Rodenburg et al. (2022b); Ibrahim et al. (2021)
8. Water management	Rodenburg (2013);Tollens et al. (2013);Zwart (2013)	Dosso-Yovo et al. (2022); Senthilkumar (2022); Ibrahim et al. (2021); Grotelüschen et al. (2022);
9. Integrated crop management	Defoer and Wopereis (2013);Tollens et al. (2013)	Ibrahim et al. (2021); Senthilkumar (2022)
10. Cropping systems (including rice agroforestry)	Tollens et al. (2013)	van Oort and Dingkuhn (2021);Husson et al. (2022); Rodenburg et al. (2022a)
11. Assessment of sustainability performance indicators	None	Arouna et al. (2021); Saito et al. (2021);Rodenburg et al. (2022a)

decades, rice production in the study area increased by an average of 89%, of which 26% and 63% were attributed to the increase in yields and the cropped area, respectively (Komatsu et al., 2022). Farmers using low inputs relative to the land area tended to increase their cropped area. Among the surveyed farms, changes in agronomic practices had limited impact on yield increases except for new varieties.

3.2. Crop simulation modeling

AfricaRice and partners have traditionally made use of crop-simulation models to determine biophysical yield limits, identify optimum sowing windows, and conduct yield gap analyses for the identification of yield-limiting or yield-reducing factors (Tollens et al., 2013). Such crop-simulation models, which are based on crop phenology and physiology, become even more powerful and useful when they can be combined with geographic information systems (GIS) and be fed with satellite-based climate data. This helps identification of areas where potential yields and yield stability are lower, risks of spikelet sterility due to extreme temperature can occur or drought risks (in rainfed rice) are higher (Saito et al., 2013). The Special Issue presents a review of all the modeling work, from the earliest to the current day (van Oort and Dingkuhn, 2021). The main models developed or used by AfricaRice and partners are RIDEV, ORYZAS, and ORYZA2000. The first model (RIDEV) could be used to simulate rice flowering responses to temperature and day length, a temperature-moderated vegetative phase extension, sterility responses to extreme temperature (heat and cold) and crop development rate as a function of floodwater temperature (van Oort and Dingkuhn, 2021). After RIDEV came ORYZAS which used RIDEV as a module to estimate climate, sowing date, location and cultivar dependent potential yield. The ORYZAS was used to identify optimum sowing windows for maximizing yield in the Sahel zone of West Africa, conduct yield gap analysis, and study rice salt tolerance (van Oort and Dingkuhn, 2021). In more recent years (since around 2010) ORYZA2000 has been improved and used to determine and map rice yield gaps and climate change impacts on rice yields (van Oort and Dingkuhn, 2021). The model that integrates climate change scenarios indicates a huge risk of yield reduction due to heat stress, especially in the dry season in West Africa (Ibrahim et al., 2021). This would necessitate adaptations such as changes in sowing dates and varietal improvement. A research paper published in this Special Issue showed the usefulness of models (the APSIM model) as a tool to evaluate nitrogen fertiliser responses of rice in rainfed lowlands across a range of hydrological conditions (Grotelüschen et al., 2022). Such insights in turn are useful to advise farmers regarding fertiliser investments and management. To make best use of modeling in agronomic research endeavors, it is recommended to generate and maintain complementary and multidisciplinary research teams around modelers with a clear, commonly shared thematic focus, and to maintain an open mind to applications and responses to newly emerging research questions (van Oort and Dingkuhn, 2021).

3.3. Yield gap analysis

The major rice environments where farmers cultivate rice in SSA, and the main production constraints these farmers face, have been identified and characterized by Diagne et al. (2013a), (2013b) on a regional level. From these analyses, rainfed lowlands appeared the most important production environment in terms of area (38%), followed by rainfed uplands (32%) and irrigated lowlands (26%). Estimated mean rice yields ranged from 0.57 to 2.95 t/ha in rainfed uplands, 0.53–3.20 t/ha in rainfed lowlands and 0.49–4.43 t/ha in irrigated lowlands. The main abiotic production constraints assessed across production environments were (in decreasing order) weeds, birds and rodents, diseases (i.e., blast and rice yellow mottle virus) and insects (i.e., termites, stemborers) according to rice farmers' own perceptions (Diagne et al., 2013a). Main soil-related abiotic constraints across environments were iron toxicity, and overall poor soil fertility, whereas main climatic constraints mentioned were drought, cold and floods (Diagne et al., 2013a). Saito et al. (2013) introduced an adapted framework for the estimation of rice yield gaps, distinguishing between farmer-based, experiment-based and model-based yield gaps. They provided a summary for yield gap analysis conducted in SSA until 2013, and pointed out that a comprehensive yield gap analysis using a standardized approach was lacking for rice in SSA. Since the year of publication of this chapter, a lot of progress has been made in that respect.

