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REVIEW

Integrated Research for Development Approach to Upgrade the Whole Rice Value-chain in Sub-Saharan Africa: Contribution of Africa Rice Center after NERICA (New Rice for Africa)

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Abstract

In the past 10 years, Japanese scientists have played a leading role in research for development in Africa Rice Center for pre-breeding, breeding, agronomy and post-harvest research which cover the biophysical aspects of the whole rice value-chain. This paper summarizes the related achievements of the center in situation and scenario analyses, varietal development, decision support tools, good agricultural practices and component technologies, land expansion for rice in lowland and improvement of water management, and post-harvest technologies. Although rice production of sub-Saharan Africa (SSA) has been increased, the situation of rice self-sufficiency in SSA has been getting worth due to faster increase of consumption than that of production. More efforts exploiting the new opportunity of One CGIAR and partnerships with governments, advanced institutes, national agricultural research systems and private sector should be made.

Discipline: Crop Science
Additional key words: agronomy, breeding, post-harvest, rice self-sufficiency in sub-Saharan Africa

Introduction

Rice is a food crop with the third largest consumption after maize and wheat in sub-Sahara Africa (SSA) and the growing rate of its consumption in SSA is highest among the food crops. Rice agri-food systems and products—rice-based cropping systems, rice related business by smallholders, milled rice and rice-based food—in SSA are all critical components to be addressed to achieve impacts in the five areas defined in One CGIAR—a new reconstructed CGIAR effective on 1 January 2022—i.e. "Nutrition, Health and Food Security", "Poverty Reduction, Livelihoods and Jobs", "Gender Equality, Youth and Social Inclusion", "Climate Adoption and Greenhouse Gas Reduction: and "Environmental Health and Biodiversity" (CGIAR System Organization 2021). The rice production of SSA is about 18.6 million ton in 2018 on a milled rice basis. But SSA imports 14 million ton (milled rice basis) in 2018 with spending 6 billion US$. This gap currently filled by imports is being enlarged since the increase of consumption (about 81% in the recent ten years in the 23 CARD—Coalition for African Rice Development—countries) is larger than that of production (about 55% in the recent 10 years in the 23 CARD countries in SSA). Efforts to achieve rice self-sufficiency can directly contribute to the impact areas, especially to food security in Africa. In 23 major rice producing and consuming countries membered in CARD, rice production increase was more attributed to land expansion than yield increase (Arouna et al. 2021a). van Oort et al. (2015a) have shown that the expansion of irrigated lowland can be indispensable to achieve rice self-sufficiency in 8 African countries with analyzing various possible future scenarios. Thus, it is important to seek and implement approaches for the expansion of rice-based systems in a sustainable manner as well as those for the intensification to achieve the impacts. In the rice-based systems, exploiting diversification is also crucial for all impact areas of One CGIAR.

In SSA, only 26% of the total rice growing area

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are under irrigated conditions (irrigated lowland); the remaining areas are rainfed environments—rainfed upland, rainfed lowland and other rainfed environments such as deep water and mangrove swamps which account for 32%, 38% and 4%, respectively (Diagne et al. 2013a). The average yields of irrigated lowland, rainfed upland and rainfed lowland are 2.2, 1.2 and 1.9 t/ha, respectively (Diagne et al. 2013a). In another more recent study, the average yield of irrigated lowland, rainfed upland and rainfed lowland are 3.9, 1.6 and 2.6 t/ha, respectively (Saito et al. 2017). The yield level is generally low. Saito et al. (2017) have also shown that the average yield of upper 10th percentile in irrigated lowland, rainfed upland and rainfed lowland farmers was 5.9, 3.5 and 4.8 t/ha, suggesting large potential for possible yield increase in the rainfed environments. To increase rice production, further intensification in all rice growing environments—especially improvement of water management in rainfed lowland (sifting from rainfed to water intensified/irrigated environments)—will be necessary.

Inland valleys (IVs) are dominant geographies in the sub-humid and humid zones in SSA (Saito et al. 2013) offering a large potential for agriculture including rice cultivation due to the availability of run-off water and ground water other than rainfall in their bottom and fringe areas. However, currently about 2% of the total area (the total of 190 M ha is an area covering the whole toposequence—from the valley bottom to the upland area—of IVs) is only utilized in Africa (Rodenburg et al. 2014). There is a huge potential for lands to be further exploited by agriculture in a necessarily sustainable manner.

Ndindeng et al. (2021a) have estimated the total quantitative and qualitative post-harvest loss for rice in SSA in 2018 was about 10.24 billion US$ representing 48% of the value of the exchange trade product. This can suggest that it is impossible to achieve rice self-sufficiency in Africa without the improvement of post-harvest practices and the improvement can greatly contribute to food security of the continent.

Yield of the 23 CARD countries increased from 2.17 t/ha in 2008 to 2.43 t/ha in 2010 soon after the food crisis in 2008, where the international prices of crops including rice jumped up, but decreased to 2.26 t/ha in 2011, when the prices had been decreased, and then since 2012 yield has been in the range of 2.30-2.35 t/ha (Roy-Macauley 2018). The enhanced relative competitiveness of local rice against imported rice in the crisis apparently boosted inputs by rice farmers and increased yield. Improving competitiveness of local rice with the improvement of values of local rice—currently low values due to the qualitative post-harvest loss as mentioned in the above paragraph—in the market and reduction of costs behind the local rice with better productivity can be crucial to increase rice production and achieve rice self-sufficiency in SSA. In SSA, rice yield is low in general and post-harvest losses in both quality and quantity are huge (Fiamohe et al. 2018). Furthermore, seed, which is an entry point of the rice value-chain, is another big issue. For instance, 55% of traditional varieties and 44% of improved varieties are cultivated from farmer self-seed and more than 70% of purchased seed are from colleagues (Beye et al. 2013). Such a situation strongly hinders the use of quality seed and adoption of newly developed varieties. Therefore, it is crucial to upgrade the whole rice value-chain to achieve rice self-sufficiency in SSA. In spite of rice production increase, the situation of rice self-sufficiency became worse in the 10 years (2008-2018) from 63% to 59% in the 23 CARD member countries due to the faster increase of rice consumption (Arouna et al. 2021a). Research for development (R4D) should produce new innovations in variety and seed systems, agronomy and post-harvest and facilitate their out-scaling.

