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Effects of alternate wetting and drying irrigation on rice productivity in Burkina Faso

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Effects of alternate wetting and drying irrigation on rice productivity in Burkina Faso

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To,

my dear Mother,

for her love, support and self-sacrifice spirit

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Abstract

Irrigated systems play a critical role in meeting the growing demand for rice (*Oryza* sp.) and ensuring global food security. In semi-arid regions of West Africa, with emerging water scarcity driven by rapid population growth and climate change, producing more rice with less irrigation water is a major challenge. Among the available water-saving technologies, alternate wetting and drying (AWD) irrigation is most promising, yet poorly known by rice farmers in those regions. Moreover, it remains questionable whether AWD can simultaneously achieve the multiple goals of saving water, while increasing rice yields, improving farmer income, and enhancing nutrient use efficiencies. The present thesis explores this issue through four research objectives: (1) investigate farmers' perception of water scarcity in irrigated rice systems, and identify key strategies and determinants of their adoption; (2) quantify actual yields, yield gaps, and their variability, and assess trade-offs or synergies between productivity and resource (water and fertilizer) use efficiencies; (3) evaluate the impact of AWD on yield, water productivity and farmer income and identify cropping practices driving AWD-associated yield gains; and (4) assess the effect of AWD on fertilizer use efficiency and the bioavailability of key nutrients. Household socio-economic and field surveys and participatory on-farm trials comparing AWD and farmers' irrigation practices, were conducted in four contrasting irrigation schemes of Burkina Faso between 2018 and 2020. Four main results emerged.

(1) Nearly 80% of the smallholder farmers have experienced water scarcity in their irrigated rice fields during the past 5 years, and perceived access to irrigation water as a key limitation to rice production in the dry season. To cope with the adverse impacts of water scarcity, farmers implemented seven types of adaptation strategies. Most popular among those are “water conservation by field bunding”, “replacing dry-season rice with less water demanding upland crops”, and “shifting out of rice production”. Membership in farmer associations increased the likelihood of implementing multiple strategies. Female-headed households were less inclined to adopt multiple adaptation strategies.

(2) Dry-season rice was less productive than wet-season rice (3.7 Mg ha^{-1} vs. 5.3 Mg ha^{-1}) and showed higher yield variability (CV: 46% vs. 29%). The yield gap was slightly higher in the dry (36%) than in the wet seasons (31%). The main determinants of yield levels and yield variability were season-specific. While the number of seedlings per hill and the source of seeds were the most important crop management practices for improving yield and reducing the variability in wet-season rice, the split of N fertilizer applications and the soil dryness index were the most important in dry-season rice. High yields were associated with improved water productivity, and high N, P, and K use efficiencies.

(3) AWD reduced irrigation water inputs by 30% compared to the farmer's irrigation practice, while increasing grain yield by 6%. Consequently, AWD increased irrigation water productivity by 64% and profitability by 5% over farmers’ irrigation practices. The AWD-associated yield gains were highest under conditions of poor irrigation management, and when using *indica* varieties.

(4) AWD did not impair crop uptake and agronomic use and recovery efficiencies of N and P.

Overall, AWD can efficiently increase water productivity and serve as a profitable water-saving technology for sustainable rice production in dry climatic zones of West Africa. This study represents the first on-farm testing of AWD under different management and environmental conditions in the semi-arid zone of West Africa. Results suggest that achieving both high yields and resource-use efficiencies are not conflicting goals, but require a reshaping of rice irrigation practices, involving a systematic monitoring of field water levels. The large-scale diffusion of AWD could contribute to mitigating water scarcity in irrigated rice-based systems in dry climatic zones of West Africa, thereby enhancing rural livelihoods and food security.

Keywords: AWD, nutrient use efficiency, *Oryza* sp., water-saving technology, water scarcity.

Zusammenfassung

Alternierende Trocknung und Wiederbewässerung: Interaktionen zwischen Wasserverbrauch, Kornertrag und Nährstoffeffizienz im Reisanbau von Burkina Faso

Der Bewässerungsanbau spielt eine entscheidende Rolle bei der Deckung der wachsenden Reisnachfrage und der Gewährleistung der globalen Ernährungssicherheit. Die zunehmende Wasserknappheit bedingt, dass in den semiariden Regionen Westafrikas mehr Reis (*Oryza* sp.) mit weniger Bewässerungswasser produziert werden muss. Unter den verfügbaren wassersparenden Technologien ist die Bewässerung mit alternierenden Phasen der Bodenaustrocknung (AWD) die vielversprechendste, bei den Reisbauern in diesen Regionen jedoch kaum bekannt. Darüber hinaus ist unklar, ob AWD gleichzeitig die vielfältigen Ziele der Wassereinsparung bei gleichzeitiger Steigerung der Reiserträge, Verbesserung des Einkommens der Landwirte und Verbesserung der Nährstoffnutzungseffizienz erreichen kann. Die vorliegende Dissertation untersucht dieses Problem anhand von vier Forschungszielen: (1) Untersuchung der Wahrnehmung der Landwirte hinsichtlich der Wasserknappheit in bewässerten Reissystemen und Identifizierung von Schlüsselstrategien und Determinanten ihrer Anwendung; (2) Quantifizierung der tatsächlichen Erträge, der Ertragslücken und deren Variabilität sowie die Bestimmung möglicher Synergien zwischen Produktivität und Wasser-/Düngemitteleffizienz; (3) Bewertung der Auswirkungen von AWD auf Kornerträge, Wasserproduktivität und das Einkommen der Landwirte sowie Bestimmung der Anbaupraktiken die zu Ertragssteigerungen führen; und (4) Auswirkung von AWD auf die Effizienz des Düngemitteleinsatzes und die Bioverfügbarkeit von Nährstoffen. Zur Ansprache dieser Ziele wurden in sozioökonomischen Befragungen von Haushalten sowie in partizipatorischen Versuchen auf landwirtschaftlichen Betrieben AWD und die Bewässerungspraktiken der Landwirte in vier unterschiedlichen Bewässerungssystemen in Burkina Faso zwischen 2018 und 2020 verglichen. Daraus ergeben sich vier Hauptergebnisse.

(1) Fast 80% der Reisbauern waren in den letzten fünf Jahren von Wasserknappheit betroffen, wobei der Zugang zu Bewässerungswasser die Produktion vor allem in der Trockenzeit einschränkt. Um die negativen Auswirkungen der Wasserknappheit zu bewältigen, implementierten die Landwirte sieben Kategorien von Anpassungsstrategien. Am beliebtesten sind dabei „Wassersparen durch Eindeichung der Felder“, „Ersatz von Reis in der Trockenzeit durch Kulturen im Trockenfeldanbau“ und „Ausstieg aus der Reisproduktion“. Die Mitgliedschaft in Bauernverbänden erhöhte die Wahrscheinlichkeit, mehrere Strategien gleichzeitig einzusetzen. Von Frauen geführte Haushalte waren weniger geneigt, mehrere Anpassungsstrategien zu übernehmen.

(2) Reiserträge waren niedriger in der Trocken- als in der Regenzeit (3,7 Mg ha^{-1} vs. 5,3 Mg ha^{-1}) und zeigte eine höhere Ertragsvariabilität (CV: 46% vs. 29%). Die Ertragslücke („yield gap“) war höher in der Trockenzeit (36%) als in der Regenzeit (31%). Hauptdeterminanten der Ertragshöhe und der Ertragsvariabilität waren saisonabhängig. Während die Anzahl der Setzlinge und die Herkunft des Saatguts einen Großteil der Ertragsvariabilität in der Regenzeit erklärten, bestimmte die Aufteilung der N-Düngergabe und der Boden-trockenheitsindex hauptsächlich die Variabilität in der Trockenzeit. Hohe Erträge gingen mit einer verbesserten Wasserproduktivität und hoher N-, P- und K-Nutzungseffizienz einher.

