Thirty years of water management research for rice in sub-Saharan Africa: achievement and perspectives

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Abstract

Rice is one of the major staple foods in sub-Saharan Africa (SSA) and is mainly grown in three environments: rainfed upland and rainfed and irrigated lowlands. In all rice-growing environments, the yield gap (the difference between the potential yield in irrigated lowland or water-limited yield in rainfed lowland and upland and the actual yield obtained by farmers) is largely due to a wide range of constraints including water-related issues. This paper aims to review water management research for rice cultivation in SSA. Major water-related constraints to rice production include drought, flooding, iron toxicity, and soil salinity.

A wide range of technologies has been tested by Africa Rice Center (AfricaRice) and its partners for their potential to address some of the water-related challenges across SSA. In the irrigated lowlands, the system of rice intensification and alternate wetting and drying significantly reduced water use, while the pre-conditions to maintain grain yield and quality compared to continuous flooding were identified. Salinity problems caused by the standing water layer could be addressed by flushing and leaching. In the rainfed lowlands, water control structures, Sawah rice production system, and the Smart-Valleys approach for land and water development improved water availability and grain yield compared to traditional water management practices. In the rainfed uplands, supplemental irrigation, mulching, and conservation agriculture mitigated the effects of drought on rice yield. The Participatory Learning and Action Research (PLAR) approach was developed to work with and educate communities to help them implement improved water management technologies.

Most of the research assessed a few indicators such as rice yield, water use, water productivity at the field level. There has been limited research on the cost-benefit of water management technologies, enabling conditions and business models for their large-scale adoption, as well as their impact on farmers' livelihoods, particularly on women and youth. Besides, limited research has been conducted on water management design for crop diversification, landscape-level water management, and iron toxicity mitigation, particularly in lowlands. Filling these research gaps could contribute to sustainable water resources management and sustainable intensification of rice-based systems in SSA.

Keywords: Oryza spp., productivity, sustainability, water

1 Introduction

Food and nutrition insecurity remains a severe problem in most SSA countries, with a high prevalence in rural areas (Livingston et al., 2011). Rice is one of the important staple foods in SSA. Rice consumption has risen rapidly since the 1960s, owing to the triple effect of rising per capita consumption, urbanization, and demographic growth (Balasubramanian et al., 2007; van Oort et al., 2015). The per capita consumption has steadily increased from 10 kg in 1961 to 54 kg in 2017, and in some countries, such as Guinea, Guinea-Bissau, Liberia, Madagascar, Mali, and Sierra Leone, annual per capita rice consumption exceeds 100 kg per capita (USDA, 2019). By 2028, SSA is expected to have the world's second-highest annual per capita rice consumption after Asia (OECD-FAO, 2019). Despite increasing rice consumption, domestic production only meets 53% of demand, and imports mostly from Asia fill the void (Arouna et al., 2021). The insufficient production of rice in SSA is due to limited rice production area and low yield (van Oort et al., 2015). Farmers' yields are low (on average 2.2 t/ha in 2017) compared to the world average (4.6 t/ha in 2019) (FAOSTAT, 2021). Previous studies attributed the lower rice yield in SSA to sub-optimal crop management practices (Saito et al., 2018; Dossou-Yovo et al., 2020), climate-related stresses (drought and flooding), soil constraints (salinity, alkalinity, iron toxicity, nitrogen, and phosphorus deficiency), and biotic stresses (weeds, birds, rodents, insects, and diseases) (Diagne et al., 2013b; Saito et al., 2019).

In SSA, rice is grown in five environments: rainfed upland, irrigated lowland, rainfed lowland, deep-water, and mangrove-swamps (Saito et al., 2013). Rainfed upland rice is typically grown on fields that are un-bunded, flat, or in sloping areas (Saito et al., 2013). Rainfed upland generally has freely draining soils with deep groundwater levels and high percolation rates (van Oort, 2018). Irrigated lowland rice is typically grown in bunded fields with one or two crops of assured irrigation per year (Saito et al., 2013). Dam-based irrigation, water diversion from rivers, and pump irrigation from wells are major sources of water in the irrigated system (Saito et al., 2013). Rainfed lowland rice is grown on level to slightly sloping, unbunded, or bunded fields in lower parts of the toposequence, and inland valleys (Rodenburg, 2013). Inland Valleys (IVs) are defined as the upper reaches of rivers systems, comprising valleys bottoms and their hydromorphic fringes (Fig. 1) (Rodenburg et al., 2014; Windmeijer and Andriesse, 1993). In rainfed lowlands, fields are flooded by rains and groundwater for part of the rice-growing season, although in some seasons, fields may not be flooded due to lack of rainfall. Rainfed lowland rice is also grown in flash-flood areas, where the water level is increased during the rice-growing season, causing short-term submergence. A fuzzy transition exists between rainfed and irrigated lowland rice-growing environments, where a water-management continuum exists ranging from strictly rainfed (no water control) to fully irrigated lowlands, which may evolve with investments in water control measures (Saito et al., 2013). Deep-water rice is found in the flood plains along the major rivers and coastal wetlands. Water depth remains high (up to 3 m) for an extended period (up to 5 months). In the mangrove-swamps, rice fields are located on tidal estuaries close to the sea. Rice can be grown during the period when freshwater floods wash the land and displace tidal flows (Saito et al., 2013). Irrigated lowland, rainfed lowland, and rainfed upland account for roughly 26, 38, and 32% of Africa's total rice area, respectively while deep-water rice and mangrove rice environments together account for 4% of the total rice area (Diagne et al., 2013a). Recent field studies show rice yield is generally lower in rainfed lowlands and uplands than in irrigated lowlands (Niang et al., 2017; Tanaka et al., 2017; Dossou-Yovo et al., 2020).

Meeting the future rice demand in SSA requires closing yield gaps, increasing cropping intensity (the number of crops grown per year on the same field), and sustainable expansion of cropland (van Oort et al., 2015). The yield gap can be defined as the difference between the potential yield in irrigated lowland or water-limited potential yield in rainfed lowland and upland and the actual yield obtained by farmers (van Ittersum and Rabbinge, 1997; van Ittersum et al., 2013; van Oort et al., 2015; Saito et al., 2017). The rice yield gap is large in SSA (5.0 t/ha in irrigated lowland, 5.3 t/ha in rainfed lowland, and 5.6 t/ha in rainfed upland), suggesting a large scope for increasing farmers' actual yield (Dossou-Yovo et al., 2020).

Major water-related challenges for reducing yield gaps in the major rice-growing environments include water scarcity, soil salinity, and iron toxicity in irrigated lowland, drought, flooding, and iron toxicity in rainfed lowland, and drought in rainfed upland. Here, water scarcity in irrigated systems occurs when there are technical failures in the irrigation infrastructure, such as when there is a collapse of a canal bank, inadequate canal cleaning leading to a shortage of water in the fields that are at the highest elevation within the irrigation area. Another technical form of water scarcity occurs when there is insufficient water that can be pumped into the upper part of the irrigation area (Totin et al., 2013). Drought in rainfed systems occurs when the rainfall amount in a given season is not enough to meet the crop water demand or when the timing of rains shifts resulting in drought spells within the season (Mishra and Singh, 2010; Totin et al., 2013).

Inland valleys are widespread geographies in SSA and are estimated to cover about 190 Mha. However, an estimated 2% of the total inland valley area is used for agricultural production because of their extreme diversity and the difficulties of controlling water in such systems (Wopereis et al., 2009). Despite this, demographic growth and increased pressure on land are forcing farmers to expand rice production in inland valleys (Becker and Johnson, 2001). Besides food production, inland valleys provide diverse market and non-market goods and ecosystem services, which benefit local communities (Rodenburg et al., 2014). For instance, inland valleys contribute to water storage, flood prevention, groundwater recharge, erosion control, and provide water sources for irrigation and domestic uses, fodder for livestock, and construction material. (Wangai et al., 2016; Costanza et al., 2017). However, several studies reported a loss in ecosystem services provided by inland valleys as a result of the rapid expansion of rice area (Ondiek et al., 2016; Djagba et al., 2019; Jellason et al., 2021). Therefore, further rice expansion in inland valleys should be balanced with the preservation of ecosystem services.

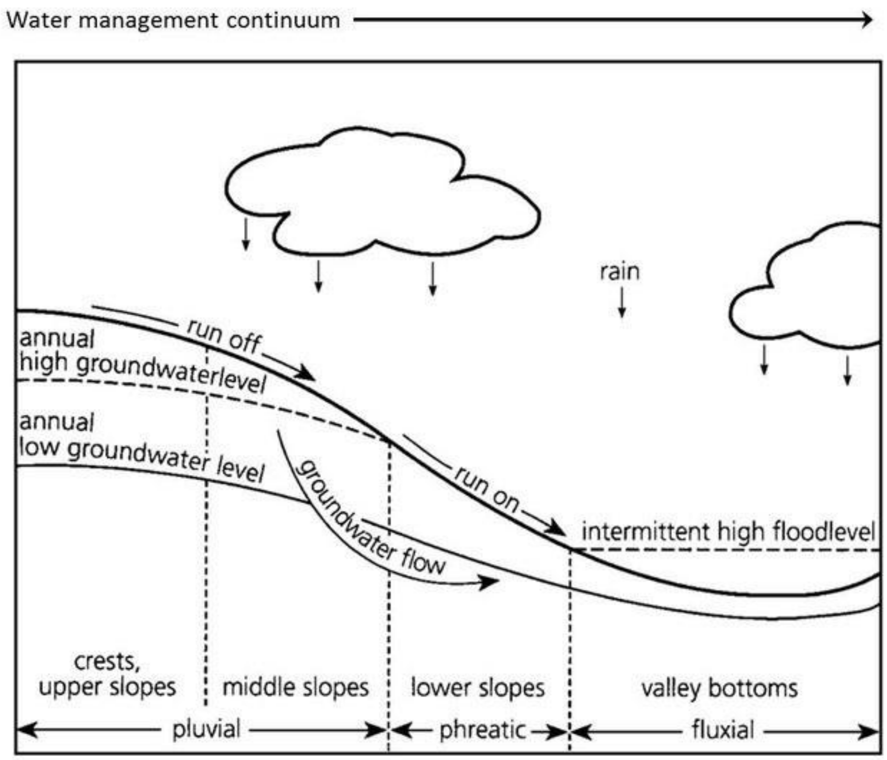

Fig. 1. *Rice production in the inland valley watershed and floodplains continuum (modified from Windmeijer et al., 2002)*