The Africa Rice Center (AfricaRice) has a success story of NERICA (New Rice for Africa) in the past. The start of breeding for interspecific (NERICA) varieties between *Oryza sativa* and *Oryza glaberrima* was in 1992 (Jones et al. 1997) and the first release of NERICA varieties was in 2002 in Côte d'Ivoire and Guinea. All upland NERICA varieties possess short growth duration and comparable yield with improved upland varieties (Somado et al. 2008) and have the respective advantages such as NERICA 4 with drought tolerance (Fofana et al. 2018), which has become popular in SSA especially in Uganda because of the drought tolerance (Britwum et al. 2020). In addition to the numbered NERICA varieties—i.e. NERICA 1-NERICA 18 for upland and NERICA-L 1-NERICA-L 60, for lowland, several upland and lowland varieties have been developed from the interspecific crosses. NERICA is also an inclusive name of the interspecific varieties developed by AfricaRice. As of February 2021, 32 lowland and 25 upland interspecific (NERICA) varieties have been released in SSA; a total of 20 and 26 countries released/adopted lowland and upland interspecific (NERICA) varieties, respectively (Africa Rice Center unpublished data). Kijima et al. (2012) have shown that the adoption of NERICA reduced the incidence of poverty from 54 to 49% in Uganda. Arouna et al. (2017) have shown that the adoption of NERICA reduced the poverty incidence by 21% on average in 16 SSA countries. It was estimated that this reduction in poverty incidence corresponds to lift about 8 million people out of poverty—spending less than 2 US$ per day per person (Arouna et al. 2017). When AfricaRice was developing NERICA varieties, scalable technologies other than varieties were limited. An example of such a technology was an ASI rice thresher-cleaner released in 1997 aiming to reduce post-harvest labor bottlenecks. The name ASI was derived from ADRAO (Association pour le Développement de la Riziculture en Afrique de l'Ouest)/SAED (Senegal River Valley National Development Agency)/ISRA (Institut Sénégalais de Recherches Agricoles) to reflect a collaborative approach by which the thresher was developed. ADRAO is a French acronym of WARDA (West Africa Rice Development Association)—the former name of AfricaRice. The ASI thresher showed some impacts in irrigated rice farming systems (Diagne et al. 2009). This paper focuses on the recent achievements AfricaRice has made in the past 10 years—the achievements can be seen along with the whole rice-value chain beyond varieties—seeking for higher impacts on rice production and farmers' welfare in SSA than before.

Attempts to upgrade the whole rice value-chain in the past 10 years

Japanese scientists have played leading roles in the R4D of AfricaRice. Takashi Kumashiro (served at AfricaRice in 2010–2015) was a Program Leader for Genetic Diversity and Improvement (GDI) responsible for germplasm conservation, pre-breeding and breeding and the coordinator of Japan Breeding Project funded by the Ministry of Finance, Japan. Koichi Futakuchi (served at AfricaRice since 1997) has been a Program Leader for Sustainable Productivity Enhancement (SPE) covering agronomy and post-harvest research since 2012 and was an interim GDI Program Leader in 2010 and 2015-2017. Kazuki Saito (served at AfricaRice since 2006) has been the global leader of the agronomy component of one of the CRPs (CGIAR Research Programs) targeting rice since the second phase of CRP in 2017—Global Leader of Flagship Project 3 "Sustainable Farming Systems" in RICE (2017 to date). He was a coordinator of the 'Africa-wide Rice Agronomy Task Force' involving scientists from >20 member countries in SSA, aiming to develop and out-scale improved agricultural practices for rice (2013-2017). Thus, biophysical R4D actions in pre-breeding, breeding, agronomy and post-harvest have been conducted under the direction of the Japanese scientists in AfricaRice. In the following sub-sections, several examples of the achievements are presented. Collaborations of the Japanese scientists with economists are also actively implemented and several joint articles have been published (e.g. Arouna et al. 2021a, Arouna et al. 2021b, Diagne et al. 2013a, Diagne et al. 2013b, Fiamohe et al. 2018, Ndindeng et al. 2021b).

1. Situation and scenario analyses

These analyses have been conducted to collect information necessary to develop demand-driven products and generate/tune research directions. The outputs of such analyses will also be able to be materials for evidence-based policy dialogues.