Analyses of irrigated rice in West Africa (Ibrahim et al., 2021) as well as across rice growing environments region-wide (Senthilkumar, 2022) make it clear that the current yield gaps, between potential and actual farmer yields are still very large in SSA. When yield gaps for rice were compared across regions at global level, SSA had a similar yield gap level as Southeast and South Asia in both irrigated and rainfed rice (Saito et al., 2021). Through a meta-analysis, Senthilkumar (2022) established that the mean farmer-based yield gaps in SSA are 3.1 t/ha for irrigated and rainfed lowlands, and 2.0 t/ha for rainfed uplands. The estimated model-based yield gaps are much greater, i.e. 5.0 t/ha for irrigated lowlands, 7.7 t/ha for rainfed lowlands and 6.0 t/ha for rainfed uplands. Komatsu et al. (2022) indicated a need to understand the causes of poor adoption of agronomic practices such as fertilizer use and water management practices. They argued that identifying the causes could help identify strategies for narrowing the yield gap through the diffusion of yield-enhancing agronomic practices. One of the underlying factors explaining the poor adoption can be that agronomic technologies are not disseminated to farmers' fields enough (Ibrahim et al., 2021). Inter-disciplinary work is recommended for the identification of scaling obstacles and to identify which agronomic technologies locally have the best fit, and which not.

3.4. Genetic improvement

A good understanding and effective management of genetic resources is the corner stone for any breeding programme. The AfricaRice genebank stores and manages over 20,000 accessions and oversees a coordinated and judicious exploitation of the genetic diversity in rice that Africa has to offer (Sanni et al., 2013). This wealth in genetic diversity has been and will be used, for instance, in breeding efforts to address abiotic stresses such as drought, salinity, submergence, phosphorus deficiency, iron toxicity and temperature extremes. Breeding for abiotic stress tolerances in farmer-preferred backgrounds, have been facilitated by the identification of major QTLs (Dramé et al., 2013). A second prerequisite for a successful breeding programme is knowledge about the target environments. Ideally, each new variety matches the local requirements in terms of traits. Important traits range from traits preferred by farmers, millers and consumers, to environmental and ecological adaptation and traits to resist, tolerate or avoid biophysical production constraints such as iron toxicity, drought, weeds and diseases. In the last decade knowledge and understanding of required traits for different target environments has been hugely enhanced by AfricaRice and partners through continent-wide surveys and field trials in key rice growing areas, combined with crop modeling, starting around 2010 (Kumashiro et al., 2013). Breeding efforts by AfricaRice and partners primarily focused on conventionally bred lines and methods (including advanced molecular techniques, but excluding genetic engineering). Hybrid rice breeding is not envisioned, as seed of such varieties would need to be replaced annually, making it a very costly technology for rice farmers. In addition, hybrid technologies would necessitate involvement and investment of the private-sector (El-Namaky and Demont, 2013), which has so far not demonstrated a keen interest in investing in a subsistence crop like rice.

Two studies in the current Special Issue, are reporting on genetic improvement and yield gains in the past 50 years and including the period since 2013. Past breeding efforts have resulted in the release of around 570 rice varieties in 10 major rice-producing SSA countries by 2020 (Futakuchi et al., 2021). Irrigated lowland rice varieties outnumber varieties for the other two major production environments, rainfed lowlands and uplands. Futakuchi et al. (2021) report on yield assessments of new rice varieties in two breeding target domains (upland and lowland in West Africa). They identify a clear scope for improvement of on-farm yields through genetic improvements and suggest to further exploit the potential of inter-specific (*O. sativa* x *O glaberrima*) breeding to achieve that, in particular capitalizing on recently identified biotic-stress tolerant *O. glaberrima* materials. Ibrahim and Saito (2022) assessed that the mean genetic yield gains (0.7–0.9 t/ha) of the past decades, across the three main rice growing environments, are generally lower than the agronomic gains in yield obtained by good agronomic practices with improved varieties (1.4–1.6 t/ha). Agronomic practices accounted for 75% of the total variation in total yield gain with variety and agronomic practice by variety interaction responsible for 19% and 6%, respectively.