Over the last three decades, Africa Rice Center (AfricaRice) in collaboration with its partners (Table S1) has conducted water management research to overcome the above-mentioned challenges related to water, reduce the yield gaps and ensure sustainable rice cultivation. Water management can be defined as human interventions to plan, develop, distribute and manage the surface and subterranean water for agricultural purposes to meet community objectives (Brooks, 2006). This paper focuses on the water management research for three major rice-growing environments: irrigated lowland, rainfed lowland, and rainfed upland. The main research topics addressed by AfricaRice and its partners are listed in Table 1. Although such accomplishments have been reported in a variety of publications, there is no comprehensive review of water management research for rice production in SSA. Aligning with this special issue on Sustainable productivity enhancement of rice-based farming systems in Africa, the focus of this review is on water-related constraints in SSA's rice-growing environments, and aims at sustainable water resources management and sustainable intensification of rice-based systems. Therefore, the objectives of this paper are to provide i) a synthesis of water management research achievements over the last 30 years (1990–2020) and (ii) perspectives for future research for development efforts in SSA. The paper is structured as follows. Firstly, we review research made on the constraints related to water management for rice cultivation in the major rice-growing environments.

Secondly, we review selected water management technologies developed over the last 30 years. At the end of this paper, we present the limitations and research gaps in the past studies and perspectives for future research.

Table 1. *Major research topics related to water resources and management and period of their implementation by Africa Rice Center and its partners in irrigated lowland (IL), rainfed lowland (RL), and rainfed upland (RU) rice-growing environments in sub-Saharan Africa*

Period	**Topic**	**Rice- growing environment**	**Reference**
1990 – 2003	Characterization of salinity stress in the Sahelian irrigated systems, and development of technologies for coping with this stress	IL	Raes et al. (1995), Ceuppens et al. (1997), Wopereis et al. (1998), Ceuppens and Wopereis (1999), Haefele et al. (1999), Asch and Wopereis (2001), Boivin et al. (2002), van Asten et al. (2002, 2003)
1991 – 2012	Agro-ecological characterization of inland valleys	RL	Andriesse et al. (1994), van Duivenbooden et al. (1997), Windmeijer et al. (2002), Abe et al. (2010), Giertz et al. (2012)
1994 – 2021	Assessing the impact of water stresses and farmers' water management practices on crop performance through on-farm surveys	IL, RL, RU	Becker and Johnson (2001), Becker et al. (2002), Fashola et al. (2007), Mdemu et al. (2016), Tanaka et al. (2013, 2015, 2017), Niang et al. (2018), Asai et al. (2021)
1995 – 2019	Irrigation schemes performance assessment	IL	Lamin and Kamara (1997), Poussin et al. (2005), Borgia et al. (2013), Djagba et al. (2013), Poussin et al. (2015), Huat et al. (2019)
1995 – 2020	Development of technologies for reducing drought risk in rainfed uplands	RU	Becker and Johnson (1998a, 1999b), Akanvou et al. (2000), Totin et al. (2013), Dossou-Yovo et al. (2016), Onaga et al. (2020), Husson et al. (2022)
2000 – 2009	Assessment of the iron toxicity effects on rice yield	RL	Aboa and Dogbe (2006), Audeberg (2006a), Diatta and Sahrawat (2006), Dixon et al. (2006), Audeberg and Fofana (2009), Cherif et al. (2009)
2000 – 2021	Land and water development technologies in inland valleys	RL	Wopereis et al. (2009), Alarima et al. (2011, 2014), Oladele et al. (2011), Usman et al. (2014), Oladele and Wakatsuki (2010), Defoer et al. (2017), Tchetan (2019), Arouna and Akpa (2019), AfrocaRice (2021)
2005 – 2021	Water-saving technologies in irrigated systems	IL	de Vries et al. (2010), Krupnik et al. (2012a, b), Awio et al. (2015), Djaman et al. (2017), Blango et al. (2019), Dossou-Yovo and Saito (2021)
2010 – 2021	Mapping of suitable lowlands for sustainable land use and rice	IL, RL	Danvi et al. (2018), Djagba et al. (2018), Akpoti et al. (2020, 2021)

2 Constraints related to water management for rice production

Understanding the constraints related to water management for rice cultivation is critical to set priorities for research and target technologies (Becker et al., 2003). Various approaches have been used to have a better understanding of the water-related stresses to rice cultivation in SSA (Table 2). In irrigated systems, field surveys, interviews, and environmental modeling were used to evaluate the factors affecting rice yield and the results indicated that water scarcity is a major constraint to rice production (Wopereis et al., 1999; Poussin et al., 2005; Borgia et al., 2013; Totin et al., 2013; Djagba et al., 2014; Poussin et al., 2015. Tanaka et al. 2013, 2015, 2017). This was attributed to poor water control as observed in partially irrigated schemes compared to fully irrigated schemes (Becker and Johnson, 1999; Tanaka et al., 2017), lack of collective action for the adequate maintenance of irrigation infrastructures (Lamin and Kamara, 1997; Poussin et al., 2005, 2015; Borgia et al., 2013; Djagba et al., 2014), and unreliable water supply (Wopereis et al., 1999; Tanaka et al., 2015) resulting in low yield and large yield variability.

Field surveys and experiments were used to evaluate the factors affecting yield and yield variability in rainfed lowlands and uplands, and the results showed that drought spells at the beginning of the rainy season, violent rains during the season, and end of season drought led to water stress for rice plants (deficit or excess in water), resulting in low rice yield, and large yield variability between farmers' fields (Deville, 1994; Lamin and Kamara, 1997; Becker and Johnson, 2001; Worou et al., 2013; Tanaka et al., 2017; Niang et al., 2017; Niang et al., 2018). These constraints were also reported to limit the response of rice plants to fertilizer application (Worou et al., 2013; Niang et al., 2018; Asai et al., 2021). Most of the previous on-farm surveys on the rice-growing environments did not include direct measurement of surface water level and soil water availability and heavily relied on the visual score for surface water conditions (i.e., flooded, wet or dry soil surface) (Tanaka et al., 2017; Niang et al., 2018).

In SSA, iron toxicity is one of the major constraints preventing the growth of rice production (Becker and Asch, 2005; Sikirou et al., 2015, 2016, 2018; Senthilkumar et al., 2019). This phenomenon is ascribed to a nutritional disorder associated with a high concentration of ferrous iron (Fe^{++}) in the soil solution of poorly drained rice fields. Iron toxicity is commonly observed in rainfed lowland and irrigated rice systems (Audebert and Fofana, 2009). Field experiments were conducted in West Africa to evaluate the effects of iron toxicity on rice yield (Table 2), and the results showed mean yield reduction of 35 – 80% in Togo (Aboa and Dogbe, 2006), 16–78 % in Côte d'Ivoire, Guinea, and Ghana (Audebert, 2006a; Diatta and Sahrawat, 2006; Audebert and Fofana, 2009; Cherif et al., 2009), and 60 – 80% in Sierra Leone (Dixon et al., 2006) with the extent of the yield loss depending on rice cultivar, iron toxicity intensity and crop management strategy (water control and mineral fertilization).

Soil salinity and alkalinity, both soil constraints that can be related to water management, have been reported to affect rice production throughout the Sahelian zone, leading to the abandonment of rice area and yield loss (Bertrand et al., 1998; Wopereis et al., 1998; Ceuppens and Wopereis, 1999; Haefele et al., 1999; Barro et al., 2000; Asch and Wopereis, 2001; van Asten et al., 2002, 2003, 2005; Ibrahim et al., 2021). The strongest effects of salinity on yield were observed around panicle initiation, whereas plants recovered best from stress at the seedling stage (Asch and Wopereis, 2001). Floodwater electric conductivity (EC) lower than 2 mS cm−1 hardly affected rice yield, while for floodwater EC levels above 2 mS cm−1, a yield loss of up to 1 t ha−1 per unit EC (mS cm−1) was observed for salinity stress around panicle initiation (Asch and Wopereis, 2001). A rice yield decline due to soil salinity can be expected if the soil electric conductivity is higher than 0.8 dS m-1 in the 0 – 20 cm soil depth (Ceuppens and Wopereis, 1999). Regarding soil alkalinity, yield reduction of up to 75% was reported in the Senegal River Valley in Senegal, Tillabery region in Niger, and Foum Gleita scheme in Mauritania (Marlet et al., 1996; 1998).

Diagne et al. (2013b) used data from household interviews to evaluate the farmers' experiences of various constraints in rice-growing environments in 40 African countries and reported that drought, flooding, soil salinity/alkalinity, and iron toxicity were major constraints faced by farmers, affecting 32 – 37% of their rice area and leading to 27 – 32% of rice yield reduction.

Mapping and crop modeling approaches were used by Haefele et al. (2014) and van Oort (2018) to evaluate the abiotic constraints to rice production at the African continent level. According to Haefele et al. (2014), drought-prone soils (with low soil water holding capacity) are a major constraint to rice production after low nutrient soils. Maps produced by van Oort (2018) showed that 20–33, 12, and 2% of Africa's total rice area, were potentially affected by drought, iron toxicity, and soil salinity/alkalinity, respectively.