Rice self-sufficiency of Africa is one of the AfricaRice's targets and some analyses have been made to suggest research directions to achieve it (Arouna et al. 2021a, Saito et al. 2015a, van Oort et al. 2015a, 2017). Arouna et al. (2021a) assessed the contribution of the CARD policy to rice production and forecasts the local rice supply and demand; the scenario analysis showed that annual increases of 3% and 5.5% in yield and area, respectively, could lead to the achievement of self-sufficiency by 2030. Lessons learnt from CARD Phase 1 suggested that value chain upgrading through private investments in modern mills sector as well as operational vertical coordination should be the priority. van Oort et al. (2015a) conducted rice yield gap assessment in eight African countries and analysis of current and future rice production-consumption scenarios, suggesting that (1) with the current trends in yield, consumption, and population growth, none of countries can achieve rice self-sufficiency in 2025 without additional area expansion in irrigated lowland; (2) five countries would be achieving self-sufficiency in 2025 with the yield increase of 80%—achieving this increasing rate is very difficult judging from the past tendency of yield increase—plus double cropping; (3) the other countries cannot achieve self-sufficiency even by such intensification without land expansion of irrigated lowland. These analyses indicate the importance of sustainable development of lowland for rice-based systems to achieve rice self-sufficiency.

Close collaboration with national agricultural research systems (NARS) in African countries is an important approach for AfricaRice to identify the demands of local people, develop technologies and bring the technologies on the ground for their out-scaling. AfricaRice launched six Africa-wide thematic Task Forces (Breeding Task Force, Agronomy Task Force, Mechanization Task Force, Processing and Value Addition Task Force, Policy Task Force and Gender Task Force) with NARS in 2011. Through Africa-wide Agronomy Task Force (22 member countries as of 2020), a survey quantitatively capturing yield gaps was made for the comprehension of the situation in farmers' rice fields. In 37 locations (12, 7 and 18 for irrigated lowland, rainfed upland and rainfed lowland, respectively), yield gap, which was defined as a difference between an average yield and the best farmers' yield in each location, was quantified (Saito et al. 2017, Tanaka et al. 2017, Niang et al. 2017, Senthilkumar et al.

2020). For further analysis of yield gap, Dossou-Yovo et al. (2020) decomposed the yield gap into efficiency, resource and technology yield gaps. Studies—expert, household and on-farm field surveys—to understand attributes causing the yield gap were also conducted (e.g. Tanaka et al. 2013, Tanaka et al. 2015, Rodenburg et al. 2019). Other approaches to capture causes of the yield gap—e.g. by on-farm experiments (Saito et al. 2015b, Saito et al. 2019) and by crop simulation modelling (Saito et al. 2017)—were also taken. The modeling approach can identify potential risks of yield loss by targeted stresses, as well as quantification of a cause for the yield gap. The yield gap study for rice is part of Global Yield Gap and Water Productivity Atlas (GYGA) (https://www.yieldgap.org/, accessed on 21 March 2021) (Saito et al. 2017). van Oort et al. (2017) developed a new method for this prioritization exercise—to identify region x crop combinations for which high impact—can be anticipated and applied it to data from GAYA.

In SSA, farmers' fields could be often affected by various abiotic and biotic stresses. Under the climate change situation, risks of stresses in agriculture including rice could become more pronounced (van Oort & Zwart 2018). To generate strategies by which countermeasures against such stresses are effectively and efficiently adopted, it is first necessary to know where a certain stress hinders rice productivity and to what extent. Large scale maps for abiotic stresses were not available in SSA; van Oort (2018) mapped four abiotic stresses relevant for rice in SSA (drought, cold, iron toxicity and salinity) for the first time. In the study, drought was the most important stress (33% of rice area potentially affected), followed by iron toxicity (12%) and then cold (7%) and salinity (2%). Hotspots for iron toxicity, cold and salinity, where varietal evaluation for resistance to these respective stresses could be made, were identified. AfricaRice scientists also recently analyzed 2845 soil samples collected from 42 study sites in 20 SSA countries (Johnson et al., 2019). Data has been used to develop 30 m resolution soil digital map for SSA (Hengl et al. 2021). Among biotic stresses, Rodenburg et al. (2016) mapped incidence of parasite weeds and associated economic losses in SSA since parasitic weeds pose increasing threats to rainfed rice production systems in the continent. Annual economic losses inflicted by all parasitic weeds exceeds a minimum value of 111 million US$ and most likely reaches roughly 200 million US$ and increases by 30 million US$ annually. Although parasite weeds were considered to be a serious constraint of other field crops such as maize and sorghum, the weeds can give huge potential risks to ruin yield of rainfed rice. In SSA several pests affecting rice production like rice yellow mottle virus, bacterial leaf blight and African rice gall midge can exist. Quantitative estimations of potential risks of these pests also should be evaluated soonest too (Saito et al. 2013).

Through Africa-wide Post-harvest and Value Addition Task Force, quantitative and qualitative losses caused by post-harvest procedures were evaluated in 12 countries (Africa Rice Center 2018). The study showed that the annual post-harvest loss of a country ranged in 14-600 million US$ (Africa Rice Center 2018). The total post-harvest loss of SSA in 2018 was estimated as huge as about 10.24 billion US$ (Ndindeng et al. 2021a). Harvesting time was revealed as a major contributor to the post-harvest losses and timely harvesting with the grain moisture content of 20-22% can save up to 23% of the yield with the current harvesting practices (Africa Rice Center 2018, Ndindeng et al. 2021a).

To enhance the market value of local rice, it is crucial to know consumers' preference for rice and grain quality attributes of rice highly preferred by consumers. Approaches taken in this study were survey of consumers including a hedonic price model and grain quality analysis of the market samples (Ndindeng et al. 2021b). A sensory evaluation was also adopted in some cases (Futakuchi et al. 2013). In the study, sample collection and analysis were completed in Benin, Cameroon, Côte d'Ivoire, Ghana, Madagascar and Nigeria. From Kenya and Uganda, samples have been collected. The study will be expanded to Mali and Senegal soon. In future, attempts will be made to covers most countries where rice is strategically important. Some results in Benin have been published (Ndindeng et al. 2021b). Lessons learned from the study in Benin are (1) any upgrading strategy should begin with the recognition of potential heterogeneity in consumer preferences for rice quality attributes and existing product categories may not fully capture the heterogeneity; (2) knowledge of the impacts of quality improvement on consumer welfare is informative for setting priorities for resource allocations in R4D.