Multi-location on-farm trials are needed to systematically assess varieties in the future, and they need to be assessed on more than just yield (Futakuchi et al., 2021). Ibrahim and Saito (2022) suggest that the future breeding focus should be on rainfed rice systems. Beyond the development of new varieties however, Futakuchi et al. (2021) point out that seed systems would urgently need to be improved, to facilitate farmers' access to seeds of new varieties.

3.5. Soil and nutrient management

Two chapters only in the seminal rice book "Realizing Africa's Rice Promise" described previous R&D efforts on soil and nutrient management practices in SSA (Haefele et al., 2013; Tollens et al., 2013). In contrast, 11 out of 19 papers in this Special Issue deal with soil and nutrient management practices (Asai et al., 2021; Chivenge et al., 2022; Grotelüschen et al., 2022; Haefele et al., 2022; Husson et al., 2022; Ibrahim et al., 2021; Johnson et al., 2021; Rakotoson et al., 2022; Rodenburg et al., 2022a; Senthilkumar, 2022). Such large number of papers in this Special Issue reflect the major focus of research on (inorganic) fertilizer management practices in the past decades in terms of agronomic practices. Within that area of research, nitrogen fertilisers received most of the attention (Ibrahim and Saito, 2022; Senthilkumar, 2022). Studies on soil and nutrient management can be differentiated by rice growing environment. Most work has been conducted on irrigated lowlands, and much less so in rainfed rice growing environments (Chivenge et al., 2022; Ibrahim and Saito, 2022; Senthilkumar, 2022). Among the papers focusing on soil and nutrient management practices, some of them investigated the interaction between fertilizer and other factors on rice yield and nutrient use efficiency. For example, Asai et al. (2021) investigated fertiliser by edaphic (soil type) and climatic (rainfall) interaction effects on upland rice yields. Ibrahim and Saito (2022) assessed agronomic and genetic gains and their interaction. Grotelüschen et al. (2022) used a crop simulation model to assess interaction between fertilizer application and water on rice yield response to fertilizer. Husson et al. (2022) investigated effect of fertilizer on upland rice yield in different cropping systems. Rodenburg et al. (2022a) quantified impact of fertilizer following different agroforestry practices on rice yield.

For rainfed upland, Asai et al. (2021) found thirteen studies with quantitative data on fertiliser effects on yields of the same rice variety. The authors used these data to conduct a meta-analysis based on a Bayesian approach. They conclude that on soils with a high clay content, nitrogen application is recommended as a high yield, low risk strategy, whereas on soils with a low clay content, the expected rainfall and financial risks become important determinants for fertiliser application decisions.

Another study, by Chivenge et al. (2022) reviewed the yield gains obtained by site-specific nutrient management (SSNM). SSNM increases mean rice yields by 24% compared with farmers' practice, and by 11% compared with blanket fertiliser application. They recommend the use of electronic decision support tools like "RiceAdvice" to guide SSNM and they highlight the potential of integration of remote sensing and weather forecast tools, alongside local input prices, into such decision support tools for an improved consideration of edaphic and climatic constraints and financial risks.

Johnson et al. (2021) assessed variations in macronutrient and micronutrient concentration in grain and rice straw samples collected at harvest from 1628 farmers' fields in 20 SSA countries. Similarly, Haefele et al. (2022) analyzed nutrient concentrations of rice (grain and straw at harvest) as well as soils collected in the 2016/17 dry season in two long-term experiments (26 years after the establishment in 1991) for intensive rice-based irrigated systems at Ndiaye and Fanaye, Senegal. Both studies found that there is a risk for P and K deficiencies without proper nutrient management practices. Rakotoson et al. (2022) reviewed historical and recent efforts for improving P management for lowland rice production in SSA together with their limitations and prospects for future research. They reported a special focus on three aspects: (1) suitable soil tests to assess the indigenous soil P supply and the yield response to P application in lowlands; (2) organic inputs and localized P application to the nursery bed (nursery P) and to the seedling roots at transplanting (P-dipping); (3) the interaction between P application and climate-induced stresses via its impact on phenological development.