(3) AWD reduzierte den Wassereinsatz um 30% im Vergleich zur Bewässerungspraxis der Landwirte, und dies ohne Ertragseinbußen. Infolgedessen steigerte AWD die Bewässerungswasserproduktivität um 64% und die Rentabilität um 5% im Vergleich zu den Bewässerungspraktiken der Landwirte. AWD-bedingte Ertragszuwächse waren unter Bedingungen schlechten Bewässerungsmanagements und bei der Verwendung von *indica*-Sorten am höchsten.

(4) AWD scheint weder die Aufnahme noch die die agronomische Nutzungseffizienz von Nährstoffen zu beeinträchtigen.

Insgesamt kann AWD die Wasserproduktivität effizient steigern und als profitable wassersparende Technologie für eine nachhaltige Reisproduktion in trockenen Klimazonen Westafrikas dienen. Bei den vorliegenden Untersuchungen handelt es sich um die ersten landwirtschaftlichen Studien von AWD unter Praxisbedingungen in der semiariden Zone Westafrikas. Die Ergebnisse deuten darauf hin, dass das Erzielen hoher Erträge und einer effizienten Ressourcennutzung keine widersprüchlichen Ziele sind. Sie erfordern allerdings eine Neugestaltung der Reisbewässerungspraktiken, einschließlich einer systematischen Überwachung der Feldwasserstände. Die verbreitete Nutzung und Anwendung von AWD könnte dazu beitragen, die Wasserknappheit in bewässerten Reissystemen in trockenen Klimazonen Westafrikas zu mildern und so zum Lebensunterhalt und zur Ernährungssicherheit im ländlichen Raum beizutragen.

Schlüsselworte: Nährstoffnutzungseffizienz, *Oryza sp.*, wassersparende Technologie, Wasserknappheit.

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Chapter 1: General introduction

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1.1. Context and problem statement

In the last century, global water consumption has been growing more than twice the rate of the world population, increasing the number of regions experiencing water scarcity (UN-Water & FAO, 2007). Water scarcity is defined as a lack of sufficient available water resources to meet the demands within a time frame and at a given place (e.g., country, region, and irrigation scheme), and under prevailing institutional arrangements and infrastructural conditions (UN-Water, 2021). It also refers to situations, where water demand exceeds the exploitable water resources. Competition for water, conflicts between users, over-extraction of groundwater, and reduced water flows are the most common warning signals of water scarcity (FAO, 2012). Demographic growth, poor land and crop management, as well as industrialization, put increasing pressure on available water resources, especially in drought-prone regions. Consequences of climate change, such as higher temperatures and erratic rainfall, have become widespread in recent decades, and exacerbate competing water demands (Seneviratne *et al.*, 2021). By 2025, over one-fifth of the worldwide population is expected to be living with absolute water scarcity (i.e., disposing of less than 500 m^3/person per year) (FAO, 2012). Sub-Saharan Africa (SSA) is the region with the largest number of water-stressed countries, with the Sudanian and the Sahelian climatic zones being the most vulnerable to water scarcity (UN-Water & FAO, 2007).

Producing 60% more food by 2050 to ensure global food security (Van Dijk *et al.*, 2021) with limited water resources and improving agricultural water productivity has become an urgent issue. Agriculture is the largest consumer of global freshwater, accounting for 72% of all water withdrawals (UN-Water, 2021). Rice (*Oryza spp.*), the most important food crop in many developing countries and a staple food consumed by more than half of the world's population (Mishra *et al.*, 2022), plays a crucial role in global food security. Irrigated lowland rice farming alone provides 75% of the world's rice supply (Global Rice Science Partnership, 2013). However, irrigated rice requires more water—about 40% of global irrigation water—than other staple crops (Surendran *et al.*, 2021) and is by far the largest consumer of freshwater (Tuong & Bouman, 2003). At the field level, irrigated rice typically requires two to three times more water than other major cereals such as wheat (*Triticum aestivum*) and maize (*Zea mays*), because rice fields are generally flooded from the transplanting to the harvest (Tuong & Bouman, 2003).

In many parts of SSA, rice is also a main staple food and the second most important source of calories, making a significant contribution to regional food security (Seck *et al.*, 2013). The expansion of rice cultivation has outpaced that of any other crop, and demand for rice in SSA is rising faster than anywhere else in the world (Arouna *et al.*, 2021b). Despite only 26% of SSA's rice being irrigated (Diagne *et al.*, 2013), irrigated lowland systems contribute most to regional rice production. However, the effects of water scarcity are not limited to upland systems but increasingly affect irrigated rice cultivation as well. Consequently, water scarcity seriously threatens rice-based livelihoods, particularly in the Sudanian and Sahelian climatic zones. Given the substantial water footprint of irrigated rice farming, there is a pressing need to develop and promote water-saving technologies that can either increase or sustain rice yields to ensure food security in the face of the growing scarcity of water resources.

1.2. State of the art regarding water-saving technologies in rice production

In response to the challenge of increasing both food production and resource- (water, nutrient) use efficiency under increasing scarcity of water resources, several water-saving technologies have been advocated (Surendran *et al.*, 2021). Strategies and technologies for reducing water inputs and increasing water productivity at the field level are based on key principles, including enhancing productivity, minimizing non-beneficial water depletions, reducing outflows, and maximizing the effective use of rainfall (Tuong *et al.*, 2005). Based on these principles, several water-saving technologies have been developed specifically for irrigated rice cultivation.

- *Transplanting in non-puddled soil*

Rice transplanting in non-puddled soil involves minimum tillage and planting rice seedlings directly into non-puddled soils using methods such as shallow beds, strip tillage on the flat, and zero tillage on the flat. This conservation practice reduces both the time and the water input required for land preparation and crop establishment, while providing similar rice yields compared to traditional puddling techniques (Haque *et al.*, 2016).

- *Direct seeding*

Direct seeding refers to establishing a rice crop from seeds sown directly in the field, rather than by transplanting seedlings from the nursery. The three principal methods of direct seeding of rice include dry seeding (sowing dry seeds into a prepared dry field), wet seeding (sowing pre-germinated seeds on a puddled wet soil surface), and water seeding (seeds sown into standing water) (Farooq *et al.*, 2011). Direct seeding reduces the significant amount of water required for land preparation, thereby decreasing overall water demand compared to the traditional transplanting system. However, it can lead to increased weed infestation and the severity of rice blast, resulting in substantial yield losses (Farooq *et al.*, 2011). Furthermore, direct seeding also presents significant drawbacks such as germination failure and higher seedling mortality (Rashid *et al.*, 2009).

- *Irrigated aerobic rice system*

The irrigated aerobic rice system is characterized by cultivating rice like an irrigated upland crop such as wheat or maize, in non-puddled, non-saturated and non-flooded soil, supplemented with irrigation if needed (Bouman *et al.*, 2005). Cultivating rice under aerobic conditions offers significant water-saving potential but at the expense of a severe yield penalty. Indeed, shifting from the traditional soil submergence regime to an aerobic system affects the bioavailability of macro- and micronutrients, such as N, P, Zn, Fe, Mn, and S (Gao *et al.*, 2006). Despite the lower yields experienced under aerobic conditions, water productivity may increase substantially, ranging from 32% to 88% compared to the traditional continuous submergence approach (Bouman *et al.*, 2005). Therefore, the irrigated aerobic rice system could serve as a viable alternative in drought-prone environments with limited water availability (Tuong *et al.*, 2005).

- *Saturated soil culture*

The saturated soil culture involves maintaining the soil at or near full saturation, using shallow irrigations to achieve a water layer of approximately 1 cm per day after the standing water has dissipated. Saturated soil culture reduced water inputs by 30-60% with a yield penalty of only 5% compared to the traditional continuous submergence practice in Central Luzon, The Philippines. This resulted in a 45% increase in water productivity (Tabbal *et al.*, 2002).

- *Raised-bed system*

The raised-bed system involves cultivating rice on raised beds with water-filled furrows between them, maintaining saturation. This approach reduces water inputs by 42% compared to the traditional continuous submergence regime, while resulting in a 17% decline in yield. Despite this reduction in yield, water productivity increases by 33% (Choudhury *et al.*, 2007; Tuong *et al.*, 2005).