2. Varietal development

A project titled "Developing the next generation of new rice varieties for sub-Saharan Africa and Southeast Asia" was funded by Ministry of Finance, Japan from January 2010 to December 2014. AfricaRice and International Rice Research Institute (IRRI) implemented the project with their partners. The project had three objectives—i.e. (1) Accelerating the development of high-impact varieties in SSA and Southeast Asia; (2) Accelerating rice variety testing, approval, and dissemination in SSA and Southeast Asia; (3) Contributing to building a new generation of rice breeders—and Takashi Kumashiro was a coordinator. In SSA, the multi-environment testing system, which was part of Africa-wide Breeding Task Force, was launched involving 29 countries in 2011. Promising lines developed by various institutions such as AfricaRice, IRRI, International Center for Tropical Agriculture (CIAT) and NARS in Africa are subject to this multi-location testing for three years to evaluation the lines in relation to stability of target traits under target environments. In the project period, about 2,100 lines in total, were evaluated in 170 sites in SSA. If a country has an interest to release a promising breeding line, the number of ARICA (Advanced Rice for Africa) is given to that line. This multi-environment testing system has been continued after the project termination. From 2013, 18 breeding lines were named as ARICA (Table 1). During the project, 19 SSA countries had 151 release events—they include other varieties than ARICAs—as a total. Historical efforts on genetic improvement for rice in SSA has been recently reviewed by AfricaRice scientists (Sikirou et al. 2015, Saito et al. 2018, Futakuchi et al. 2021).

Due to the success of NERICA, *O. glaberrima* has continuously been a breeding material and interspecific breeding has been continued. Among the 18 ARICA lines, six lines are interspecific varieties (ARICA 1, 3, 4, 6, 14 and 15). This fact proves the high effectiveness to exploit interspecific hybridization to develop new varieties with high performance. Screening of the *O. glaberrima*

Table 1. List of ARICA lines as of March 2021

ARICA number	Designation	Environment	Characteristics	Suitable countries
ARICA 1	WAB2094-WAC 2-TGR 2-B	Rainfed lowland	High yielding over the best check (NERICA-L 19, BW 348-1)	Mali, Burkina Faso
ARICA 2	WAB2056-2-FKR 2-5-TGR 1-B	Rainfed lowland	High yielding over the best check (BW 348-1, NERICA-L 19, WITA 12)	Mali, Nigeria
ARICA 3	WAB2076-WAC 1-TGR 1-B	Rainfed lowland	High yielding over the best check (BW 348-1, NERICA-L 19, WITA 12). Good grain quality	Mali, Nigeria, Burkina Faso, Togo
ARICA 4	ART3-11-L1P1-B-B-2	Upland	High yielding over the best check (NERICA 4)	Uganda
ARICA 5	WAB95-B-B-40-HB	Upland	High yielding over the best check (NERICA 4)	Uganda
ARICA 6	IR75887-1-3-WAB1	Rainfed lowland	Iron-toxicity tolerant	Guinea, Ghana
ARICA 7	WAS21-B-B-20-4-3-3	Rainfed and irrigated lowland	Iron-toxicity tolerant	Ghana, Senegal
ARICA 8	WAT1046-B-43-2-2-2	Rainfed and irrigated lowland	Iron-toxicity tolerant	Burkina Faso, Guinea
ARICA 9	SIM2 SUMADEL	Rainfed and irrigated lowland	Cold tolerant	Mali
ARICA 10	WAS200-B-B-1-1-1	Rainfed and irrigated lowland	Cold tolerant	Mali
ARICA 11	IR63275-B-1-1-1-3-3-2	Mangrove	Salt tolerant	Gambia
ARICA 12	FAROX521-288-H1	Irrigated lowland	High yielding over the best check (WITA 9)	Senegal
ARICA 13	WAB2151-TGR1-WAT B4	Irrigated lowland	High yielding over the best check (WITA 4)	Senegal
ARICA 14	ART15-11-8-5-2-B-1	Upland	High yielding over the best check (NERICA 1, 3, 4, 8)	Côte d’Ivoire
ARICA 15	WAB881-SG-12	Upland	High yielding over the best check (NERICA 8)	Côte d’Ivoire
ARICA 16	CNAX3031-78-2-1-1	Upland	High yielding over the best check (NERICA 1, WAB56-104)	Benin, Burkina Faso, Mali
ARICA 17	scrid017-1-4-4-4-1	High elevation	High yielding over the best check (X-JIGNA, WAB56-104, Ediget)	Ethiopia
ARICA 18	FAROX521-83-H1	Rainfed lowland	High yielding over the best check (NERICA-L 19, WITA 9)	Côte d’Ivoire

(Source: AfricaRice website at https://www.africarice.org/arica, accessed on 21 March 2021) collection of AfricaRice in relation to resistance to stresses such as drought, iron toxicity, stagnant flooding, submergence, anaerobic germination and heat (early morning flowering to avoid a head stress) has been continued (e.g. Sikirou et al. 2016, Sikirou et al. 2018).

Collaboration between AfricaRice and Japan International Research Center for Agricultural Sciences (JIRCAS) has mostly been in the research area of varietal development. AfricaRice tested promising varieties from JIRCAS under the African environments.