Due to low rice production, high demand for rice, and the existence of exploitable rainfed lowland areas (e.g., inland valleys), rice harvested area has been expanding (FAOSTAT, 2021). To the best of our knowledge, there is no publication, describing lowland rice area expansion over years through household surveys except for one paper (Komatsu et al., 2022). Komatsu et al. (2022) conducted a survey in 2000 and a follow-up survey in 2020 around the city of Bouaké in Côte d'Ivoire and reported that rice production increased by an average of 89% over the 20 years and that 25 % and 64% of this increase were attributed to the increase in yields and the cropped area, respectively. However, this study did not assess the impact of such rice area expansion on ecosystem services. Scenario analyses were performed by Duku et al. (2016) and Danvi et al. (2018) using the Soil and Water Assessment Tool (SWAT) model. The results showed that unplanned cropland expansion results in declining water resources and ecosystem services, which in return affect lowlands productivity. Duku et al. (2016) showed that streamflow in Benin's Upper Ouémé watershed could irrigate between 20,000 and 30,000 ha of rice fields in the dry season. However, much of the water availability is dependent on the conservation of the vast forest and woodlands in the watershed. The irrigation potential would be reduced by 15,000 to 20,000 ha if these regions were lost. Danvi et al. (2018) investigated the effects of rice intensification on water availability in inland valleys of Central Benin and reported that bund construction would increase water availability but nitrogen application at the recommended level would have a limited effect.

***Table 2**. Main water-related constraints in irrigated lowland (IL), rainfed lowland (RL), and rainfed upland (RU) rice-growing environments in sub-Saharan Africa*

Main constraints	**Main causes of the constraints**	**Research approach**	**Countries**	**Rice-growing environment**	**References**
Drought and flooding	Low rainfall and its poor distribution, poor drainage, and/or sandy soils	Field surveys and experiments	Benin, Burkina Faso, Cameroon, Chad, Côte d'Ivoire, Democratic Republic of Congo, Ethiopia, The Gambia, Ghana, Guinea, Madagascar, Mali, Niger, Nigeria, Sierra Leone, Tanzania, Togo	RL, RU	Deville (1994), Lamin and Kamara (1997), Becker and Johnson (2001), Tanaka et al. (2017), Niang et al. (2018), Asai et al. (2021)
Drought, flooding, salinity, iron toxicity	NA	Interviews	40 countries*	IL, RL, RU	Diagne et al. (2013b)
Iron toxicity	High iron concentration in soil solution	Field experiment	Côte d'Ivoire, Ghana, Guinea, Sierra Leone, Togo	RL	Aboa and Dogbe (2006), Audebert (2006a), Audebert and Fofana (2009), Diatta and Sahrawat (2006), Dixon et al. (2006), Cherif et al. (2009)
Soil alkalinity	Alkaline soil, irrigation water, or groundwater table	Field experiments, field surveys	Niger	IL	Marlet et al. (1996, 1998); Wopereis et al. (1998); van Asten et al. (2005)
Soil salinity	Saline soil, irrigation water, or groundwater table	Field surveys and on-station experiments	Benin, Burkina Faso, Mali, Mauritania, Senegal	IL	Bertrand et al. (1998); Wopereis et al. (1998); Ceuppens and Wopereis (1999); Barro et al. (2000); Asch and Wopereis (2001); van Asten et al. (2002, 2003)

Water scarcity	Unreliable water supply	Field surveys, interview, environmental modeling	Benin, Burkina Faso, Cameroon, Côte d'Ivoire, Ghana, Mali, Mauritania, Niger, Rwanda, Senegal, Togo and Uganda	IL	Wopereis et al. (1999), Poussin et al. (2005); Borgia et al. (2013); Totin et al. (2013); Djagba et al. (2014), Poussin et al. (2015), Tanaka et al. (2013, 2015, 2017)
Drought	Decrease in rainfall combined with an increase in air temperature	Mapping	Burkina Faso, Mali and Nigeria	RL	Dossou-Yovo et al. (2019)
Drought	Low water-holding capacity soil and climate stress	Mapping and crop modeling	Africa	RL, RU	Haefele et al. (2014), Van Oort (2018)
Iron toxicity	High iron concentration soil	Mapping	Africa	NA	Van Oort (2018)
Soil salinity	High sodium concentration soil	Mapping	Africa	NA	Van Oort (2018)
A decline in water resources and ecosystem services	Unplanned cropland expansion in lowlands	Field surveys, and water resources modeling	Benin	RL	Deville (1994), Duku et al. (2016), Danvi et al. (2018)

NA: Data not available
IL, RL, and RU are irrigated lowland, rainfed lowland, and rainfed upland, respectively.
*The 40 countries covered in the study by Diagne et al. (2013b) were Algeria, Angola, Benin, Burkina Faso, Burundi, Cameroon, Central African Republic, Chad, Comoros, Côte d'Ivoire, Democratic Republic of Congo, Egypt, Ethiopia, Gabon, Ghana, Guinea, Guinea-Bissau, Kenya, Liberia, Madagascar, Malawi, Mali, Mauritania, Morocco, Mozambique, Niger, Nigeria, Rwanda, Senegal, Sierra Leone, Somalia, South Africa, Sudan, Tanzania, The Gambia, Togo, Uganda, Zambia, and Zimbabwe.

The above studies were conducted in different locations with different approaches for assessing different indicators (yield, water resources) (Komatsu et al., 2021; Duku et al., 2016; Danvi et al., 2018). Further research is needed to assess the effects of rice area expansion and intensification practices on water resources and ecosystem services.

In SSA, where water scarcity is a major driver for low rice yields, the development and expansion of large-scale irrigation schemes have long been emphasized as a solution to intensify agricultural production, support rural economic development, and enhance resilience to climate variability and change (Aw and Diemer, 2005). Various projects were initiated since the early twentieth century by building dams and associated surface water canal irrigation infrastructure. After more than 30 years, impact assessment studies suggested that most of the irrigation schemes were sub-optimally used due to poor water governance, land tenure policy, management practices, and market functioning and limited crop diversification opportunities, and access to credit (Djagba et al., 2014; Lamin et al., 1994; Poussin et al., 2005, 2015; Borgia et al., 2013; Huat et al., 2019).

3 Water management practices for sustainable rice cultivation

In this section, we review water management technologies developed by AfricaRice and its partners to overcome the challenges presented in the previous section and enhance sustainable rice cultivation. These are in the decreasing order of number studies: (i) improving water control and increasing rice yield in inland valleys; (ii) reducing drought risk in rainfed upland; 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 (Fig. 2).

3.1 Water management technologies for improving water control and increasing rice yield in inland valleys

Several studies were implemented to develop, evaluate and adapt water management technologies to improve water control and increase rice yield in inland valleys of SSA. In 1993, AfricaRice brought together collaborators from 17 African countries and launched the Inland Valley Consortium (IVC), which aimed to identify and develop technologies for the long-term use of IV agro-ecosystems, both for intensification and diversification. Various studies were conducted by the IVC, including the agro-ecological characterization of IVs (Andriesse et al., 1994; van Duivenbooden et al., 1997; Windmeijer et al., 2002; Abe et al., 2010; Giertz et al., 2012), and design and assessment of the effects of land and water development technologies on rice yield (Becker and Johnson, 2001; Touré et al., 2009; Wopereis et al., 2009). Based on IVs characterization works and testing and evaluation of technologies such as bunding (Becker and Johnson, 2001), the Participatory Learning and Action Research (PLAR) for Integrated Rice Management (IRM) (PLAR-IRM) has been developed (Table 3). PLAR-IRM is a bottom-up social learning process to promote technological change through improving farmers' capacity to exchange knowledge, experiences, and practices, take appropriate decisions, and get organized for action (Wopereis et al., 2007). A technical manual (Wopereis et al., 2007) and a facilitators' guide (Defoer et al., 2004) containing modules on water, crop, and pest management issues were developed on this approach. Many of the management practices discussed throughout the manual and the facilitator guide contribute directly (through modules on infrastructures for better water management such as contour bunds, water-retention dikes, diversion barriers, and canal systems) or indirectly (through modules on the field preparation) to improved water management. Experience in Madagascar demonstrates that PLAR-IRM can contribute to better water control through field bunding, and land leveling and raise rice yields in inland valley systems (Defoer and Wopereis, 2013). Based on these results, the Kindai University, Japan and AfricaRice introduced and evaluated the Sawah technology in West Africa through the Japanese-funded Smart-IV project (AfricaRice, 2015).

Sawah is an Asian rice cultivation technology that involves leveled fields and improved bunding with inlet and outlet for irrigation and drainage to achieve full water control and continuous flooding (Table 3). On-farm demonstrations and pilot studies were conducted to evaluate the agronomic, and economic performances of the Sawah system as well as its potential for adoption (Oladele and Wakatsuki, 2010; Alarima et al., 2011; Oladele et al., 2011; Igwe and Wakatsuki, 2012; Nwite et al., 2012; Alarima et al., 2013; Usman et al., 2014, Schmitter et al., 2015). The key findings are summarized in Table 4. Overall, the Sawah system increased rice yield (Oladele and Wakatsuki, 2010; Igwe and Wakatsuki, 2012; Usman et al., 2014; Schmitter et al., 2015), improved the soil chemical properties (Nwite et al., 2012), reduced soil erosion (Igwe and Wakatsuki, 2012), and increased the profitability of rice cultivation (Raufu, 2014). The major constraints to Sawah adoption were 1) the scarcity of power tillers for land preparation, 2) shortfalls in skills for site selection, 3) limited knowledge about bunding and dykes construction, and 4) the overall complexity of water management (Alarima et al., 2011). The determinants of Sawah adoption include farmer's age, educational level, year of experience in rice production, contact with extension agents, attendance in previous Sawah training, and land tenure arrangement (Oladele et al., 2011; Alarima et al., 2013).