- *Ground cover rice production system or mulching*

Ground cover rice production system or mulching involves covering the soil surface using crop residues such as straw or plastic film to enhance the plant growth by increasing the soil temperature in cold climates and to prevent soil evaporation. Ground cover rice production can reduce water input by 60–85% with relatively minor yield penalties (Tao *et al.*, 2006), or even result in an 18% yield increase under certain conditions (Liu *et al.*, 2013c) compared to traditional continuous submergence. Additionally, it helps control the germination and development of weeds (Tao *et al.*, 2015). However, this technology has the drawback of generating high methane (CH_4) emissions (Kreye *et al.*, 2007), and potentially environmental pollution by plastic residues (Gao *et al.*, 2019; Huang *et al.*, 2020).

- *Planting improved rice varieties*

Planting early maturing and high-yielding cultivars can substantially reduce crop duration and increase the average rice yield, thereby increasing water productivity (Singh *et al.*, 2021; Tuong & Bouman, 2003). Drought-tolerance, deep rooting pattern, higher harvest index, deep and thick root system, and high transpiration efficiency are desired traits for improving the performance of rice variety under limited water availability (Heredia *et al.*, 2022; Singh *et al.*, 2021).

- *Alternative irrigation systems and other modern technologies*

Pressurized irrigation systems, including furrow (Vories *et al.*, 2002), sprinkler (Kahlown *et al.*, 2007; Pinto *et al.*, 2020), and subsurface drip systems (Samoy-Pascual *et al.*, 2022), have the potential to increase irrigation water productivity by providing water to match phenological requirements, minimizing runoff and deep drainage losses, and generally keeping the soil drier, thereby reducing soil evaporation. Precision irrigation technologies, including sensor-based irrigation scheduling, automated water delivery systems, and remote monitoring, enable precise water management tailored to the specific needs of rice crops. Soil moisture sensors, weather stations, and crop models help optimize irrigation timing, duration, and volume, ensuring efficient water use while maximizing yield potential. In regions with controlled irrigation water, automating irrigation systems can address issues such as increased labour demand, weed infestation, and the risk of water stress (Champness *et al.*, 2023). However, despite being very efficient water-saving technologies, their large-scale diffusion in smallholder farms is constrained by high implementation costs, required advanced knowledge and skills, and socio-psychological barriers.

- *System of Rice Intensification (SRI)*

The System of Rice Intensification (SRI) is a set of crop management practices designed to optimize rice plant productivity, while minimizing water, chemical, and seed inputs. While adaptable to local agro-ecological and socioeconomic conditions (Stoop *et al.*, 2002), in its initial version developed by de Laulanié (1993) in Madagascar for lowland / irrigated rice, SRI is based on six key components: (i) transplanting young (8 to 12-day-old) seedlings, (ii) planting single seedlings per hill with minimal root disturbance, (iii) maintaining wide hill-spacing, (iv) providing water through intermittent submergence, (v) incorporating organic fertilizer, and (vi) frequent weeding, preferably performed using a rotary weeder. SRI generates substantial yield gains, while requiring less water than conventional rice cultivation (Stoop, 2011). Furthermore, it enhances soil fertility and mitigates the global warming effect of greenhouse gases (Thakur *et al.*, 2016). Despite its success, SRI adoption among smallholder farmers in Sub-Saharan Africa (SSA) remains limited due to high labour requirements and limited availability of organic fertilizer (Moser & Barrett, 2003).

- *Alternate wetting and drying irrigation (AWD)*

Developed in the 1970s by the International Rice Research Institute (IRRI) in collaboration with national agricultural research agencies, alternate wetting and drying irrigation (AWD) involves periodically allowing the soil to dry between irrigation events, rather than continuously maintaining soil under submergence (Bouman & Tuong, 2001). For this reason, it is also synonymous with intermittent irrigation. However, properly implementing AWD requires a perforated field water tube (**Figure 1.1**) enabling farmers to monitor the water table easily. It is guided by three basic key rules: (i) shallow flooding for 15 days after seeding or transplanting to enable seedlings to recover from the transplanting shock and to suppress weed emergence, (ii) maintaining a thin layer of 2 to 5 cm of ponded water one week before and one week after flowering, as this phase is very sensitive to water stress, and (iii) periodically introducing aerobic cycles during all other growing periods, allowing fields to dry down to a threshold water table depth before re-flooding (Ishfaq *et al.*, 2020; Lampayan *et al.*, 2015a). In practice, AWD irrigation is differentiated into two categories, according to either the soil water potential or the soil water table threshold: (i) alternate wetting and moderate soil drying, which involves re-irrigation when the water level reaches 15 cm below the soil surface (or soil water potential ≥ -20 kPa) (**Figure 1.2**); and (ii) alternate wetting and severe soil drying (AWD30), where re-irrigation occurs when the field water level drops below 15 cm and up to 30 cm below the soil surface (or soil water potential < -20 kPa) (He *et al.*, 2020a). Globally, alternate wetting and moderate soil drying irrigation, considered as "safe" AWD procedure, reduced the water input by 23% without yield penalty compared to continuous submerged soil practices (Carrijo *et al.*, 2017). Other potential benefits of AWD include: (i) improving grain quality by reducing total As (Das *et al.*, 2016) and Hg content in rice grains (Rothenberg *et al.*, 2016), (ii) reducing the emissions of greenhouse gases and thus the global warming effect (Linquist *et al.*, 2015), (iii) improving N use efficiency (Wang *et al.*, 2016), and (iv) reducing energy/fuel demand in case of irrigation by pumping (Lampayan *et al.*, 2015a).

On the basis of these potential benefits, alternate wetting and drying irrigation (AWD) has become one of the most prominent and widely recommended water-saving technologies in top rice-producing countries in Asia (Cheng *et al.*, 2022; Chu *et al.*, 2018), and America (Linquist *et al.*, 2015). In the semi-arid zones of West Africa, AWD is largely unknown to smallholder farmers (Johnson *et al.*, 2023a). Furthermore, while most studies confirm the water-saving ability and higher water productivity of AWD compared to the continuous submergence regime, conclusions on yields are highly variable and site-specific. Few studies reported an increase in yield with AWD (Liu *et al.*, 2013a; Maneepitak *et al.*, 2019), others presented a reduction (Islam *et al.*, 2018), while many others showed no yield penalty (Lampayan *et al.*, 2015b; Liao *et al.*, 2020). There are also potential drawbacks, including increased weed infestation (de Vries *et al.*, 2010) and reduced nutrient use efficiency, as well as decreased bioavailability of certain micronutrients (e.g., B, Cu, and Mn) due to the introduction of aerobic conditions (Ishfaq *et al.*, 2020). Moreover, it remains debatable whether AWD can achieve the multiple goals of saving water while increasing rice yield, farmer income, and nutrient use efficiencies in diverse edaphic and climatic environments. Before recommending AWD diffusion in SSA, testing by smallholder farmers and additional investigation are needed to address local socio-environmental conditions.

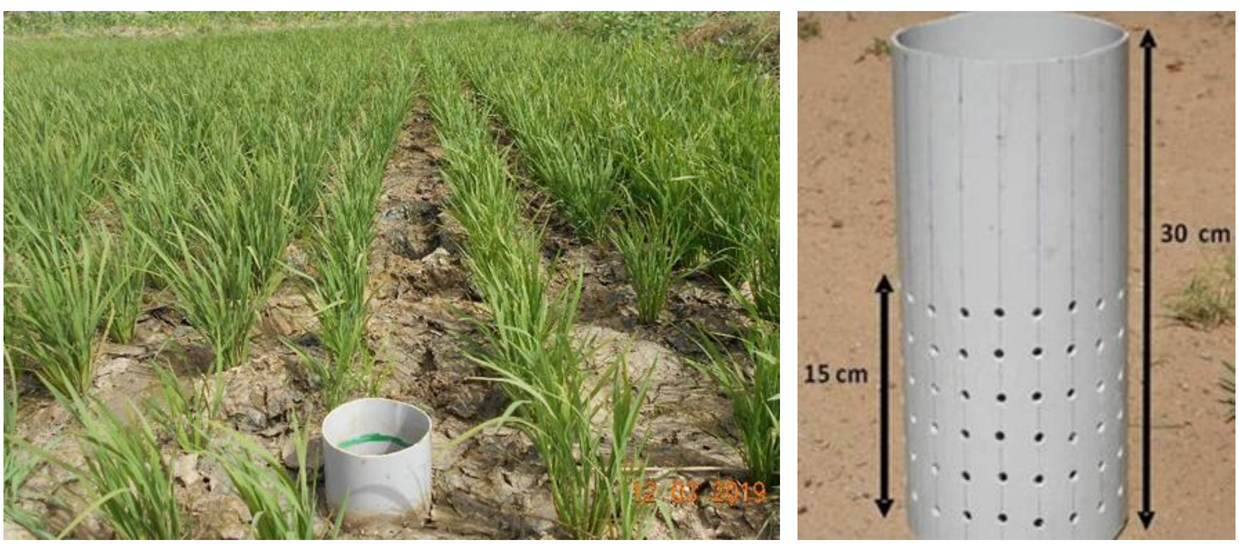


Figure 1.1. *Alternate wetting and drying tube (or perfected field water tube) in a rice field (Sourou Valley, Burkina Faso).*