3. Decision support tools

Governments and development agencies have generally recommended abstracted, simplified, blanket advice when promoting the adoption of improved technologies. In view of limited adoption of such recommendations, however, blanket advice on fertilizer application can result in some farmers over or other farmers under using the input, with negative consequences for yield and profits. Therefore, site-specific and situation-specific decision supports will produce better yield and profits to all farmers in the site. The cost of adapting extension advice to local conditions was prohibitively expensive before. But advances in current information and communication technology (ICT) has made decision support tools (DSTs) adoptable to many people with greatly reduced costs. Popularity of electric devices can now be seen world-widely including Africa. AfricaRice started the development of DST in 2011 and a site-specific fertilizer management recommendation based on prior field trials, which has less nitrogen application than farmers' practices, produced 20% higher yield than did the farmers' practices in Senegal (Saito et al. 2015b). The results encouraged AfricaRice to develop a new DST called RiceAdvice (https://www.riceadvice.info/en/riceadvice/, accessed on 21 March 2021), which is an Android-based application. RiceAdvice provides a fertilizer application recommendation based on necessary information, e.g. the variety used, last season's yield, types of fertilizer available, fertilizer prices, paddy prices, target yield, entered by a user (Zossou et al. 2021). An impact study in Nigeria showed (1) households who were just given the personalized recommendation by RiceAdvice increased their yield by 7% and their profit by 10%; (2) on average, the personalized recommendation increased yields without increasing the overall quantity of fertilizer used (Arouna et al. 2021b). RiceAdvice has been positively evaluated in Eastern and Southern Africa (Ethiopia, Madagascar and Rwanda) too (Cotter et al. 2020). Other ICT tools are also being developed; a tool to assist constructing proper cropping calendar based on weather data called Cropping Calendar Construction (CCC) tool (https://models.pps.wur.nl/cropping-calendar-construction-ccc-model, accessed on 21 March 2021) has been developed based on improved climate risk simulations for rice in SSA (van Oort et al. 2014, 2015b) and another tool making a recommendation for weed management (RiceAdvice-WeedManager: https://www.riceadvice.info/en/weedmanager/, accessed on 21 March 2021) is under piloting.

4. Good agriculture practices and component technologies

Through Africa-wide Agronomy Task Force, component technologies of good agricultural practices (GAP) were co-identified with NARS and GAP suitable to each country was introduced. Feedback from farmers was taken to revise the component technologies for more suitable GAP. The introduction of GAP to farmers effectively improved farmers' yield. For example, in Tanzania average yield increases of 1 t/ha in 2013 and 2.7 t/ha in 2014 compared to farmers' practices were achieved when following GAP; these yield advantages were mainly obtained by a higher panicle number, improved harvest index and improved weed control (Senthilkumar et al. 2018).

Fertilizer is one of the major crop management factors to determine crop yield and efficient applications as directed by DST such as RiceAdvice can improve yield even with less amount of total application than that in the traditional practices (Arouna et al. 2021b). Development of more effective/efficient fertilizer application methods has also been our research target. For instance, in dry-seeded, dibbled rice cultivation, a micro-dose of 20-30 kg of DAP per hector placed in the planting hole resulted in an average net increase in profit of 91 US$ to 136 US$ per hector and benefit/cost ratio of 3-12 in the experiment in farmers' rice fields (Vandamme et al. 2018). In transplanted rice cultivation, phosphorus (P) application to the nursery bed increased grain yield by 10-14% in the field with higher soil P supply and 30-40% in the field with lower soil P supply (Vandamme et al. 2016).

Weeds are the predominant biotic constraint as perceived by farmers in SSA; an estimated 70% of farmers perceive weeds as a major problem across all rice growing environments (Diagne et al. 2013b). AfricaRice has attempted to introduce mechanical weeders for more effective and labor-saving weeding practices for lowland rice (Gongotchame et al. 2014). Rodenburg et al. (2015) evaluated the following weeding technologies: two hand-operated mechanical weeders, the straight-spike and the twisted-spike floating weeder. Although no differences in weed control efficacy were observed between mechanical and hand weeding, weeding time was significantly reduced (32-97%) by mechanical weeding compared with hand weeding (Rodenburg et al. 2015). To understand farmers' perceptions on mechanical weeders, three to six different weeder types were evaluated at 10 different sites across seven countries in SSA (Johnson et al. 2018). Among the mechanical weeders tested, ring hoe was most preferred; the probability of farmers' preference of the ring hoe over their usual practices—herbicide, traditional hoe and hand weeding—was 52%, 95% and 91%, respectively and this particular preference of ring hoe was not related to gender, years of experience with rice cultivation, rice field size, weed infestation level, water status or soil texture (Johnson et al. 2018). Apart from the evaluation of mechanical weeders, AfricaRice has started the validation of motorized weeders, which could potentially save more weeding time than mechanical weeders, for lowland rice. Small scale mechanization such as mechanical weeders is indispensable equipment for further laborsaving intensification of rice cultivation. Farmers‘ field trials in Madagascar repeated in two seasons showed that compared with manual practices, labor requirement for seeding was reduced by 70% by the adoption of mechanical seeders and that for seeding and basal fertilizer application was reduced by 80% by the adoption of a fortiseeder (unpublished data).