Despite the positive effects of the Sawah system on rice yield, and farmers revenue, the scaling potential of the system was very limited because an important requirement in the selection of inland valleys for Sawah system development was the availability of a permanent and significant water source that can be tapped to irrigate fields. However, only limited inland valleys are endowed with permanent water resources in West Africa (AfricaRice, 2015). As a result, AfricaRice and partners developed a new approach called "Smart-Valleys", which can be applied in IVs where full water control is not possible (AfricaRice, 2015).

Table 3. *Water management technologies developed or evaluated by Africa Rice Center and its partners in irrigated lowland (IL), rainfed lowland (RL), and rainfed upland (RU) in Sub-Saharan Africa*

Technology	**Characteristics**	**Application domains**	**References**
Bund	Small dikes around the rice field	IL, RL	Becker and Johnson (2001), Toure et al. (2009)
Contour bund	Small dikes made of soil material, built in the valley bottom following the contour lines	IL, RL	Windmeijer et al. (2002)
Water retention dikes	Dikes that are constructed perpendicular across the valley bottom	IL, RL	Windmeijer et al. (2002)
Diversion barriers	Concrete construction to dam up the water, and direct water into peripheral canals to divert it to sides of the valley bottom	IL, RL	Windmeijer et al. (2002)
Interception canal system	Widening and deepening the central drain and constructing peripheral canals along the sides of the valley bottom	IL, RL	Windmeijer et al. (2002)
Artificial lake	Small dam to create an artificial lake and use water for irrigation in part of the valley bottom downstream of the dam	IL, RL	Windmeijer et al. (2002)
Participatory Learning and Action Research (PLAR)	A participatory approach to improve farmers' crop and water management, stimulating farmer experimentation, and identifying researchable issues	IL, RL	Defoer and Budelman (2000), Defoer et al. (2004), Defoer and Wopereis (2013)
Sawah	A rice-growing method that involves bunding, land leveling, and puddling to achieve complete water control and continuous flooding in the fields	RL	Wakatsuki et al. (2009)
System of rice intensification	Line transplanting of single young seedlings at wide spacing, mechanical weed control, alternate wetting and drying irrigation, and the application of organic soil fertility amendments	IL	Krupnik et al. (2012 a, b)
Alternate wetting and drying (AWD) / intermittent irrigation	Use of field water tube or soil tensiometer to monitor the water level in rice fields, and irrigate when soil water drops below a threshold or a soil water potential	IL	De Vries et al. (2010), Djaman et al. (2017), Blango et al. (2019), Dossou-Yovo and Saito (2021)
Smart-Valleys	Low cost and participatory approach for water control in inland valleys	RL	Defoer et al. (2017)

Mulching	Application of crop residue on the soil surface to increase soil moisture	RU	Becker and Johnson (1998a, 1999b); Akanvou et al. (2000), Totin et al. (2013), Dossou-Yovo et al. (2016)
Conservation agriculture	Reduced or no mechanical soil disturbance, permanent soil cover (consisting of a field or a dead mulch of crop residues), and diversified crop rotation	RU	Bruelle et al. (2015, 2017), Rodenburg et al. (2020)
Supplemental irrigation	Addition of limited amounts of water to essentially rainfed crops to improve and stabilize yields when rainfall fails to provide sufficient moisture for normal plant growth	RU	Onaga et al. (2020)
Suitable lowlands mapping for rice-based systems	Machine learning approach to identify suitable inland valleys and irrigated lowlands for expansion of rice cultivation with ecosystem services preserved	IL, RL	Djagba et al. (2018), Akpoti et al. (2020), Akpoti et al. (2021)
Leaching	The fraction of the irrigation water that is percolated out of the bottom of the root zone to prevent soil salinity from rising above some specifiable level	IL	Ceuppens et al. (1997), Ceuppens and Wopereis (1999)
Flushing	Washing away the surface accumulated salts by flushing water over the surface	IL	West Africa Rice Development Association (1996), Raes et al. (1995)

Table 4. *Agronomic and economic performances, and determinants of adoption of the Sawah and Smart-Valleys approaches for land and water development in inland valleys in Sub-Saharan Africa*

References	Country	Objective	Key findings
Sawah			
Usman et al. (2014)	Nigeria	To assess the effects of the Sawah system on rice yield compared to the traditional farmers' cultivation practices	Sawah increased farmers' yield on average by 55% compared to farmers' cultivation practices.
Nwite et al. (2012)	Nigeria	To evaluate the effects of Sawah, and soil amendment (rice husk; rice husk ash; poultry droppings at 10 t/ha and NPK 20:10:10 at 400 kg/ha) on soil chemical properties and rice yield	Sawah increased soil pH, organic carbon, and total nitrogen, while the amendment improved pH, total nitrogen, and cation exchange capacity. The highest rice yield (7.5 t/ha) was achieved with Sawah amended with poultry dropping.

Igwe and Wakatsuki (2012)	Nigeria, Ghana	To evaluate the effects of Sawah on soil degradation and rice yield	Sawah can improve input efficiency, and when the Sawah system has been integrated into improved agronomic practices, such as the system of rice intensification, paddy yields have increased from a low value of 2 t/ha through to 4 t/ha. Moreover, Sawah rice production has achieved stability of soil degradation, reducing regular soil erosion to within the soil loss tolerance limit that ensures sustainable production.
Raufu (2014)	Nigeria	To assess the economic performance of rice production under Sawah system	Rice production under Sawah system is profitable through the cost and return analysis. The gross ratio (total cost/total revenue) is 0.149 indicating that for every USD$ 0.149 expended there is the total revenue of USD$ 1.00. Rice production under Sawah was related to farming experience, fixed cost, farm size, cost of labour and fertilizer, and age of the respondents.
Alarima et al. (2011)	Nigeria	To assess the constraints for Sawah adoption in rice-growing environments	Major constraints were related to technology and mechanization particularly nonavailability of power tiller, unavailability of technical guidance on the use of power tiller, lack of skill for seed and site selection, lack of knowledge about weed management, lack of knowledge about bunding and dykes construction, and complexity of water management
Alarima et al. (2013)	Ghana	To assess the determinants of adoption of the Sawah system	Age, educational level, year of experience in rice production, contact with extension agents, attendance in previous Sawah training, land tenure arrangement, the yield from Sawah farm, and attributes of Sawah technology
Oladele et al. (2011)	Nigeria, Ghana	To explore the linkages among land tenure, investment, and adoption of Sawah rice production technology	Land tenure rights were the main determinants of continuous adoption and sustained profit from Sawah technology.
Oladele and Wakatsuki (2010)	Nigeria, Ghana	To synthesize the experiences from the development and dissemination of Sawah rice eco-technology	Sawah increases yield, improves the efficiency of fertilizer, improves nitrogen fixation by soil microbes and algae, increases the use of wetlands, improves soil organic matter accumulation, suppresses weed growth, and enhances the immune mechanism of rice through nutrient supply. In Ghana, Sawah increased rice yield from 1.4 t/ha to 4.8 t/ha while in Nigeria from 2001 to

			2009, the number of Sawah adopters increased from 3 to 1000 farmers on a total area of 200 ha.
Smart-Valleys			
Tchetan (2019)	Benin	To evaluate the effects of Smart-Valleys on rice yield and farmers income	Smart-Valleys increased rice yield by 90% and doubled the gross margin (difference between gross revenue and total costs).
Arouna and Akpa (2019)	Benin,To go	To evaluate the determinants of adoption and impacts of Smart-Valleys approach	The determinants of the Smart-Valleys approach were land tenure, total available area, paddy price, and production in the lowland. Adoption of Smart-Valleys approach increased rice yield by 0.9 t/ha and farmers net income by $USD 267/ha.
AfricaRice (2020)	Liberia, Sierra Leone	To evaluate the determinants of adoption and impacts of Smart-Valleys approach	The determinants of adoption of the Smart-Valleys adoption were the household size and education level, access to extension services, membership to an association, the secure land tenure system, total farm area available, use of fertilizer, and availability of tractor for land preparation. Adoption of the Smart-Valleys approach increased farmers' yield by 2.4 t/ha and income by $US 1157.

Smart-Valleys is a low-cost participatory bottom-up approach for land and water development in IVs (Table 3). The approach consists of three phases: selection, development, and management of IVs (Fig. 3). The approach begins with a site selection process, which includes an exploration to identify potential sites based on rice value in the local area, land tenure, market opportunity, physical accessibility, and soil and water resources. If a site is deemed suitable, development starts with farmer meetings to coordinate cooperative lowland development. Working with field technicians, and following the land topography, farmers collectively design and construct a system of drainage canals, irrigation infrastructure, and bunded and leveled fields — thereby improving water control. The third phase of the approach (management of the Smart-Valleys) entails farmers maintaining, adapting, and extending the Smart-Valleys site to achieve long-term performance (Fig. 3) (For more information on the Smart-Valleys approach, see Defoer et al., 2017). The agronomic and economic performances, as well as the determinants of adoption and impacts of the Smart-Valleys approach, were evaluated in various sites in West Africa (Arouna and Akpa, 2019; Tchetan, 2019; AfricaRice, 2020) (Table 4). From 2012 to 2020, the Smart-Valleys approach has been adopted by 14,027 rice farmers on 241 sites covering a total area of 1615 ha in six West African countries: Benin, Burkina Faso, Liberia, Sierra Leone, Benin, and Togo. Dissemination of the Smart-Valleys approach was achieved through demonstration sites development by field technicians and lead farmers in the early phases of the Smart-Valleys introduction, while ongoing expansion (scaling out) was achieved by scaling partners (AfricaRice, 2020). Adoption of the Smart-Valleys approach increased farmers' yield by 0.9 – 2.4 t/ha and farmers net income by 267 – 1157 $US (Table 4). Enabling conditions for the large-scale adoption of the Smart-Valleys approach included securing land tenure rights, strengthening farmers' capacity, availability of power tiller for land preparation and fertilizer, and higher paddy market price (Table 4). Policy briefs were developed to communicate the findings with the Smart-Valleys approach to policymakers and encourage the inclusion of the approach in national rice development strategies of West African countries (AfricaRice, 2021).