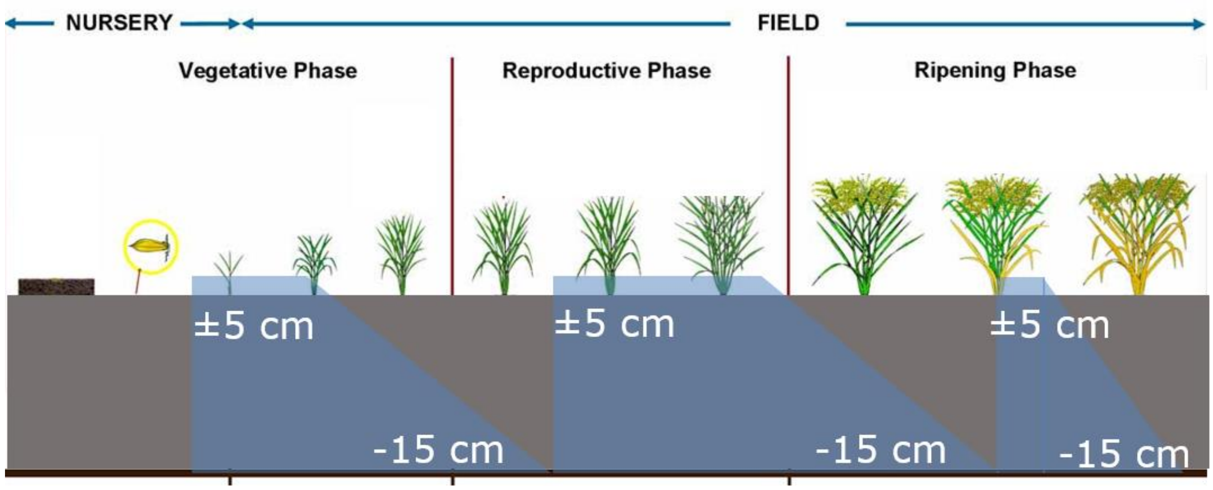


Figure 1.2. *Alternate wetting and moderate drying irrigation*

The blue shadows represent the field water level. Shallow flooding (2-5 cm) is applied for 15 days after transplanting. Then, periodic aerobic cycles are introduced, except during the flowering stage, allowing fields to dry down to a threshold water table depth of 15 cm before re-flooding.

1.3. Study area

This Ph.D. study was conducted in Burkina Faso (6°W and 3°E, 9°N and 15°N), a landlocked country in West Africa, highly vulnerable to adverse impacts of climate change as most Sahelian countries (The World Bank Group, 2011). The population of Burkina Faso is approximately 22.5 million people, mostly residing in rural areas and relying on agricultural activities for their livelihoods. Burkina Faso has experienced recurrent years of drought and severe water shortages, significantly affecting river discharge and groundwater tables (Mouhamed *et al.*, 2013). Over 42% of the population lives in water-scarce areas (https://worldwater.io/).

Burkina Faso is divided into three main climatic zones: The Sudanian zone (located above the isohyet 900 mm), the Sudano-Sahelian zone (between the isohyets 600 and 900 mm), and the Sahelian zone (below the isohyet 600 mm). Each climatic zone is characterized by an unimodal precipitation regime and experiences distinct wet and dry seasons, with the wet season extending over five months in the South and two months in the North (CILSS, 2016; MAHRH, 2011). Its croplands are characterized by low soil fertility, poor nutrient availability (Hengl *et al.*, 2021), and widespread soil degradation as reported in most Sahelian countries (Nachtergaele *et al.*, 2012; Niemeijer & Mazzucato, 2002).

Cereals are the main source of food calories and are produced mainly on smallholder farmland. In 2020, Burkina Faso (like most other Sahelian countries) depended on 10% of cereal imports and recorded a prevalence of undernourishment of nearly 20% (FAO, 2020). While being only the fourth most cultivated cereal after sorghum (*Sorghum bicolor*), maize (*Zea mays*), and pearl millet (*Pennisetum glaucum*) (FAO, 2020), rice (*Oryza spp.*) production area and particularly its per capita consumption of 41 kg $person^{-1}$ $year^{-1}$ (UN, 2021; USDA, 2024) have been rapidly increasing. There has been a progressive shift towards greater rice consumption due to economic growth and associated consumer preference for rice (Seck *et al.*, 2012). Over the past 25 years, this shift in diets, coupled with a sharp population increase (100%), has led to a substantial rise (470%) in rice consumption in Burkina Faso (**Figure 1.3**). In 2023, domestic production only covered 36% of the demand, while imports covered the remaining (**Figure 1.4**). Although significant achievements have been made in increasing domestic production (370%) over the past 25 years, it has primarily been driven by expanding the cultivating area (480%) rather than yield increase (-18%) (**Figure 1.5**). Similar trends are visible in most sub-Saharan African countries (Yuan *et al.*, 2024). This situation undermines food security and underscores the importance of benchmarking actual productivity and generating updated insights regarding drivers of yield variability to provide context-specific suggestions and recommendations for reducing variability and increasing yield in Burkina Faso.