Recently, fertilizer prices have been globally increasing, due to various reasons including the Russia-Ukraine crisis (AfricaRice, 2022). We expect that the cumulative knowledge and technologies for soil and nutrient management in rice, presented in this Special Issue, will become part of recommended practices and contribute to improved fertilizer use efficiency, so that smallholder farmers in SSA could maintain or increase yield while using less fertilizer. Furthermore, to avoid heavy dependency on inorganic fertilizer for yield-enhancement in SSA, the use of organic amendments, crop residue recycling, crop rotation and soil conservation measures should be stimulated (Senthilkumar, 2022).

3.6. Weed management

Important weed species of rice systems have been categorized according to the rice growing environments they dominate and along that same categorization, weed-inflicted yield and financial losses have been determined (Rodenburg and Johnson, 2013). Whether rice is transplanted or direct seeded is another determinant for expected weed-inflicted rice yields. If weeds are left uncontrolled, yield losses range from 28% to 74% in transplanted lowland rice and from 28% to 89% in direct-seeded rice. Rice grown in rainfed uplands is even less forgiving towards neglecting weed control, as yield losses range from 48% to 100%. A range of weed management technologies have been assessed and fine-tuned over the years, such as the characterization and identification of weed-competitive or striga-resistant rice varieties (Tollens et al., 2013).

The Special Issue paper by Rodenburg et al. (2022b) reviews the progress in weed research targeted to rice systems in SSA, with a special focus on the period of the last 12 years. Ibrahim et al. (2021) reviewed weed management options in irrigated rice systems in the Sahel of West Africa. Senthilkumar (2022) included weed management practices in a meta-analysis to assess impact of agronomic practices on yield. Compared to a no-weeding control, weed management contributed to an average of 2.5 t/ha yield increase, across environments. Compared to farmers' practices (i.e., one or two weeding interventions), recommended weed management practices narrowed the yield gap by 0.7 t/ha in irrigated lowlands.

Rodenburg et al. (2022b) report tremendous progress in parasitic weed research, with special attention for the hemi-parasitic weed species *Striga asiatica* and *S. hermonthica* in rainfed uplands, and the facultative parasitic weed *Rhamphicarpa fistulosa*, regarded as a newly emerging production constraints in rainfed lowlands. Parasitic weed resistant and tolerant rice varieties have been identified alongside agronomic interventions, ranging from timing of crop establishment to the use of combined organic and mineral fertilisers. A good example of a novel technology for smallholder farmers to control ordinary weeds, is the range of hand-held push weeders that have been tested by AfricaRice and partners. Push- and rotary weeders have been positively evaluated as a labor-saving technology and farmer participatory work identified the most practical and affordable weeder models (Rodenburg et al., 2022b). It was concluded that in future, there should be more attention for the development of preventive weed management strategies for the rainfed uplands, where there are inherently fewer options to address weeds. Among other recommendations, it was also suggested that climate change effects on weed species distributions and competitiveness and weed community compositions should be studied alongside climate change effects on the effectiveness of weed management strategies, in order to be better prepared for the weed problems of the (near) future.

3.7. Mechanization

Rickman et al. (2013) provided a holistic overview of mechanization advances and future needs in rice systems in SAA. Although mentioned in passing in several papers such as the use of power tillers in Rodenburg et al. (2022a) and Dossou-Yovo et al. (2022), and weeders (which was mentioned in above section as well) in Rodenburg et al. (2022b) and Ibrahim et al. (2021), mechanization has not been the subject of a dedicated paper in the current Special Issue. The most explicit section on mechanization advances was presented in the paper on weed management by Rodenburg et al. (2022b) where weeding implements were discussed. A spin-off of this work on hand-held push weeders was the farmer- and engineer-participatory work conducted by AfricaRice and the private partner Intermech in Tanzania, to develop an adapted motorized weeder, whereby the most suitable traits of different models from Asia (India and Japan) were adopted. This has however not yet been reported in the literature.