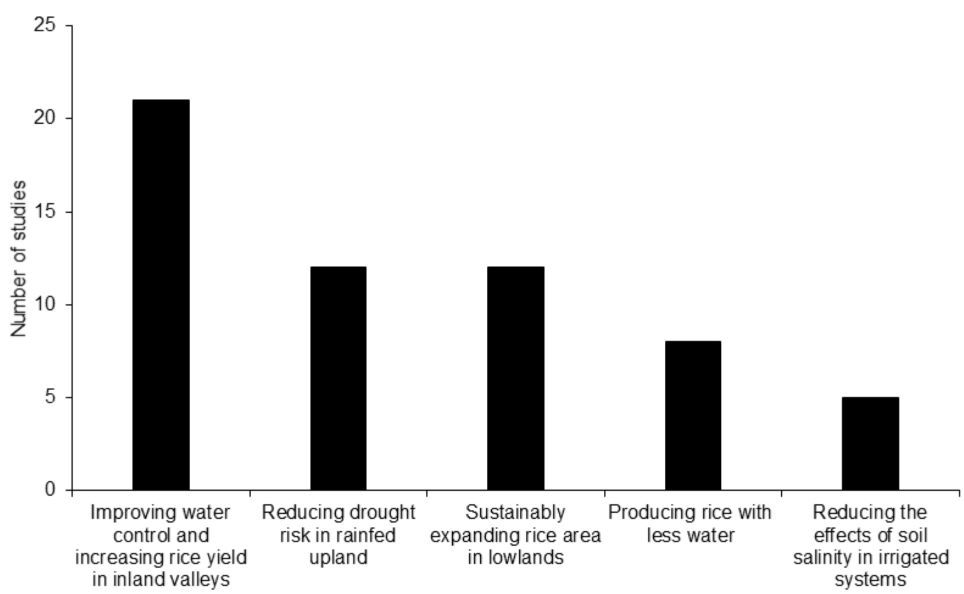

Fig. 2. *Number of studies for sustainable rice cultivation conducted by AfricaRice and its partners disaggregated per topic*

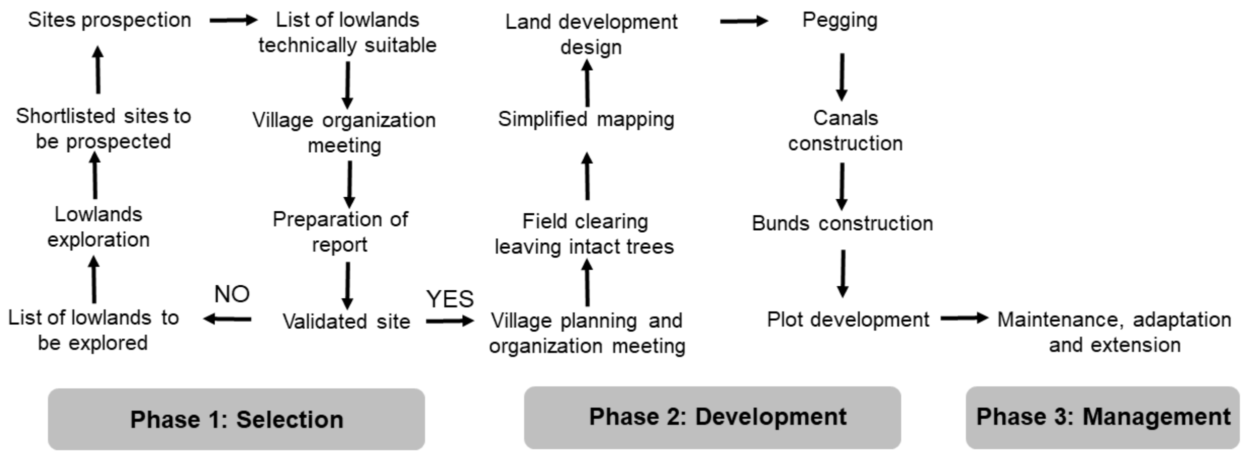

Fig. 3. *Diagram of the low-cost and participatory land and water development approach in inland valleys called Smart-Valleys. Source: Defoer et al. (2017)*

3.2 Reducing drought risk in rainfed upland

Mulching, supplemental irrigation, and conservation agriculture were evaluated by AfricaRice and its partners to mitigate the effects of drought on rainfed upland rice. Mulching is the method of covering the soil surface around plants with an organic or synthetic mulch to minimize evapotranspiration and create favorable conditions for plant growth (Table 3) (Kader et al., 2017). In several agro-ecological zones of West Africa, mulching was reported to increase soil moisture, soil water infiltration, and rice yield, and reduce yield loss under drought conditions (Becker and Johnson 1998a, 1999b; Akanvou et al., 2000; Totin et al., 2013; Dossou-Yovo et al., 2016).

Supplemental irrigation during dry spells of the rainy season can enhance the productivity of rice (Table 3). In Uganda, Onaga et al. (2020) reported that supplemental irrigation of 20 mm of water using sprinklers every five days during windows of dry weather starting from panicle initiation stage significantly increased rice yield by 37%, fertilizer use efficiency by 54%, and profitability of rice cultivation by 32%.

Conservation agriculture is based on three principles: reduced or no mechanical soil disturbance, permanent soil cover (consisting of living vegetation or a mulch of dead vegetation or crop residues), and diversified crop rotation (Table 3) (Kassam et al., 2014). Bruelle et al. (2015, 2017) recorded higher and more stable upland rice yields in regions of Madagascar with unpredictable and inconsistent rainfall under CA due to reduced soil temperature oscillations, and improved water penetration, and soil water availability. However, Rodenburg et al. (2020) reported increased rice yield, but decreased maize yield under CA practices in rice – maize rotation system in Madagascar, suggesting that the results with CA may be cropping system-specific. Husson et al. (2022) reported that when water stress occurred, rice yields under CA systems were higher than under conventional tillage systems in Bouaké, Côte d'Ivoire.

3.3 Sustainable cropland expansion in lowlands with limited effects on ecosystem services

Meeting rice demand in SSA will require yield gap closure and sustainable rice expansion (van Oort et al., 2015). Areas with the highest potential for rice development coupled with the lowest risks for negative impacts on biodiversity and ecosystem services should be exploited for rice expansion on a priority basis (Rodenburg et al., 2014). Most of the lands with the highest potential for rice development are in the irrigated and rainfed lowlands (van Oort et al., 2017). Spatially detailed and context-specific assessments are required to identify the high potential land for rice development (Akpoti et al., 2019). Two main approaches were used by AfricaRice and its partners to identify the high potential lowlands for rice development: the deductive approach and the inductive approach (Table 7) (Akpoti et al., 2019). The deductive approach, generally termed as traditional or multi-criteria evaluation, relied on the qualitative evaluation of the societal benefits of different land uses (Akpoti et al., 2019). Earlier assessments of the IVs potential for rice development in West Africa were made using the deductive method and biophysical factors (Andriesse and Fresco, 1991; Andriesse et al., 1994; Thenkabail and Nolte, 1995), biophysical and socio-economic factors (Boateng, 2005; Olaleye et al., 2008; Obalum et al., 2011; Danvi et al., 2016), or biophysical, socio-economic, technical, and eco-environmental factors (Gumma et al., 2009). At the field level, the deductive method performed well for land suitability mapping, but it failed to capture the most important predictors at a broad scale (country and continental level assessment). Besides, the deductive approach is based on factor ratings determined using experts' opinions. This frequently generates a bias in the assessment, particularly when a significant number of variables is considered (Akpoti et al., 2019). The recent use of the inductive technique for lowland suitability assessment for rice cultivation helped to address the limitations of the deductive approach through the deployment of machine learning algorithms.

Machine learning (ML) is based on geospatial modeling, which simulates landscape conditions by connecting landscape attributes spatially. This approach helps in the selection of critical environmental and socio-economic factors that affect land suitability for rice cultivation. The capacity to handle huge spatial datasets and a large number of predictors with growing data complexity is a benefit of ML techniques (Crisci et al., 2012). Djagba et al. (2018) and Akpoti et al. (2020, 2021) used machine learning models on datasets containing more than 30 biophysical and socioeconomic characteristics to identify high-potential rice expansion areas in rainfed and irrigated lowlands in West African countries (Table 7). According to Akpoti et al. (2020), achieving rice self-sufficiency in Togo and Benin would require the cultivation of 54 and 60% of suitable IVs, respectively. Thus, in Togo and Benin, respectively, 66 and 40% of appropriate IVs areas can be safeguarded for their significant ecosystem services. These findings showed how machine learning can be used to select high-potential inland valleys for rice development to attain rice self-sufficiency while protecting ecosystem services.