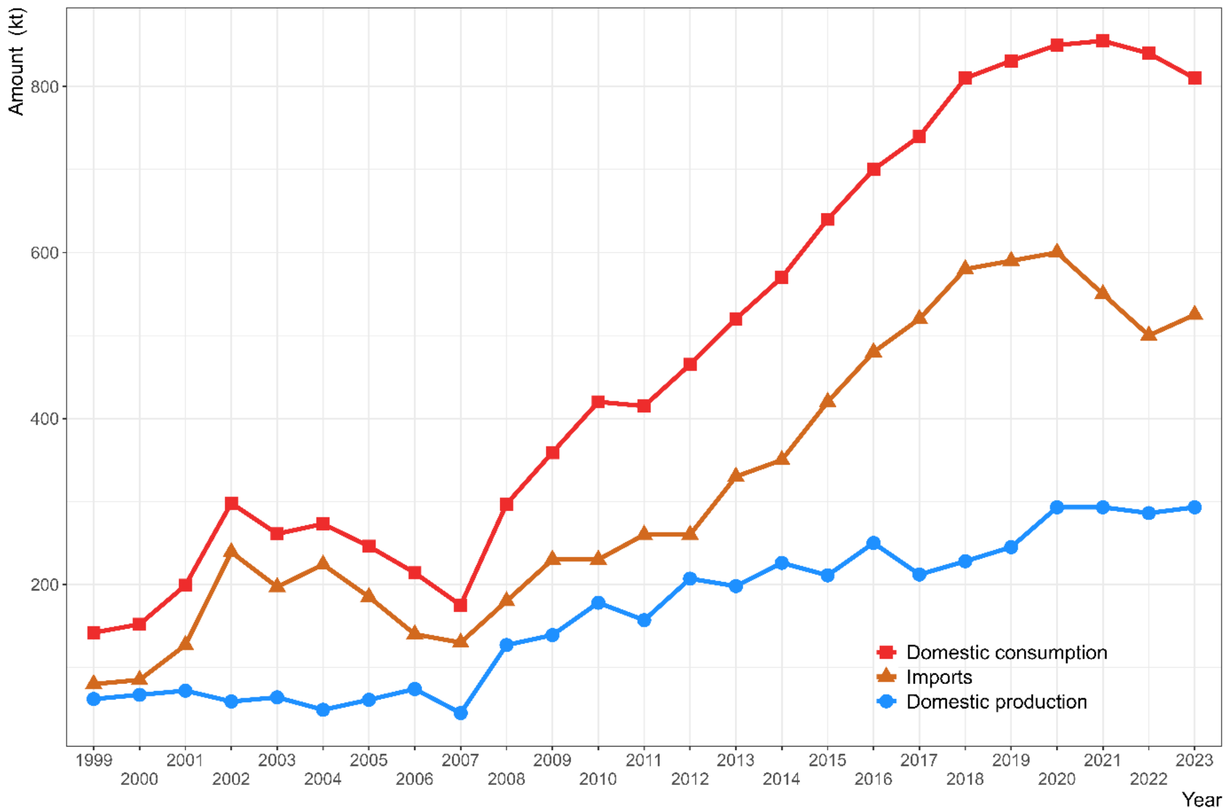


Figure 1.3. *Historical trends in rice production, domestic consumption, and imports in Burkina Faso over the past 25 years (1999-2023).*

The data reported are from the USDA (2024) database.

About 100,000 smallholder farmers in Burkina Faso engage in rice production, achieving an average grain yield of 2 Mg ha^{-1}. The predominant rice production systems include rainfed upland, rainfed lowland, and irrigated lowland. Burkina Faso has three primary rice-producing regions: The Western region, Bagré, and Boucle du Mouhoun. In 2009, irrigated lowland systems contributed over 50% of the country's total rice production, despite occupying only 23% of the rice land area (MAHRH, 2011). Irrigated rice is mostly cultivated in the Sudanian and Sudano-Sahelian zones (Akpoti *et al.*, 2021).

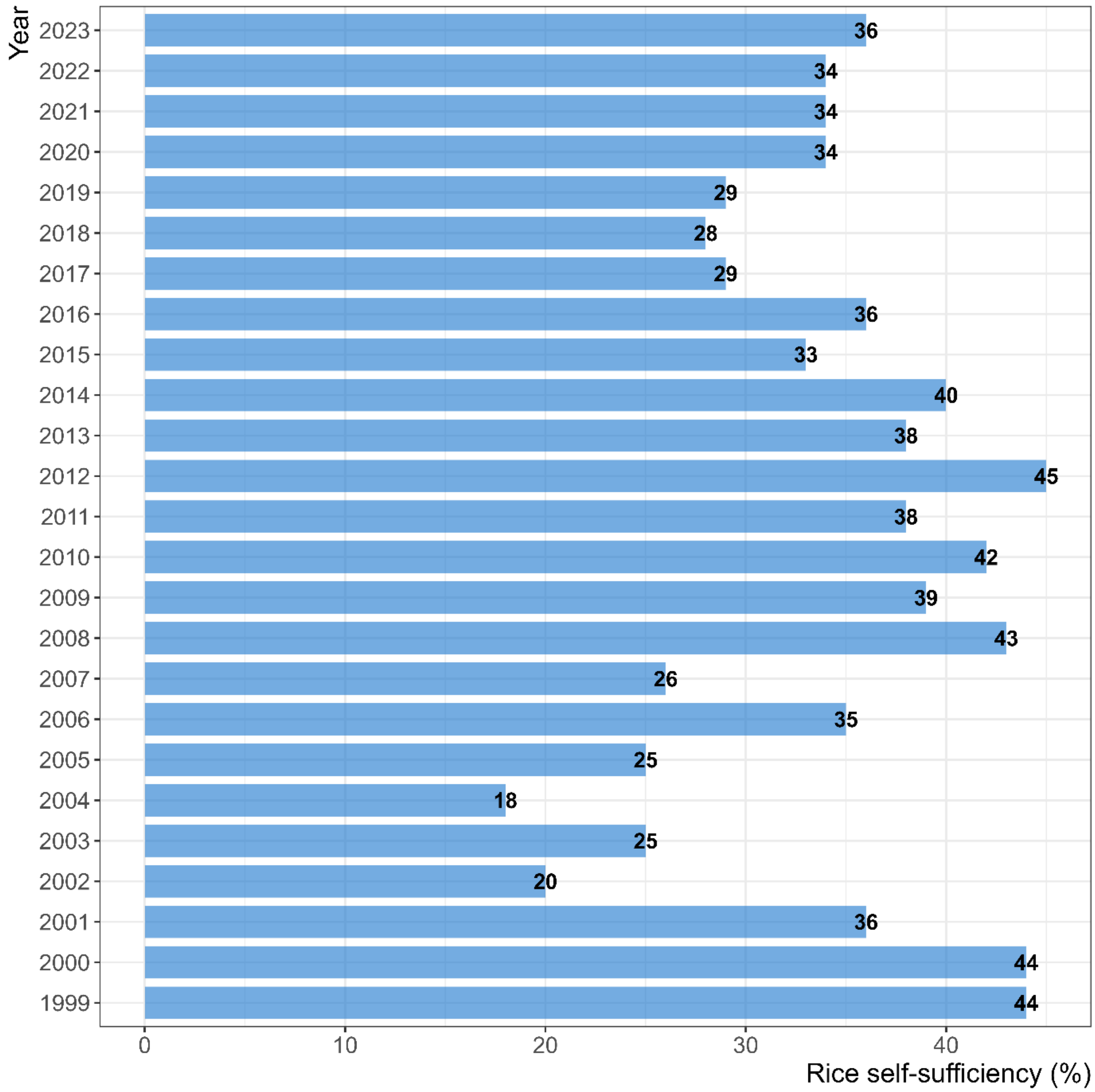


Figure 1.4. *Historical trends in rice self-sufficiency in Burkina Faso over the past 25 years (1999-2023). The data reported are from the USDA (2024) database.*

1.4. Research questions and hypotheses

The general objective of this Ph.D. research project is to assess AWD technology's efficiency under different socio-environmental conditions, aiming to identify suitable crop management practices and niches that will facilitate large-scale diffusion in the semi-arid zones of West Africa. The main research questions and corresponding hypotheses were:

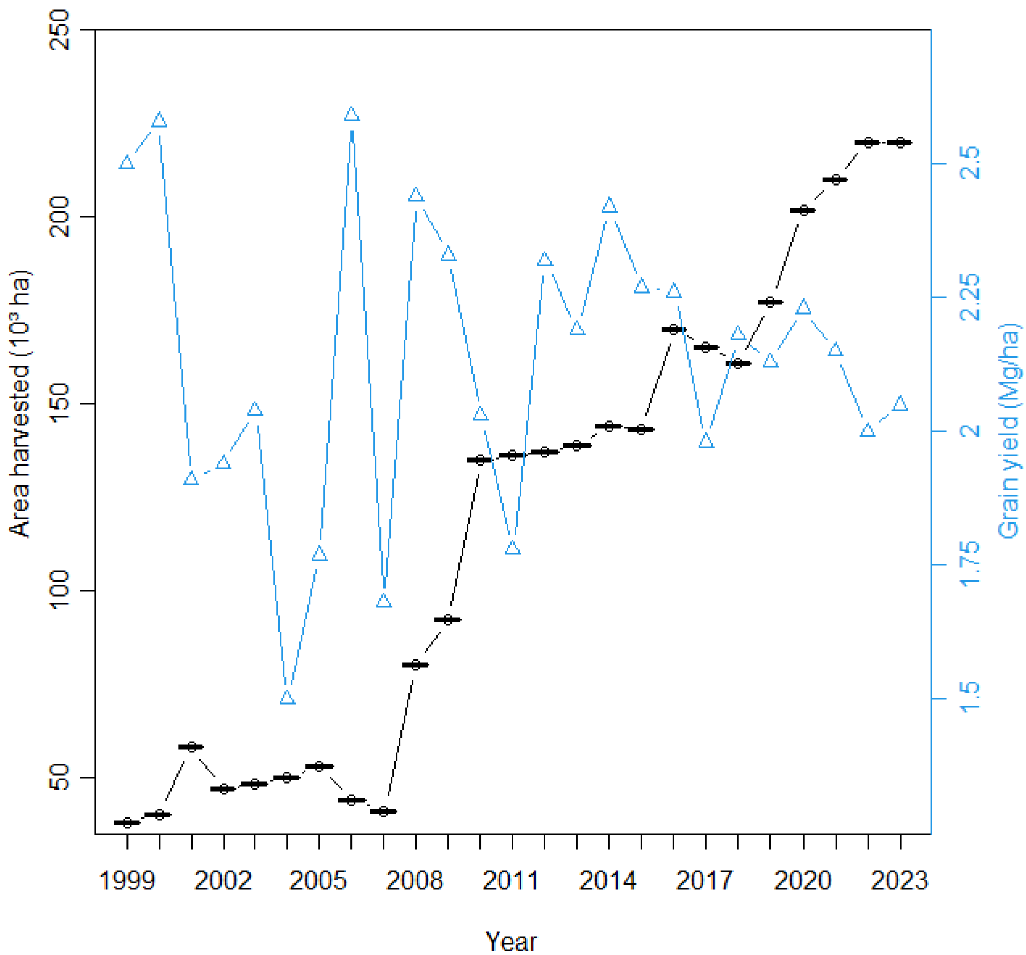


Figure 1.5. *Historical trends in average rice yield and harvested area in Burkina Faso over the past 25 years (1999-2023).*

The data reported are from the USDA (2024) database.

- *What are smallholder farmers' perceptions about water scarcity in irrigated systems in dry climatic zones of West Africa and what are their key adaptive response strategies?*

The hypothesis is that various factors, including climatic and environmental conditions, institutional dynamics, socio-economic and demographic factors, irrigation scheme water supply, and farmers' perceptions of water scarcity influence the adaptation strategies chosen by farmers to address water scarcity in their irrigated rice fields.

- *What are actual and attainable rice yields, and which crop management practices improve yields and water productivity while reducing their variability?*

The first hypothesis is that actual yields obtained by farmers in the dry zones of West Africa are higher in wet than dry seasons, as the water scarcity affects less the fields in wet seasons and that the determinants of variability of yield and water productivity are season-specific. It is also surmised that increasing yields and narrowing the yield gap are associated with increased resource- (water and fertilizer) use. Consequently, achieving both high yields and high resource-use efficiencies may be conflicting goals, potentially leading to trade-offs due to overuse and waste of resources.

- *What are the overall gains in grain yields, water productivity, and profitability associated with AWD over farmers' irrigation practices and which crop management practices favour the yield gains?*

The hypothesis is that biophysical conditions, crop management practices, varietal choice, and the growing season may differentially influence the yield gains associated with AWD in the dry climatic zones of West Africa.

- *What are the effects of alternate wetting and severe soil drying on grain yield, nutrient uptake and use efficiency and are there synergies or trade-offs between water productivity and N and P use efficiency?*

It is hypothesized that due to increased N losses during the drying phases and reduced availability of P under aerobic soil conditions, alternate wetting and severe soil drying irrigation may reduce the N and P use efficiency compared to farmers' irrigation practices.

Each research question and its corresponding hypotheses are addressed in separate research papers.

1.5. Methodological approach and thesis outline

This thesis is based on a participatory and interdisciplinary research approach (Descheemaeker *et al.*, 2019). Farmers were involved in all phases of the research, providing opportunities to bridge the gap between farmers' and researchers' perceptions of the irrigated rice farming systems. Additionally, it combines household surveys and participatory on-farm trials to gain both general and specific socio-economic and agronomic insights.

This thesis comprises six chapters: the current one (Chapter 1 or General introduction), four research papers (Chapters 2, 3, 4 and 5), and a General discussion and conclusion (Chapter 6). Using expert interviews and socio-economic household surveys in contrasting irrigation schemes, Chapter 2 sheds light on farmers' perceptions of water scarcity, key adaptation strategies, and the determinants of their adoption. Then, Chapter 3 gathers results from yield gap surveys and assesses key performance indicators such as water productivity, and nutrient use efficiency. It examines the effects of current environmental conditions on rice productivity, including water scarcity and management practices, while exploring the trade-offs or synergies between productivity and resource- (water and fertilizer) use efficiency. Chapters 4 and 5 focus on participatory on-farm trials comparing AWD to farmers’ irrigation practices. Chapter 4 presents results from comparisons of alternate wetting and moderate soil drying (i.e., AWD at the threshold level of -15 cm) to farmers’ irrigation practices in contrasting irrigation schemes, intending to identify the environmental conditions and cropping practices determining yield gain of AWD over farmers’ irrigation practices. Modern analytical methods such as machine-learning algorithms (random forest, brute force, Shapley additive explanation) were used to identify the drivers of the AWD-associated yield gains. Building on the promising results of alternate wetting and moderate soil drying, Chapter 5 delves into an in-depth study exploring the possibility of further reducing water inputs. This study tests the hypothesis that acute soil drying may impair fertilizer use efficiency and reduce the bioavailability of key nutrients. It presents results from comparisons of alternate wetting and severe soil drying (i.e., AWD at the threshold level of -30 cm) to farmers' irrigation practices. Finally, Chapter 6 synthesizes the key findings of the four research chapters and draws policy recommendations specific to irrigated rice systems in arid and semi-arid zones of West Africa. It concludes with a discussion of the study's limitations and outlines future research prospects.

1.6. Contribution of the thesis

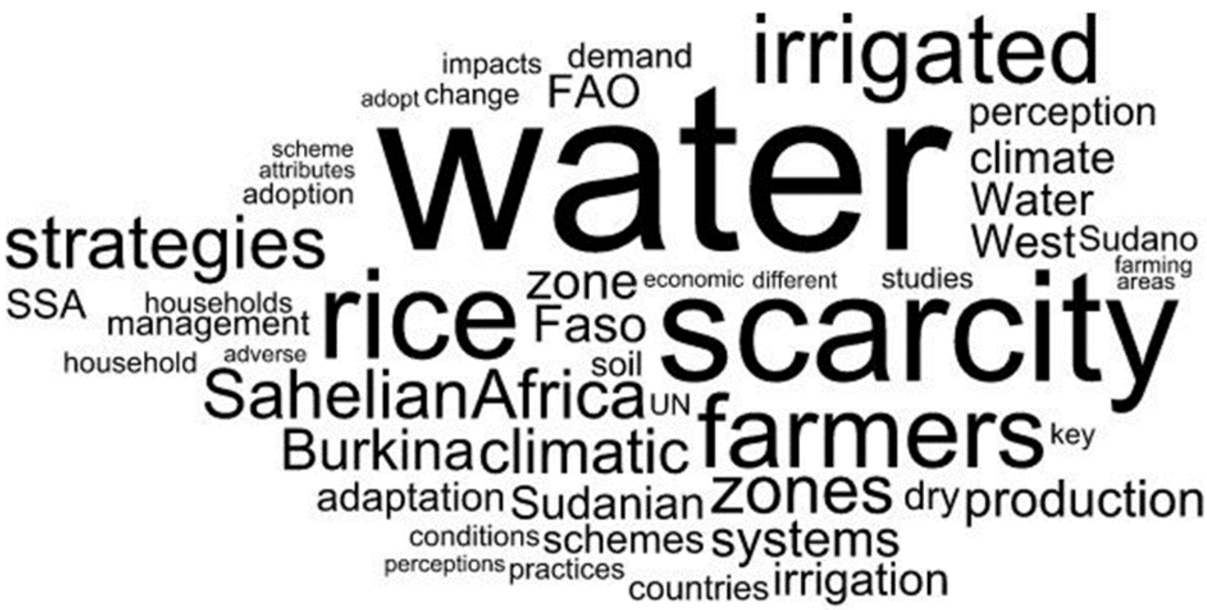
The originality and novelty of this thesis lie in its analytical approach, which combines household surveys and participatory on-farm trials, contrasting with previous studies in the region that primarily relied on research-managed trials (de Vries *et al.*, 2010; Dembelé *et al.*, 2005; Djaman *et al.*, 2018). As a result, the most important contributions of this thesis include:

- Providing insights into the spatial and temporal dynamics of water availability and the perception of water scarcity by farmers, addressing a gap in the literature for irrigated rice-based systems in West Africa.
- Providing updated information on actual yield and exploitable yield gaps in irrigated systems in Burkina Faso. This contribution is particularly significant given that the most recent field survey-based data available dates back

approximately 20 years ago (Segda *et al.*, 2004; Wopereis *et al.*, 1999), highlighting the critical need for updated insights into current agricultural productivity and potential yield improvements.