3.8. Water management

SSA has abundant water and land resources, allowing future expansion of agricultural area and increased food production. However, the judicious use of these natural resources require a good understanding of spatial and temporal differences in water availability, as well as best management strategies and adapted agronomy (Zwart, 2013). The sustainable exploitation of the widely and abundantly distributed inland valleys, for instance, require the identification and distinction of low-risk and productive valleys from those that have a high value in terms of biodiversity and non-agricultural ecosystem services but a low agricultural production potential (Rodenburg, 2013). Next, these valleys need to be characterized and assessed in terms of their specific hydrology in order to implement the best fitting water management strategies. The past thirty years of water management research in rice systems in SSA were reviewed by Dossou-Yovo et al. (2022). This paper showed a wide range of technologies that has been tested for their potential to address some of the water-related challenges across different rice growing environments in SSA, and discussed limitations of previous studies and potential future research areas. The topics included in their paper were (i) improving water control and increasing rice yield in inland valleys; (ii) reducing drought risk in rainfed uplands; (iii) sustainably expanding rice area in lowlands with limited impacts on ecosystem services; (iv) producing rice with less water, and (v) reducing the effects of soil salinity in irrigated systems. Senthilkumar (2022) quantified the impact of different water management options such as water conservation practices (e.g. bunding, leveling) and water-saving practices (e.g. alternate wetting and drying) on yield of irrigated rice through meta-analysis. Yield increase was 1.0 t/ha with water conservation practices, while yields reduced by 0.7 t/ha with water-saving practices. Grotelüschen et al. (2022) assessed impact of supplemental irrigation in a floodplain and an inland valley in East Africa using the locally-validated APSIM model and historical weather data over 30 years. They concluded that supplemental irrigation may be a better investment for rice grown in floodplains, compared to inland valleys.

3.9. Integrated crop management

Tollens et al. (2013) emphasized the importance of integrated crop management practices for rice as any single component technology cannot solve the multiple constraints farmers face. Through literature review, Senthilkumar (2022) and Ibrahim et al. (2021) found that, although a limited number of publications deal with such integrated crop management practices, those publications clearly showed that across rice growing environments the use of integrated crop management practices (referring to integration of good agricultural practices -GAPs- including soil and nutrient, water, and weed management practices), contribute to a reduced yield gap. An integration of GAPs makes a larger contribution to narrowing the yield gap than use of single GAPs. However, the yield gain obtained from such an integrated approach is still much smaller than the identified yield gaps based on simulation models (Senthilkumar, (2022)). Future rice agronomy research should focus more on integration of GAPs rather than testing of single GAPs only, and be carried out in farmers' fields, as opposed to more controlled fields of research stations (Ibrahim and Saito, 2022).

3.10. Cropping systems

Two studies of this Special Issue focused explicitly on agroecological solutions to rice-based cropping systems. Husson et al. (2022) investigated whether conservation agriculture practices in a rice-maize rotation could help farmers in Cote d′Ivoire adapt to climate change, whereas Rodenburg et al. (2022a) conducted a global meta-analysis on rice yields following different agroforestry practices, and reviewed suitable and adapted agroforestry solutions and tree species for rice farms in SSA.

Growing upland rice under a conservation agriculture practice combining no-till, crop residue mulching and cover crops (e.g., stylo, pigeon pea, crotalaria) seem to provide yield benefits in dryer years over mono-crop rice systems with conventional tillage. While these findings would need to be confirmed over a longer time frame, such systems would increase crop yield stability in areas with a high climatic risk (Husson et al., 2022). Cropping systems in such areas would need to be based on minimal inputs, in order to minimize risks of low or negative returns. The use of pigeon pea was therefore recommended as cover crop, as it requires relatively low labor inputs while producing an income generating product (peas).

The integration of trees in rice production systems, can generate yield benefits too (Rodenburg et al., 2022a). The spatial and temporal arrangements of such integration, the tree species, and the use of fertiliser, emerged as yield determining factors. If no fertilisers are used, growing trees simultaneously with rice (e.g., in a classical intercrop arrangement, or in the hedgerow-alley system) can benefit rice yields. However, applying mineral fertilisers instead of integrating trees, would be a more effective solution to increase rice yields. In rice cropping systems where the benefits from the tree component compensate the competition from trees (e.g., in short term fallows) or where the competition effect is completely avoided (e.g. when trees are grown as green manure before the rice, or when prunings from trees growing outside the rice field are used as green manure) clear gains in rice yields are obtained, irrespective of fertiliser inputs (Rodenburg et al., 2022a). Tree species that have proven yield benefits and are adapted to rice growing conditions in SSA (e.g. *Sesbania rostrata*, *Acacia auriculiformis*, *A. nilotica*, *Gliricidia sepium* and *Gmelia arborea*) are recommended. There exists a wide range of additional benefits of trees. While these benefits obviously comprise important drivers for tree integration in rice farms, they were not systematically and quantitatively reported in rice-agroforestry literature.