Table 5. *Papers on water-saving technologies in irrigated rice systems in sub-Saharan Africa and their effects on yield, total water use and water productivity*

Source	Country	Season [a]	Control [b]	Treatment [c]	Yield control (t/ha)	Yield treatment (t/ha)	WU[d] control (mm)	WU treatment (mm)	WP[e] control (kg/m^3)	WP treatment (kg/m^3)
de Vries et al. (2010)	Senegal	DS	CF	AWD	10.4	9.0 (-15)	1218	940 (-21)	0.9	1.0 (8)
		DS	CF	AWD-flooded	10.4	9.4 (-10)	1218	1030 (-15)	0.9	1.0 (9)
		DS	CF	Flooded-AWD	10.4	9.3 (-10)	1218	997 (-17)	0.9	1.0 (12)
		WS	CF	AWD	3.9	3.0 (-22)	1065	595 (-43)	0.3	0.3 (8)
		WS	CF	AWD-flooded	3.9	4.8 (23)	1065	720 (-30)	0.3	0.5 (69)
		WS	CF	Flooded-AWD	3.9	5.1 (31)	1065	680 (-35)	0.3	0.6 (87)
		DS	CF Weedy	Flooded - AWD Weedy	3.0	4.7 (57)	-	-	-	-
		DS	CF Weedy	AWD - flooded Weedy	3.0	0.2 (-93)	-	-	-	-
		DS	CF Weedy	AWD Weedy	3.0	0.2 (-93)	-	-	-	-
		WS	CF Weedy	Flooded - AWD Weedy	2.7	3.4 (58)	-	-	-	-
		WS	CF Weedy	AWD - flooded Weedy	2.7	3.0 (1)	-	-	-	-
		WS	CF Weedy	AWD Weedy	2.7	1.6 (-53)	-	-	-	-
Krupnik et al. (2012a)	Senegal	DS	RMP Weed-free	SRI Weed-free	6.7	6.4 (-5)	1329	1023 (-23)	0.5	0.6 (23)
		WS	RMP Weed-free	SRI Weed-free	5.7	5.8 (2)	835	579 (-31)	0.7	1.1 (53)
		DS	RMP Weedy	SRI Weedy	3.7	2.5 (-32)	1338	1054 (-21)	0.3	0.2 (-13)
		WS	RMP Weedy	SRI Weedy	4.7	3.3 (-31)	840	545 (-35)	0.6	0.7 (10)
		WS	RMP	SRI	5.2	5.0 (-5)	930	750 (-19)	0.6	0.7 (18)
		DS	RMP	SRI	4.9	5.0 (2)	1292	854 (-32)	0.4	0.6 (56)
Krupnik et al. (2012b)	Senegal	WS	RMPF0S0	SRIF0S0	3.7	3.3 (-9)	1004	803 (-20)	0.4	0.4 (14)
		WS	RMPF0S0	SRIF0S1	3.7	3.6 (-1)	1004	RMPF0S0	0.4	0.5 (24)
		WS	RMPF0S0	SRIF1S0	3.7	6.0 (63)	1004	803 (-20)	0.4	0.7 (104)
		WS	RMPF0S0	SRIF1S1	3.7	6.5 (78)	1004	803 (-20)	0.4	0.8 (123)

		DS	RMPF0S0	SRIF0S0	3.0	2.8 (-7)	1449	907 (-37)	0.2	0.3 (49)
		DS	RMPF0S0	SRIF0S1	3.0	3.2 (8)	1449	907 (-37)	0.2	0.4 (73)
		DS	RMPF0S0	SRIF1S0	3.0	6.2 (110)	1449	907 (-37)	0.2	0.7 (236)
		DS	RMPF0S0	SRIF1S1	2.95	7.4 (151)	1449	907 (-37)	0.2	0.8 (301)
Djaman et al. (2017)	Senegal	DS	CF	AWD 30	7.7	8.1 (5)	1148	855 (-26)	0.7	0.9 (41)
		WS	CF	AWD 30	6.6	6.3 (-3)	908	824 (-9)	0.7	0.8 (7)
		DS	CF	AWD 60	7.7	7.2 (-7)	1148	705 (-39)	0.7	1.0 (51)
		WS	CF	AWD 60	6.6	5.3 (-20)	908	760 (-16)	0.7	0.7 (-4)
Blango et al. (2019)	Sierra Leone	DS	CF-B	ARS+B	3.4	3.6 (6)	1659	1600 (-4)	0.2	0.2 (10)
		DS	CF-B	ARS-B	3.4	3.3 (-3)	1659	1571 (-5)	0.2	0.2 (2)
		DS	CF-B	AWD+B	3.4	3.1 (-9)	1659	1378 (-17)	0.2	0.2 (10)
		DS	CF-B	AWD-B	3.4	2.7 (-21)	1659	1102 (-34)	0.2	0.2 (20)
		DS	CF-B	CF+B	3.4	3.7 (9)	1659	1138 (-31)	0.2	0.3 (59)
		WS	CF-B	ARS+B	2.1	2.3 (10)	1355	1314 (-3)	0.2	0.2 (13)
		WS	CF-B	ARS-B	2.1	2.2 (5)	1355	1294 (-4)	0.2	0.2 (10)
		WS	CF-B	AWD+B	2.1	2.4 (14)	1355	1455 (7)	0.2	0.2 (6)
		WS	CF-B	AWD-B	2.1	1.9 (-10)	1355	1310 (-3)	0.2	0.1 (-6)
		WS	CF-B	CF+B	2.1	2.8 (33)	1355	1333 (-2)	0.2	0.2 (35)
Dossou-Yovo and Saito (2021)	Cote d'Ivoire	DS	CF	Safe AWD	5.9	5.6 (-6)	899	686 (-24)	0.7	0.8 (23)

[a] DS: dry season; WS: wet season

[b] Control treatments are CF: continuous flooding; CF Weedy: continuous flooding under weedy condition; RMP Weed-free: recommended management practice under weed-free condition; RMP Weedy: recommended management practice under weedy condition; RMP: recommended management practice; RMPF0S0: recommended management practices without fertilizer and without rice straw; CF-B: continuous flooding without biochar addition.

[c] Alternative treatments are: AWD: alternate wetting and drying applied throughout the season; AWD-flooded: treatment that starts as AWD and changes to continuous flooding; Flooded-AWD: treatment that starts as continuous flooding and changes to AWD; Flooded-AWD Weedy: treatment that starts as continuous flooding and changes to AWD under weedy condition; AWD-flooded Weedy: treatment that starts as AWD and changes to continuous flooding under weedy condition; AWD weedy: alternate wetting and drying applied throughout the season under weedy condition; SRI Weed-free: system of rice intensification under weed-free condition; SRI Weedy: system of rice intensification under weedy condition; SRI: system of rice intensification; SRIF0S0: system of rice intensification without fertilizer and without rice straw; SRIF0S1: system of rice intensification without fertilizer and with rice straw; SRIF1S0: system of rice intensification with fertilizer and without rice straw; SRIF1S1: system of rice intensification with fertilizer and with rice straw; AWD 30: AWD applied when the soil water potential

reaches 30 kPa; AWD 60: AWD applied when the soil water potential reaches 60 kPa; ARS+B: aerobic rice with biochar; ARS-B: aerobic rice without biochar; AWD+B: alternate wetting and drying + biochar; AWD-B: alternate wetting and drying without biochar; CF+B: continuous flooding + biochar; Safe AWD: safe alternate wetting and drying

[d] WU: total water use (irrigation and rainfall)

[e] WP: Water productivity

Values in brackets denote relative deviations of the parameter (yield, water use or water productivity) of treatment from control: Deviation (%) = (Parameter value treatment/Parameter value control) – 1) × 100.

Table 6*. Water-saving technologies effects on weed biomass in irrigated rice systems in sub-Saharan Africa*

Source	Country	Site	Season [a]	Control [b]	Water treatment [c]	Weed biomass control (g/m^2)	Weed biomass treatment (g/m^2)
Krupnik et al. (2012a)	Senegal	Delta	DS	RMP Weedy	SRI Weedy	419	457 (9)
		Delta	WS	RMP Weedy	SRI Weedy	323	520 (61)
		River Valley	DS	RMP Weedy	SRI Weedy	300	324 (8)
		River Valley	WS	RMP Weedy	SRI Weedy	71	147 (107)
Dossou-Yovo and Saito (2021)	Cote d'Ivoire	Lokapkli	DS	CF	Safe AWD	221	153 (-31)
		Mbe	DS	CF	Safe AWD	196	114 (-42)

Values in brackets denote relative weed biomass deviations of treatment from control: Deviation (%) = (Weed biomass treatment/Weed biomass control) – 1) × 100.

[a] DS: dry season; WS: wet season

[b] RMP Weedy: recommended management practices under weedy conditions; CF: continuous flooding

[c] SRI Weedy: system of rice intensification under weedy conditions; Safe AWD: safe alternate wetting and drying

Table 7. *Main approaches, and indicators used for irrigated (IL) and rainfed (RL) lowlands suitability assessment for rice cultivation in sub-Saharan Africa*

Method	**References**	**Indicators**	**Rice-growing environment**
Deductive approach			
	Andriesse and Fresco (1991) Andriesse et al. (1994) Thenkabail and Nolte (1995)	• Biophysical factors: soil properties, landscape, climate, and reconnaissance survey	RL
	Gumma et al. (2009)	• Biophysical factors: climate, soil properties, topography	RL

		• Technical factors: agronomic experience in rice cultivation, water management, nutrient management, and soil fertility management • Socio-economic factors: accessibility to road, market, land tenure, labour force, access to credit, gender, policy • Eco-environmental factors: diseases (malaria, bilharzia, onchocerciasis), and species of conservation significance	
	Boateng (2005)	• Biophysical factors: soil, climate, hydrology, slope	RL
	Olaleye et al. (2008)	• Socio-economic factors: road network, market center	
	Danvi et al. (2016)	• Biophysical factors: climate, soil, landscape	RL
	Obalum et al. (2011)	• Biophysical factors: soil properties	RL
Inductive approach			
	Djagba et al. (2018)	• Biophysical factors: climate, soil properties, hydrology, topography • Socio-economic factors: demography, market, accessibility, sociology	RL
	Akpoti et al. (2020)	• Biophysical factors: climate, soil, hydrology, land use • Socio-economic factors: population density, travel time to cities, distance to road network	RL
	Akpoti et al. (2021)	• Biophysical factors: climate, soil, hydrology, land use	IL