5. Land expansion for rice in lowland and improvement of water management

To achieve rice self-sufficiency in SSA, expansion of lowland rice is indispensable (van Oort et al. 2015a). AfricaRice developed a Smart-Valleys approach which is a farmers' participatory approach to develop inland valleys for lowland rice and rice-based systems. The Smart-Valleys approach is also suitable to improve water management of existing rainfed lowland, which can secure the effectiveness of further intensification such as augmented fertilizer application. The approach is entirely participatory throughout the whole steps from the sensitization to the design and implementation of the system, and includes the following three pillars: drainage canals, irrigation infrastructure (where water resources are available), and bunded and leveled rice fields in the inland valleys (Arouna & Akpa 2019). The adoption of the Smart-Valleys approach increased the yield by 0.9 t/ha and the net income by 267 US$ per hectare compared to the non-adopters (traditional rainfed lowland rice practice) under the condition of climate change, which made yield levels low in the study, in Benin and Togo (Arouna & Akpa 2019).

To have provision for further actions to exploit lowland to achieve rice self-sufficiency, it is crucial to have information on the spatial distribution of inland valleys which are suitable for the development by the Smart-Valleys approach at the national, regional and continental scales. Akpoti et al. (2019) developed an ensemble model approach to characterize the inland valleys suitability for lowland rice using 4 machine learning algorithms based on environmental niche modeling (ENM)—i.e. Boosted Regression Tree (BRT), Generalized Linear Model (GLM), Maximum Entropy (MAXNT) and Random Forest (RF). The method was validated in Benin and Togo.

Alternative wet and dry (AWD) is an option of irrigated lowland to save water without sacrificing yield so that it is a crucial technology under the climate change situation (Djaman et al. 2018). In view of the importance of irrigated lowland to achieve rice self-sufficiency (van Oort et al. 2015a), Akpoti et al. (2021) assessed potentially irrigable lands for irrigated lowland rice cultivation under water-saving technology in Burkina Faso. The methodology could be applicable to other countries.

6. Post-harvest technologies

Parboiling is widely practiced in SSA and AfricaRice developed a new "Grain quality enhancer, Energy-efficient and durable Material (GEM)" parboiling system (Ndindeng et al. 2015a). Parboiling can improve milled rice quality with reducing chalkiness and grain breakage and furthermore the GEM parboiling system produced parboiled rice with better quality of milled rice than did traditional parboilers (Ndindeng et al. 2015a, Zohoun et al. 2018). The GEM parboiler also improved nutrition—e.g. protein, lipid, phosphorous, potassium and magnesium (Zohoun et al. 2018). To reduce the use of woods for energy sources including for parboiling with exploiting rice milling by-products, a machine to make fuel briquettes from rice milling by-products (Ndindeng et al. 2015b) and a fun-assisted gasifier using husks (Ndindeng et al. 2019) were developed. The fan of a gasifier is driven by solar panel battery which is now widely available in SSA.

Conclusion

In the past 10 years, AfricaRice has conducted R4D targeting the whole rice value-chain to increase the rice production in SSA beyond varieties and the Japanese scientists have contributed to most of the R4D actions. However, the situation of rice self-sufficiency in SSA has been getting worth due to faster increase of consumption than production (Arouna et al. 2021a). To bring sufficient amount of local rice meeting the demands to the market in SSA, expansion of lowland rice area (van Oort et al. 2018) and reduction of post-harvest losses (Ndindeng et al. 2021a) are crucial actions, as well as yield increase. More efforts exploiting the new opportunity of One CGIAR and partnerships with governments, advanced institutes, NARS and private sector should be made. In the CRP scheme since 2011, AfricaRice and JIRCAS have together been members of the CRP targeting rice and AfricaRice has enjoyed the technical collaboration with JIRCAS. We expect further collaborations not only in technical aspect but also in other areas such as capacity strengthening of NARS scientists and detachment of Japanese scientists. Various types of application for remote trainings are available after the COVID-19 pandemic and such remote trainings could be effective, especially in the theoretical part of the R4D actions; the remote trainings provided by scientists with advanced knowledge in Japan will benefit NARS scientists. Utilizing outside human resources can be a direct measure to strengthen an institute to secure critical mass and exploit new expertise and knowledge; AfricaRice will continue to appreciate to receive Japanese scientists from JIRCAS and National Agricultural Research Organization (NARO), Japan either in secondment or in transfer. Some efforts to introduce AfricaRice to Japanese agricultural scientists—e.g. Kazuki Saito presented his research experience in a mini-symposium of the 247th Meeting of Crop Science Society of Japan in 2019 (Fushimi 2019)—have been made. Efforts of the introduction, which could be in a larger scale by webinars, will have to be continued. We hope the One CGIAR as more attractive systems to both young and senior Japanese scientists.

References

Africa Rice Center (2018) Annual Report 2017. Africa Rice Center: Abidjan, Côte d'Ivoire. pp. 39.

Akpoki, K. et al. (2019) Mapping suitability for rice production in inland valley landscapes in Benin and Togo using environmental niche modeling. *Sci. Total Environ.* **709**, 136165.

Akpoki, K. et al. (2021) The potential for expansion of irrigated rice under alternate wetting and drying in Burkina Faso. *Agric. Water Manage.* **247**, 106758.

Arouna, A. & Akpa, A. K. A. (2019) Water management technology for adaptation to climate change in rice production: evidence of Smart-Valley approach in West Africa. *In* Sustainable Solutions for Food Security. Sarkar, A. et al. (eds.). Springer Nature: Basel, Switzerland. 211-227.

Arouna, A. et al. (2017) Contribution of improved rice varieties to poverty reduction and food security in sub-Saharan Africa. *Global Food Sec.* **14**, 54-60.

Arouna, A. et al. (2021a) One size fits all?: Experimental evidence on the digital delivery of personalized extension advice in Nigeria. *Am. J. Agric. Econ.* **103**, 596-619.