- Comparing AWD with current farmers' irrigation practices, rather than with continuous field submergence.
- Demonstrating the feasibility of the AWD technology and its implementation by smallholder rice farmers in a local context with less reliable irrigation water supply.
- Testing AWD in a wide range of management and environmental conditions involving farmers from various socio-economic backgrounds to identify suitable crop management practices and ecological niches for the implementation of AWD technology.
- Providing knowledge on AWD-associated effects that have to date not been addressed, such as the effects on yield variability as a possible risk factor, performance differentiation during dry and wet seasons, mineral fertilizer use efficiency, and uptake of nutrients (N, P, K, Mn, and Zn).

Chapter 2: Farmers' perception and management of water scarcity in irrigated rice-based systems in dry climatic zones of West Africa [α]



Word cloud visualization of the 50 most frequent words in this chapter

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[α] This chapter was published as:
Johnson J-M, Becker M, Dossou-Yovo ER, Saito K. 2023. Farmers' perception and management of water scarcity in irrigated rice-based systems in dry climatic zones of West Africa. *Agronomy for Sustainable Development* **43**: 32. DOI: 10.1007/s13593-023-00878-9.

Abstract

Water scarcity threatens irrigated agriculture in sub-Saharan Africa (SSA). Knowledge of farmers' perceptions and drivers for decision-making in view of coping with water scarcity is so far lacking but needed to improve local technologies and frame policies fostering their adoption. Here, for the first time, we investigated farmers' perception of water scarcity, key adaptation strategies, and the determinants of their adoption in irrigated rice schemes in dry climatic zones of West Africa. We surveyed 572 farming households and conducted expert interviews with key informants in four contrasting irrigated rice schemes in Burkina Faso between April 2018 and August 2019. Information was gathered on biophysical field characteristics, grain yields, agronomic and water management practices, farmers' perception of water scarcity, their adaptive responses, and social-economic attributes of adopting households. Nearly 80% of the respondents reported having experienced water scarcity during the past 5 years. To cope with the adverse effect of water scarcity, farmers implemented seventeen different adaptation strategies that could be categorized into seven groups. Most popular among those were "Water and soil conservation practices" (consisting mainly of field bunding and leveling), "No rice cultivation", and "Crop rotation". Farmers in drier areas (Sudano-Sahelian zone) were less likely to adopt and implement several adaptation strategies to water scarcity compared to farmers in wetter areas (Sudanian zone). Belonging to farming associations increased the probability of implementing several strategies to alleviate water scarcity, while female-headed households tended to have a lower propensity to adopt and implement concomitantly several adaptation strategies in comparison with their male counterpart. The dissemination of scheme- and household-specific technology options could contribute to mitigating water scarcity in irrigated rice-based systems in the dry climatic zones of West Africa, thus contributing to rural livelihood and food security.

Keywords: Burkina Faso, climate change, drought, mitigation, *Oryza spp.*, Sahel

2.1. Introduction

In the last century, global water consumption has been growing more than twice the rate of the world population, increasing the number of regions experiencing water scarcity (UN-Water & FAO, 2007). Water scarcity is defined as a gap between available supply and expressed demand for water at a given place (e.g., country, region, catchment, and irrigation scheme) and under prevailing institutional arrangements and infrastructural conditions. It also refers to situations where water demand exceeds the exploitable water resources. Unsatisfied demand, competition for water, conflicts between users, over-extraction of groundwater, and reduced water flows are the most common warning signals of water scarcity (**Figure 2.1**) (FAO, 2012). Demographic growth, poor land and crop management, as well as regional economic development are exacerbating the pressure on water resources, especially in drought-prone regions. By 2025, over one fifth of the worldwide population is expected to be living with absolute water scarcity (FAO, 2012). Sub-Saharan Africa (SSA) is the region with the largest number of water-stressed countries, with the Sudanian and the Sahelian climatic zones being the most vulnerable to water scarcity (UN-Water & FAO, 2007).

Figure 2.1. *Water level in the dam supplying water to the Zoungou irrigation scheme on different dates* ***(a)*** *25th July 2018,* ***(b)*** *24th February 2019,* ***(c)*** *17th March 2019,* ***(d)*** *25th March 2019,* ***(e)*** *2nd April 2019, and* ***(f)*** *5th November 2019.*

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Of all sectors of the economy, agriculture is the largest consumer of global freshwater, using 72% of all water withdrawals (UN-Water, 2021), with irrigated rice being by far the largest consumer of freshwater (Tuong & Bouman, 2003). Water scarcity is expected to be exacerbated by climate change, heat waves, and soil degradation, entailing multiple adverse impacts on crop production. Such impacts are not only restricted to upland systems but increasingly affect also irrigated rice. Being a traditional staple food in many parts of Africa, the expansion of the growing area of rice has been larger than that of any other crop (Arouna *et al.*, 2021b), and demand for rice in SSA increases faster than anywhere else in the world. Indeed, from 2008 to 2018, the annual rice consumption in SSA increased by 81% (FAO, 2020). Despite only 26% of SSAs rice being irrigated (Diagne *et al.*, 2013), irrigated lowland systems contribute most to regional rice production. However, particularly in the Sudanian and the Sahelian climatic zones, water scarcity seriously threatens rice-based livelihoods. The farm-level adoption of water-saving strategies depends on available technologies and farmers' adaptive capacity, particularly on farmers' perception of the extent of the problem and the location-specific benefits of new production strategies. Thus, there is an urgent need to understand farmers' perception of water availability, and farmers' differential ability to respond adequately and promptly to water scarcity.

Most previous studies on adaptation strategies by smallholder farmers in SSA focused on climate change (Bryan *et al.*, 2013; Zamasiya *et al.*, 2017), with few studies analyzing the actual occurrences of droughts events (Masih *et al.*, 2014), presenting an integrated assessment of drought risks for irrigated systems (Meza *et al.*, 2020), or addressing issues of irrigation water management under conditions of water scarcity (Pereira et al. 2002). Assessment of the determinants of smallholder farmers' adaptation strategies to the effects of climate variability has been conducted in different SSA countries such as Benin (Gbemavo *et al.*, 2022), Botswana (Mogomotsi *et al.*, 2020), Ethiopia (Alemayehu & Bewket, 2017; Tofu *et al.*, 2022), Kenya and Tanzania (Shikuku *et al.*, 2017), Uganda (Atube *et al.*, 2021), and Zimbabwe (Jiri *et al.*, 2017). Leal Filho et al. (2022) recently described water scarcity trends in Africa and outlined climate impacts on key water-related sectors. However, none of these studies take into account farmers' perceptions of water scarcity and household-specific willingness and capability to adopt water scarcity-mitigating strategies, and no studies are available for irrigated rice-based systems in West Africa. Filling this gap, the present paper provides insights into the spatial and temporal dynamics of water availability, the perception of water scarcity by farmers, and emerging patterns of practices aimed at mitigating water scarcity in the dry climatic zones of West Africa. We addressed the following objectives: 1) characterize rice-based farming systems and water management practices in four irrigated lowlands of Burkina Faso, 2) investigate the farmers' perceptions of the spatial and temporal dynamics of water scarcity, 3) identify farmers' strategies to control or cope with water scarcity, and 4) determine key biophysical factors and household attributes affecting the adoption of these strategies at farm level.