RL and IL are rainfed lowland and irrigated lowland, respectively

3.4 Water management for producing rice with less water

Alternate wetting and drying (AWD) and the system of rice intensification (SRI) were evaluated by AfricaRice and partners to produce rice with less water in the irrigated systems (Table 5). AWD is a water-saving technology that enables irrigated rice cultivation with less water than the conventional practice of maintaining the field continuously flooded. Under AWD, fields are subjected to intermittent flooding where irrigation is interrupted, and water is allowed to subside until the soil reaches a certain moisture level, after which the field is re-flooded (Bouman et al., 2007). Different thresholds were used to irrigate the rice fields under AWD in West Africa such as when the soil water drops below 15 cm (Blango et al., 2019; Dossou-Yovo and Saito, 2021), the soil water potential reaches 30 KPa or 60 KPa (Djaman et al., 2017) or when the soil surface cracks, but reflooding should be done less than three times per week (de Vries et al., 2010). Different timings were also used to irrigate under AWD such as throughout the season, AWD until panicle initiation then flooding until maturity, and flooded until panicle initiation and then AWD (Table 5). Under weed-free conditions, AWD reduced water use by 15 – 43% and increased water productivity by 8 – 87% without significantly affecting rice yield in Senegal and Cote d'Ivoire compared to continuous flooding (de Vries et al., 2010; Djaman et al., 2017; Dossou-Yovo and Saito, 2021), except when AWD was applied throughout the season (de Vries et al., 2010), at the threshold of 60 KPa (Djaman et al., 2017) or when the irrigation scheduling started with AWD until panicle initiation and changed to continuous flooding (de Vries et al., 2010). However, under weedy conditions, AWD reduced rice yield by 53 – 93% compared to continuous flooding except for the treatment that started with continuous flooding until panicle initiation and changed to AWD (de Vries et al., 2010). These results indicated that AWD can achieve major savings of irrigation water in irrigated systems. However, important pre-conditions for farmers to achieve similar yields compared to continuous flooding are good weed control, the application of an irrigation regime that starts as flooded and then changes to AWD, and the use of a threshold of a soil water potential of 30 KPa or 15 cm below the soil surface for irrigating the rice field (Table 5). Regarding the suitable season for AWD application, Akpoti et al. (2021) showed that the whole dry season was suitable for AWD against 25 – 100% of the rainy season depending on the soil percolation in the irrigated schemes.

SRI includes transplanting young and single seedlings at wide spacing, rice straw mulching, and alternate wetting and drying irrigation. Under the weed-free condition, substantial field-level water savings and significant increases in water productivity were obtained with SRI compared to recommended farmers' practices with limited effect on the yield, through AWD practices in Senegal (Table 5). However, when subjected to weed competition, mean rice yield was significantly reduced in SRI compared to recommended farmers' practices fields (Table 5). Besides, SRI through AWD practices was reported to increase weed biomass under weedy conditions (Table 6). These results are however contradictory to the ones reported by Dossou-Yovo and Saito (2021) who observed lower weed biomass under AWD (Table 6). This discrepancy can be explained by the difference in the timing of irrigation in the two studies. In the SRI study, alternate wetting and drying was applied throughout the growing season (Krupnik et al., 2012a), while in AWD study, the fields were maintained flooded during the first 10 days after transplanting, and during the flowering stage (Dossou-Yovo and Saito, 2021). The early flooding of the field in the safe-AWD fields might have limited the establishment of weeds as many weed species will not germinate under anaerobic conditions (Rodenburg and Johnson, 2009). In the fourth and fifth of six seasons, Krupnik et al. (2012b) found higher rice yield under SRI compared to recommended management approaches, partly due to improved nitrogen recovery from both fertilizer and rice straw incorporation. This shows that resource-poor farmers unable to buy balanced N-P-K fertilizers who employ SRI could benefit from this fertility management method, but favorable effects may only appear after several seasons (Krupnik et al., 2012b).

3.5 Water management for mitigating the effects of soil salinity in irrigated systems

Leaching and flushing reduced the effects of soil salinity on rice yield in irrigated systems (Table 3). Salt can be reduced in irrigated systems by maintaining water ponded on the soil surface to temporarily transport salts downwards (leaching) and prevent the capillary rise of salt from the water table to the soil surface (Ceuppens and Wopereis, 1999). According to West Africa Rice Development Association (1996) and Raes et al. (1995), flushing combined with field drainage conducted two to three times during the growing season can be enough to significantly reduce the quantity of salt by 1.0 to 1.5 t/ha. However, these practices require a significant amount of water (on average 2,300 m^3/ha of water per hectare) (Raes et al., 1995), and may be difficult for farmers to apply in schemes where water is scarce. In such a case, Ceuppens et al. (1997) reported that increasing rice cropping intensity (double rice cropping) with field drainage can significantly reduce the soil salinity in irrigated rice fields.

4 Synthesis and perspectives for future research

This review shows that significant research-for-development efforts on water management have been undertaken by AfricaRice and its partners over the last 30 years to address the challenges of flooding, drought, water scarcity, iron toxicity, salinity, and unplanned cropland expansion leading to loss of ecosystem services in the major rice-growing environments. Despite these efforts and achievements, considerable challenges persist for the sustainable use of land and water resources for achieving food security with limited environmental impacts. In this section, we discussed the limitations and research gaps in the past studies and provided perspectives for future research.

- Most of the field experiments assessed a few indicators such as rice yield, water use, and water productivity only. However, beyond field experiments, water conditions (e.g., standing water level, groundwater level, soil water availability) were not measured in field surveys, resulting in mislinkage between crop simulation modeling, mapping, and field studies (Grotelüschen et al., 2021). There has been limited research on the cost-benefit, enabling conditions, business models for large-scale adoption, and impact of water management technologies on farmers' livelihoods particularly on women and youth.

Previous research reported that women and youth are especially vulnerable to climate change because of poverty, gender inequality, insecure land rights, a high reliance on rainfed agriculture, and a lack of access to education and information (Perez et al., 2015; Jost et al., 2016; Lawson et al., 2019; Rao et al., 2019). Collaborations among value chain stakeholders should be formed engaging development agents and policymakers to institutionalize out-scaling and stimulate spillover effects for large-scale dissemination (Tittonell et al., 2012; Makate, 2019; Woltering et al., 2019). Also, the engagement of the private sector with viable business models and pilot demonstrations is required to ensure long-term adoption of the technologies (Westermann et al., 2018; Minh et al., 2020; Rosenstock et al., 2020; Van Loon et al., 2020). Following the adoption of technologies, impact monitoring and assessment studies should be conducted to evaluate the progress over time and location and document their impact on farmers' livelihoods, as well as the enabling conditions, lessons learned, and then communicate to policymakers.

- Previous water management research has primarily focused on rice, with no consideration given to how to design water management to facilitate crop diversification. Crop diversification can contribute to improved nutrition and more stable farm household incomes (Sibhatu and Qaim, 2018). Low-cost land and water management technologies such as Smart-Valleys combined with solar irrigation can convert rainfed sites to irrigated sites, allowing for vegetable and legume cultivation in the lowlands during the dry season. Likewise, supplemental irrigation can be applied for off-season crop production. Further studies should examine the agronomic and economic performance of off-season crops (vegetables and legumes) under supplemental irrigation to promote off-season crops cultivation.
- Most of the water management technologies were applied only to the field level and not to the landscape level. Rice intensification in lowlands can have negative effects on ecosystem services such as water quality decline with impact on drinking water and recreational values, and reduced water quantity that can lead to loss of lowlands (MA, 2005). Some of the changes have negative feedback on the food and fiber production in lowlands systems, for example through reductions in pollinators and degradation of land beyond the field level (Bossio et al., 2010). It has also been reported that water management interventions upstream can harm downstream water resources through changes in water discharge and contamination (Deville, 1994). Conflicts in irrigation schemes frequently arise due inequitable land and water allocation, and leadership tensions (Kramm and Wirkus, 2010; Akuriba et al., 2020), resulting in a lack of collective action and poor irrigation scheme performance (Lamin et al., 1994; Poussin et al., 2005; Borgia et al., 2013; Poussin et al., 2015; Huat et al., 2019). Planning and managing water at the community and landscape levels can help mitigate conflicts and ensure sustainable water resources management. However, limited studies were conducted on water management at the community and landscape levels in SSA.