Arouna, A. et al. (2021b) Moving toward rice self-sufficiency in sub-Saharan Africa by 2030: Lessons learned from 10 years of the Coalition for African Rice Development. *World Develop. Prospect.* **21**, 100291.

Beye, A. M. et al. (2013) Development of an integrated rice seed sector in sub-Saharan Africa: meeting the needs of farmers. *In* Realizing Africa's Rice Promise. Wopereis, M. C. S. et al. (eds.). CABI International: Oxfordshire, UK; AfricaRice: Cotonou, Benin. 179-187.

Britwum, K. et al. (2020) Confronting genetic gains with markets: Retrospective lessons from New Rice for Africa (NERICA) in Uganda. *Outlook Agric.* **49**, 298-310.

CGIAR System Organization (2021) CGIAR 2030 Research and Innovation Strategy. CGIAR System Organization: Montpellier, France. https://hdl.handle.net/10568/110918

Cotter, M. et al. (2020) Creating the data basis to adapt agricultural decision support tools to new environments, land management, and climate change. *J. Agron. Crop Sci.* **206**, 423-432.

Diagne, A. et al. (2013a) Estimation of cultivated area, number of farming households and yield for major rice-growing environments in Africa. *In* Realizing Africa's Rice Promise. Wopereis, M. C. S. et al. (eds.). CABI International: Oxfordshire, UK; AfricaRice: Cotonou, Benin. 35-45.

Diagne, A. et al. (2013b) Farmer perceptions of the biophysical constraints to rice production in sub-Saharan Africa, and potential impact of research. *In* Realizing Africa's Rice Promise. Wopereis, M. C. S. et al. (eds.). CABI International: Oxfordshire, UK; AfricaRice: Cotonou, Benin. 46-68.

Diagne, M. et al. (2009) Adoption and impact in the Senegal River Valley of an award-winning post-harvest technology: the ASI rice thresher. Mimeo, Africa Rice Center: Cotonou, Benin. 1-38.

Djaman, K. et al. (2018) Effects of alternate wetting and drying irrigation regime and nitrogen fertilizer on yield and nitrogen use efficiency of irrigated rice in the Sahel. *Water* **10** (6), 711.

Dossou-Yovo, E. R. et al. (2020) Decomposing rice yield gaps into efficiency, resource and technology yield gaps in sub-Saharan Africa. *Field Crops Res.* **258**, 107963.

Fofana, M. et al (2018) Physiological and agronomic responses of four rice varieties to drought in the rainforest. *Not. Sci. Biol.* **10**, 220-227.

Fiamohe, R. et al. (2018) How Can West African Rice Compete in Urban Markets? A Demand Perspective for Policymakers. *EuroChoice* **17**, 51-57.

Fushimi, E (2019) Research career path in international agricultural research institutes. *Jpn. J. Crop Sci*. **88**, 218. [In Japanese]

Futakuchi, K. et al. (2013) Improving grain quality of locally produced rice in Africa. *In* Realizing Africa's Rice Promise. Wopereis, M. C. S. et al. (eds.). CABI International: Oxfordshire, UK; AfricaRice: Cotonou, Benin. 311-323.

Futakuchi, K. et al (2021) History and progress in genetic improvement for enhancing rice yield in sub-Saharan Africa *Field Crops Res.* **267**, 108159.

Gongotchame, S. et al. (2014) Participatory evaluation of mechanical weeders in rice production systems in Benin. *Crop Protection* **61**, 32-37.

Hengl, et al. (2021) African soil properties and nutrients predicted at 30–m spatial resolution using two-scale ensemble machine Learning. *Scientific Reports.* **11**, 6130.

Johnson, J. M. et al. (2018) Farmers' perception on mechanical weeders for rice production in sub-Saharan Africa. *Exp. Agric.* **55**, 117-131.

Johnson, J. M. et al. (2019) Near-infrared, mid-infrared or combined diffuse reflectance spectroscopy for assessing soil fertility in rice fields in sub-Saharan Africa. *Geoderma.* **354**, 113840

Jones, M. P. et al. (1997) Interspecific *Oryza sativa* L. x *O. glaberrima* Steud. progenies in upland rice improvement. *Euphytica*, **92**, 237-246.

Kijima, Y. et al. (2012) Assessing the impact of training on lowland rice productivity in an African setting: evidence from Uganda. *World Dev.* **40**, 1610-1618.

Ndindeng, S. A. et al. (2015a) Upgrading the quality of Africa's rice: a novel artisanal parboiling technology for rice processors in sub-Saharan Africa. *Food Sci. Nutr.* **3**, 557-568.

Ndindeng, S. A. et al. (2015b) Quality optimization in briquettes made from rice milling by-products. *Energy Sustain. Dev.* **29**, 24-31.

Ndindeng, S. A. et al. (2019) Evaluation of fan-assisted rice husk fuelled gasifier cookstoves for application in sub-Sahara Africa. Renew. *Energy.* **139**, 924-935.

Ndindeng, S. A. et al. (2021a) Valuation of rice post-harvest losses in sub-Saharan Africa and its mitigation strategies. *Rice Science*. **28** (3). http://www.ricescience.org/EN/Y2021/V28/I3/1

Ndindeng, S. A. et al. (2021b) Hedonic pricing of rice attributes, market sorting, and gains from quality improvement in the Beninese market. Agric. Resource Econ. Rev. (First View), 1-17. https://doi.org/10.1017/age.2020.24

Niang, A. et al. (2017) Variability of yields and its determinants in rice production systems of West Africa. *Field Crops Res.* **207**, 1-12.