3.11. Assessment of sustainability performance indicators

Several papers in this Special Issue observed that apart from yield, impact of agronomic practices on performance indicators such as yield stability, profit and resource use efficiency, was poorly evaluated in the past decades, and this would need to be taken into account in future work for measuring the increase in productivity while minimizing environmental degradation (Arouna et al., 2021; Dossou-Yovo et al., 2022; Ibrahim et al., 2021; Rodenburg et al., 2022a; Saito et al., 2021).

Saito et al. (2021) indicate that there is need to have simple but robust key performance indicators (KPIs), and they proposed a new term, 'agronomic gain', based on an improvement in KPIs, including productivity, resource use efficiencies, and soil health that a specific single or combination of agronomic practices delivers under certain environmental conditions. Arouna et al. (2021) quantified five performance indicators (grain yield, net profit, labor productivity, and nitrogen and phosphorus use efficiencies) to benchmark rice production systems in SSA. Haefele et al. (2022) confirmed that intensive rice cultivation is sustainable in irrigated rice systems with proper nutrient management practices. However, appearing likely deficiencies of some nutrients suggest that it is essential to have regular monitoring of both soil and plant nutrients. For diversified cropping systems such as agroforestry systems, additional performance indicators could be long-term socio-economic impact measures, a food consumption score for measuring food and nutrition security, gender equity and biodiversity (Rodenburg et al., 2022a).

4. Synthesis

Agronomy plays an important role in reducing yield gaps and improving livelihoods, without negatively impacting environments. The current Special Issue presents (1) achievements in the past decades in terms of rice agronomy in sub-Saharan Africa, (2) the state-of-the-art regarding technology development and (3) views on future directions in rice agronomy research.

Based on findings presented in individual papers of this Special Issue, we arrive at six main recommendations. First, there is a need to focus more on rainfed rice-based systems, which dominate SSA in terms of area but where rice yields remain low (Chivenge et al., 2022; Husson et al., 2022; Ibrahim and Saito, 2022; Rodenburg et al., 2022b; Senthilkumar, 2022; van Oort and Dingkuhn, 2021). Second, more attention also needs to be paid to research beyond plot-level agronomy, i.e., on the farming system or landscape level (Dossou-Yovo et al., 2022; Rodenburg et al., 2022a) and for developing integrated cropping and farming systems and integrated agronomic solutions to important biophysical production constraints (Husson et al., 2022; Rodenburg et al., 2022a; Rodenburg et al., 2022b\; Senthilkumar, 2022). Third, related to this, a commonly shared view is that current and future agronomic rice research should center around sustainability issues, including judicious management of finite (fossil) resources, climate change adaptation and mitigation, and conservation of biodiversity and environmental and ecological integrity (Asai et al., 2021; Husson et al., 2022; Rakotoson et al., 2022; Rodenburg et al., 2022a; Rodenburg et al., 2022b). Fourth, to operationalize such research, the development and use of sustainability performance indicators is required (Arouna et al., 2021; Dossou-Yovo et al., 2022; Ibrahim et al., 2021; Rodenburg et al., 2022a; Saito et al., 2021). Fifth, the development of more labor-saving technologies, for instance by increasing the mechanization rate, has also been indicated as a future priority area (Arouna et al., 2021; Ibrahim et al., 2021; Rodenburg et al., 2022b). How this can be reconciled with the need to move away from fossil-fuel dependencies in food production systems, is one of the expected near-future challenges. Sixth, working together with scientists of non-agronomic disciplines *stricta sensa* (e.g., breeding, remote sensing, grain quality, social science), those having different expertise within the area of agronomy (e.g., field agronomy, crop modeling), and stakeholders outside the research arena (e.g., extension, policy and decision makers, input suppliers, farmer organizations) is essential for addressing the various challenges smallholder farmers are facing and for improving the process of R&D (Ibrahim et al., 2021; Rakotoson et al., 2022; Rodenburg et al., 2022b; Saito et al., 2021; van Oort and Dingkuhn, 2021).

Ultimately it is our hope that the papers presented in this Special Issue inform the readership of Field Crops Research on the state-of-the art in rice agronomy in SSA, and on ways that the insights and advances generated over the past five decades may contribute to enhanced rice production and self-sufficiency in this region.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

No data was used for the research described in the article.

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