- The land suitability analyses for expansion of rainfed and irrigated lowlands rice (Akpoti et al., 2020, 2021) entailed large uncertainties. Lowland suitability studies conducted were based on the assumption that the current distribution of the cultivated lowlands represents the 'best bet' environments for rice. However, this is not always true since rice expansion has also occurred in marginal areas due to high population densities in many regions in SSA as reported by Seck et al. (2010), Dossou-Yovo et al. (2017), and Kim et al. (2021). Also, most of the land suitability assessment studies did not include predictors of varieties and crop management practices. The adoption of novel techniques and the introduction of new crop varieties may influence where rice is planted and introduce biases in the lowlands' suitability assessment mapping. Thus, efforts to introduce new spatial explicit predictors data related to technological adoptions and new varieties could improve the models' predictive power (Akpoti et al., 2020). Other limitations to machine learning approach for lowland suitability assessment include the quality of predictors. For instance, the climate and the soil-related covariates used are themselves model predictions with subsequent related limitations including under-sampled locations in Africa (Fick and Hijmans, 2017; Hengl et al., 2015; Hengl et al., 2017). Furthermore, the lowland suitability studies lacked the assessment of the models' uncertainties as well as the sensitivity to the predictors. Therefore, the models' results should be considered as a hypothesis to test and validate rather than findings for decision making.
- The maps of drought, iron toxicity, and soil salinity for the African continent require improvement. The maps by van Oort (2018) were biased in their allocation of rainfed and irrigated rice. Maps of total rice area were used, and these were multiplied by the country-specific fractions of irrigated lowland, rainfed lowland, rainfed upland and "other" (mainly mangrove) from Diagne et al. (2013a). Therefore, the study did not provide information on the spatial distribution of these stresses per rice-growing environment. This is especially an issue for those stresses that are strongly tied to specific rice-growing environments such as drought in rainfed upland, iron toxicity in poorly drained lowlands, and salinity in irrigated systems. Also, the mapping studies did not include groundwater data which is an important determinant in the occurrence of stresses such as drought, flooding, iron toxicity, and soil salinity. The resolution of soil data used (250 m) was also too coarse to identify soil properties as important predictors of drought occurrence in lowlands (Dossou-Yovo et al., 2019). Further mapping studies should include high-resolution groundwater and soil data and should be conducted for the major rice-growing environments. Besides, there is currently no continent-wide flood risk mapping available to assist the most affected farmers with flood coping technologies.
- There are currently no long-term studies on the effects of water management practices such as AWD on soil fertility, soil salinity, and weed infestation, as well as the incentives for farmers to use water-saving technologies in the irrigated schemes of SSA.
- Rice fields in irrigated systems have been identified as major sources of methane emission as they evolve under anaerobic conditions (Liang et al., 2016). In SSA, irrigated rice

contributed to about 40% of the total rice production (FAOSTAT, 2021), and previous studies reported that achieving rice self-sufficiency in the region requires an increase in irrigated rice production (Saito et al., 2015; van Oort et al., 2015). The question is whether such an increase in irrigated rice production can occur without greater greenhouse gas emissions (van Ittersum et al., 2016). In Asia, water management technologies such as safe AWD were reported to reduce greenhouse gas emissions from rice fields (Jiang et al., 2019), while maintaining rice yield compared to continuous flooding (Carrijo et al., 2017). The effects of water management technologies on greenhouse gas emissions may be different in Africa compared to Asia due to differences in soil types, climatic conditions, and management practices that are reported to significantly impact greenhouse gas emissions (Kim et al., 2013; Borges et al., 2015; Dossou-Yovo et al., 2016; Kim et al., 2016; Rosenstock et al., 2016). However, in SSA, limited research exists on the effects of water management practices on greenhouse gas emissions and rice yield.

- Water governance, defined as the institutions, processes, procedures, rules, and regulations involved in water management, plays an important role in efficient, adequate, and equitable water allocation in irrigation schemes (Dirwai et al., 2019). Several studies have linked the poor irrigation scheme performance in SSA to poor water governance (Dittoh et al., 2013; Poussin et al., 2015; Venot and Hirvonen, 2013; Akuriba et al., 2020). However, as mentioned by Akuriba et al. (2020), little is known about the indicators for assessing water governance in irrigation schemes, and how these indicators are related to the irrigation schemes performance.
- Despite the potential for increasing rice production by expanding rice cultivation areas in the lowlands, iron toxicity is common, resulting in low rice yields (Audebert and Fofana 2009, Cherif et al., 2009). Previous studies conducted by AfricaRice and its partners focused on the evaluation of varieties tolerant to iron toxicity and nutrient management (Camara, 2006; Diatta and Sahrawat, 2006; Dixon et al., 2006; Gridley et al., 2006; Jusu et al., 2006; Lokossou, 2006; Sikirou et al., 2015, 2016, 2018). There has been limited investigation on the effects of water management technologies on iron toxicity mitigation in lowlands.
- Direct-seeded rice, which refers to the method of directly sowing seeds in the field rather than transplanting rice seedlings, has been advocated to minimize water requirements (Humphreys et al., 2010; Kumar and Ladha, 2011; Devkota et al., 2019, 2020). Reduced water requirement in direct-seeded rice compared to transplanted rice could be attributed to shorter crop growth duration and land preparation period, and lower water loss through seepage, percolation, and evaporation (Kumar and Ladha, 2011). The effects of direct-seeded rice versus transplanted rice on grain yield in Asia, on the other hand, were inconclusive and were reported to vary according to management practices, soil type, and climate conditions (Xu et al., 2019). Direct-seeded rice may have a different effect on water use and rice yield in Africa than in Asia due to poor crop establishment, land leveling, water control, weed management, inappropriate use of herbicide, and limited availability

of trained direct-seeded rice service providers and technicians in Africa (Touré et al., 2009; Tanaka et al., 2013, 2017; Niang et al., 2017, 2018; Rodenburg et al., 2019). To be adopted in SSA, direct-seeded rice may need to be adapted to the local context, and the incentives, roles, and responsibilities of the various organizations working with farmers and farming communities should be identified. However, little is known about the effects of direct-seeded rice on rice yield and water productivity in SSA, as well as the appropriate domains and enabling conditions for its promotion, and this requires further research.

- Although mulching and conservation agriculture have the potential to increase soil water use and mitigate the effects of drought on the rainfed crop, they can result in lower rice yields in the short term due to nitrogen immobilization, necessitating more nitrogen fertilizer to compensate for the temporary nitrogen loss (Becker et al., 2007). Other studies, however, reported additive nitrogen, phosphorus, and potassium uptake with a sustained application of rice straw, which may positively affect rice yield in the long term (Eagle et al., 2000; Yadvinder-Singh et al., 2005; Krupnik et al., 2012b). Furthermore, the scarcity of crop residues is a significant barrier to mulching or conservation agriculture adoption in many farming situations (Giller et al., 2009). Mulching with crop residues can alter resource flow in farms, where crop residues are used for a variety of purposes (e.g. fodder, fuel, or construction material) (Dasappa, 2011; Valbuena et al., 2012, 2015). Besides, the typical farm sizes in SSA are small, and mulching materials are in short supply, making the reported application rates of 3 – 10 t/ha required to increase yield unrealistic. Mulch retention is not always possible, either. Farmers in some African countries, including Zimbabwe and Mozambique, have complained that leaving crop residue as mulch attracts termites, which feed on the following crop, causing lodging and yield loss, particularly in dry areas or during dry spells (Giller et al., 2009; Sumberg and Thompson, 2012). In the humid and sub-humid climatic zones, the water-conserving effect of mulching can be detrimental when it exacerbates poor drainage, and water-logging conditions, or when it inhibits the necessary warming up of the soil especially in cooler environments (Erenstein, 2003). Further study is required for a critical assessment of the ecological and socio-economic conditions in which mulching or conservation agriculture are best suited for enhancing farmers' resilience to climatic stresses in Africa. Filling the research gaps identified in this study could contribute to sustainable water resources management and sustainable intensification of rice-based systems in SSA.

5 Conclusions

This study reviewed water management research for rice cultivation in SSA. Water-related stresses are a major driver for low rice yields and large yield gaps. A wide range of technologies has been tested by AfricaRice and its partners for their potential to address some of the water-related challenges across SSA. However, most of the research assessed a few indicators such as rice yield, water use, water productivity at the field level. There has been limited research on the cost-benefit of water management technologies, enabling conditions, and business models for their large-scale adoption, as well as their impact on farmers' livelihoods, particularly on women and youth. Besides, limited research was conducted on water management design for crop diversification, landscape-level water management, and iron toxicity mitigation, particularly in lowlands. Filling these research gaps could contribute to sustainable water resources management and sustainable intensification of rice-based systems in SSA.

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Supplementary information

Table S.1: *AfricaRice partners involved in development and validation of water management technologies in sub-Saharan Africa*

Partners*	**Country**	**Technologies**
Bonn University	Germany	Bunding, mulching, inland valley mapping for sustainable rice development
CARI	Liberia	Smart-Valleys
CIMMYT	Bangladesh	SRI
CIRAD	France	Conservation agriculture, mulching
CNRA	Côte d'Ivoire	Conservation agriculture
CSIR - SRI	Ghana	Sawah
Forschungszentrum Jülich GmbH	Germany	Mulching
IER	Mali	Inland valley mapping for sustainable rice development
INERA	Burkina Faso	Smart-Valleys
INRAB	Benin	Smart-Valleys, inland valley mapping for sustainable rice development
IRD	Senegal	Soil salinity control
IRRI	Philippines	Bunding
ISRA	Senegal	AWD, soil salinity control
ITRA	Togo	Smart-Valleys

IWMI	Ghana	Inland valley, irrigation scheme mapping for sustainable rice development
Kinki University	Japan	Sawah
SLARI	Sierra Leone	Smart-Valleys, inland valley mapping for sustainable rice development
UAC	Benin	Mulching, inland valley mapping for sustainable rice development
UENR	Ghana	Inland valley mapping for sustainable rice development
University of Nebraska-Lincoln	USA	AWD
WUR	Netherlands	AWD, mulching, inland valley mapping for sustainable rice development

[a] CARI: Central Agricultural Research Institute; CIMMYT: International Maize and Wheat Improvement Center; CIRAD: Centre de coopération internationale en recherche; CNRA: Centre National de Recherche Agronomique de Côte d'Ivoire; Council for Scientific and Industrial Research - Soil Research Institute (CSIR-SRI); IER: Institut d'Economie Rurale; INERA: Institut de l'Environnement et de Recherches Agricoles du Burkina Faso; INRAB: Institut National des Recherches Agricoles du Bénin; IRD: Institut de Recherche pour le Développement; IRRI: International Rice Research Institute; ISRA: Institut Sénégalais de Recherches Agricoles; ITRA: Institut Togolais de Recherche Agronomique; IWMI: International Water Management Institute; SLARI: Sierra Leone Agricultural Research Institute; UAC: Université d'Abomey Calavi; UENR: University of Energy and Natural Resources; WUR: Wageningen University & Research