Rodenburg, J. et al. (2014) Sustainable rice production in African inland valleys: Seizing regional potentials through local approaches. *Agric. Sys.* **123**, 1-11.

Rodenburg, J. et al. (2015) Labor-Saving Weed Technologies for Lowland Rice Farmers in sub-Saharan Africa. *Weed Tech.* **29**, 751-757.

Rodenburg, J. et al. (2016) Parasitic weed incidence and related economic losses in rice in Africa. *Agric. Ecosys. Env.* **235**, 306-317.

Rodenburg, J. et al. (2019) Status quo of chemical weed control in rice in sub-Saharan Africa. *Food Sec.* **11**, 69-92.

Roy-Macauley, H. (2018) Trends in Rice Production and Consumption during the CARD period 2008–2018. Paper presented at the 7th General Meeting of the Coalition for African Rice Development, Tokyo, Japan, in 2–4 October 2018.

Saito, K. et al. (2013) Towards a better understanding of biophysical determinants of yield gaps and the potential for expansion of the rice area in Africa. *In* Realizing Africa's Rice Promise. Wopereis, M. C. S. et al. (eds.). CABI International: Oxfordshire, UK; AfricaRice: Cotonou, Benin. 188-203.

Saito, K. et al. (2015a) Rice yield growth analysis for 24 African countries over 1960–2012. *Global Food Sec.* **5**, 62-69.

Saito, K. et al. (2015b) On-farm testing of a nutrient management decision-support tool for rice in the Senegal River Valley. *Computers Electron. Agric.* **116**, 36-44.

Saito, K. et al. (2017) Yield gap analysis towards meeting future rice demand. In Achieving Sustainable Rice Cultivation. Vol 2: Cultivation, Pest and Disease management. Sasaki, T. (ed.). Burleigh Dodds Science Publishing: Cambridge, UK. DOI: 10.19103/AS.2016.0003.26

Saito, K. et al. (2018) Progress in varietal improvement for increasing upland rice productivity in the tropics. *Plant Prod. Sci.* **21**, 145-158.

Saito, K. et al. (2019) Yield-limiting macronutrients for rice in sub-Saharan Africa. *Geoderma.* **338**, 546-554.

Senthilkumar, K. et al. (2018) Increasing paddy yields and improving farm management: results from participatory experiments with good agricultural practices (GAP) in Tanzania. *Paddy Water Env.* **16**, 749-766.

Senthilkumar, K. et al. (2020) Quantifying rice yield gaps and their causes in Eastern and Southern Africa. *J. Agron. Crop Sci.* **206**, 478-490.

Sikirou, M. et al. (2015) Genetic improvement of iron toxicity tolerance in rice - progress, challenges and prospects in West Africa. *Plant Prod. Sci.* **18**, 423-434.

Sikirou, M. et al. (2016) Soil-based screening rice for tolerance to iron toxicity using pots. *Plant Prod. Sci.* **19**, 489-496.

Sikirou, M. et al. (2018) Screening African rice (O. glaberrima) for tolerance to abiotic stress: I. Fe toxicity. *Field Crops Res.* **220**, 3-9.

Somado, E. A. et al. (2008) NERICA: the New Rice for Africa – a Compendium. Africa Rice Center: Cotonou, Benin. pp. 195.

Tanaka, A. et al. (2013) Factors affecting variation in farm yields of irrigated rice in southern-central Benin. *Eur. J. Agron.* **44**, 46-53.

Tanaka, A. et al. (2015) Causes of yield stagnation in irrigated lowland rice production system in the Senegal River Valley. *Field Crops Res.* **176**, 99-107.

Tanaka, A. et al. (2017) On-farm rice yield and its association with biophysical factors in sub-Saharan Africa. *Eur. J. Agron.* **85**, 1-11.

Vandamme, E. et al. (2016) Strategic phosphorus (P) application to the nursery bed increases seedling growth and yield of transplanted rice in low P supply. *Field Crops Res*. **186**, 10-17.

Vandamme, E. et al. (2018) Phosphorus micro-dosing as an entry point towards sustainable intensification in rice systems in sub-Saharan Africa. *Field Crops Res*. **222**, 39-49.

van Oort, P. A. J. (2014) A simple model for simulating heat induced sterility in rice as a function of flowering time and transpirational cooling. *Field Crops Res.* **156**, 303-312.

van Oort, P. A. J. et al. (2015a) Assessment of rice self-sufficiency in 2025 in eight African countries. *Global Food Sec*. **5**, 39-49.

van Oort, P. A. J. (2015b) Improved climate risk simulations for rice in arid environments. *PLoS ONE*, **10**, e0118114.

van Oort, P. A. J. et al. (2017) Can yield gap analysis be used to inform R & D prioritization? *Global Food Sec.* **12**, 109-118.

van Oort, P. A. J. (2018) Mapping abiotic stresses for rice in Africa: Drought, cold, iron toxicity, salinity and sodicity. *Field Crops Res*. **219**, 55-75.

van Oort, P. A. J. & Zwart, S. J. (2018) Impacts of climate change on rice production in Africa and causes of simulated yield changes. *Glob. Change Biol*. **24**, 1029-1045.

Zohoun, E. V. et al. (2018) Physicochemical and nutritional properties of rice as affected by parboiling steaming time at atmospheric pressure and variety. *Food Sci. Nutr.* **6**, 638-652.

Zossou, E. et al. (2021) Participatory diagnostic for scaling a decision support tool for rice crop management in northern Nigeria. *Development in Practices*. In press. https://doi.org/10.1080/09614524.2020.1770699