2.2. Material and Methods

2.2.1. Description of the study area

The survey was carried out in Burkina Faso, which covers diverse dry climatic conditions (the Sudanian and Sudano-Sahelian zones) encountered in most Sahelian countries of West Africa and these being highly vulnerable to adverse impacts of climate change (The World Bank Group, 2011). Burkina Faso is divided into the Sudanian zone (located above the isohyet 900 mm), the Sudano-Sahelian zone (between the isohyets 600 and 900 mm), and the Sahelian zone (below the isohyet 600 mm) (**Figure 2.2**). Each climatic zone is characterized by a unimodal precipitation regime and experiences distinct wet and dry seasons, with the wet season extending over five months in the South and two months in the North (CILSS, 2016; MAHRH, 2011). The country also experiences variable rainfall and an increase in air temperatures (Fig. S1, S2, and S3). Its croplands are characterized by low soil fertility, poor nutrient availability (Hengl *et al.*, 2021), and widespread soil degradation as reported in most Sahelian countries (Nachtergaele *et al.*, 2012; Niemeijer & Mazzucato, 2002).

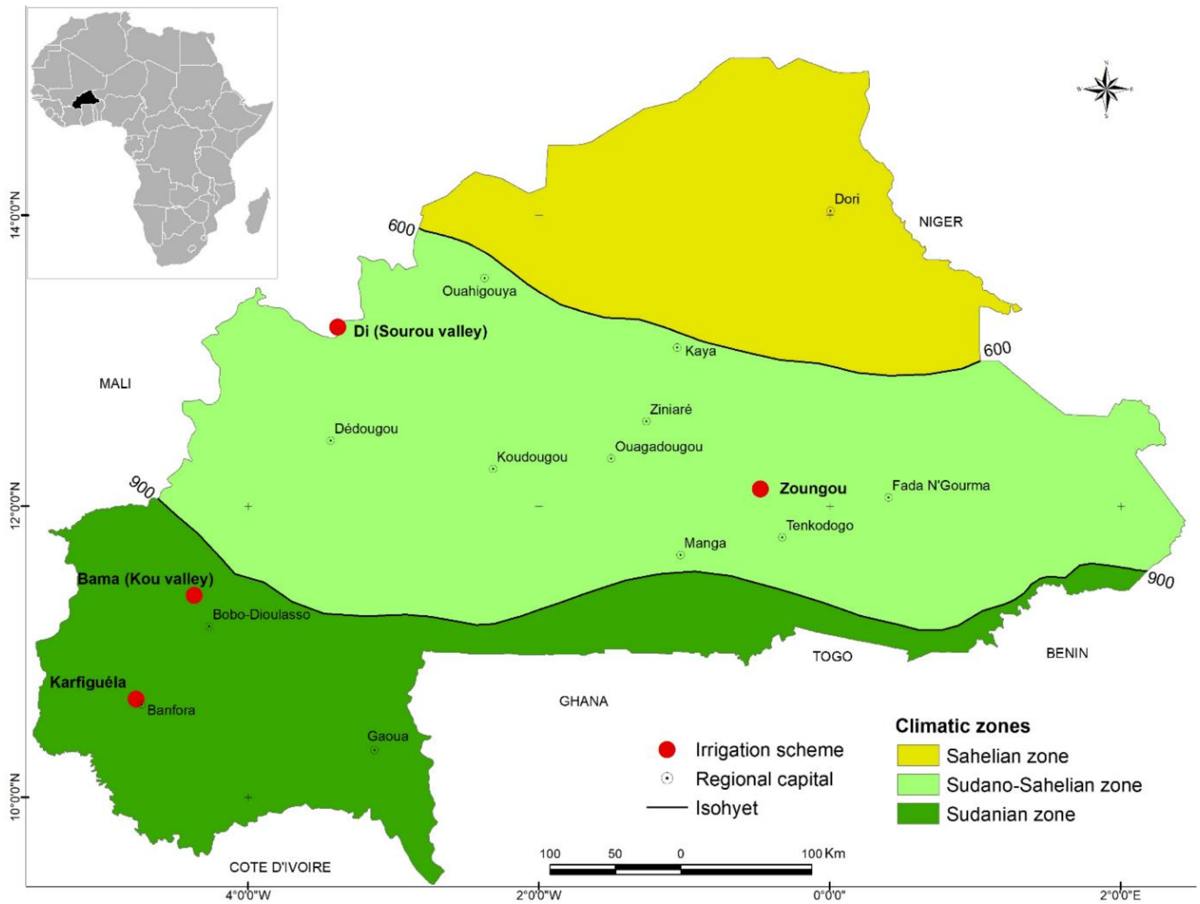


Figure 2.2. *Map of Burkina Faso showing climatic zones delimitation and study sites.*

Cereals are the main source of food calories and are produced mainly on smallholder farmland. In 2020, Burkina Faso (like most other Sahelian countries) depended on 10% of cereal imports and recorded a prevalence of undernourishment of nearly 20% (FAO, 2020). While being only the fourth most cultivated cereal after sorghum (*Sorghum bicolor*), maize (*Zea mays*), and millet (*Pennisetum glaucum*) (FAO, 2020), rice (*Oryza spp.*) production area and particularly its per capita consumption of 41 kg person^{-1} year^{-1} (UN, 2021; USDA, 2024) have been rapidly increasing. Its local production meets only 29% of the demand (USDA, 2024). The irrigated lowland systems accounted for 53% of Burkina Faso's national rice production in 2009, while having been produced on only 23% of the rice land area (MAHRH, 2011).

2.2.2. Data collection methods and data sources

The core data are derived from a household survey conducted in four irrigated rice production schemes in Burkina Faso from April 2018 to August 2019. Multiple-stage sampling techniques were employed to select the respondent farm households. We focussed on the two climatic zones where irrigated rice is mostly cultivated: the Sudanian and Sudano-Sahelian zones (Akpoti *et al.*, 2021). Two sites were selected as being representative of irrigated lowland rice-growing areas in those zones, namely Karfiguela and Kou Valley irrigation schemes in the Sudanian zone, and Zoungou and Sourou Valley irrigation schemes in the Sudano-Sahelian zone (**Figure 2.2**). These four sites cover diverse geographic and socio-economic conditions prevailing in West Africa. **Table 2.1** presents in detail the attributes and differences between these irrigation schemes, providing a summary of their climate, soil, irrigation, and production system characteristics. Finally, random sampling techniques were used to select smallholder rice farming households in each scheme. While assuming a confidence interval of 95% and aiming for a precision level (or sampling error) of ± 8%, the sample size was determined using the formula below (Yamane, 1967):

$$n = \frac{N}{1 + N(e)^2} \qquad (1)$$

where n is the sample size, N is the population of the smallholder rice farming households per irrigation scheme and e is the level of precision. Thus, the sample size of smallholder rice farming households was 138, 141, 185, and 108 in Karfiguela, Kou, Zoungou, and Sourou irrigation schemes, respectively.

Table 2.1 *Farm characteristics of the study sites (irrigation schemes)*

	Karfiguela	Kou Valley (Bama)	Zoungou	Sourou Valley (Di)
Location				
Administrative region	Cascades	Hauts bassins	Plateau central	Boucle du Mouhoun
Latitude (°)	10.67	11.39	12.12	13.23
Longitude (°)	-4.81	-4.41	-0.51	-3.42
Altitude (m)	243	329	290	282
Climate				
Climatic zone	Sudanian	Sudanian	Sudano-Sahelian	Sudano-Sahelian
Average annual rainfall (mm)	1110	1005	764	727
Average annual maximum temperature (°C)	33.4	33.8	34.8	35.5
Average annual minimum temperature (°C)	21.2	21.2	21.4	21.9
Soil				
Soil type	Luvisol, Nitisol	Luvisol, Regosol	Planosol, Vertisol	Fluvisol
pH (H_2O)	5.7	5.2	6.3	6.6
Organic carbon (g kg^{-1})	6.4	8.0	5.7	6.4
Total nitrogen (g kg^{-1})	0.8	0.9	0.6	0.9
Extractable phosphorus (mg kg^{-1})	8.0	6.4	7.2	6.4
Irrigation system				
Commissioning date	1975	1970	1993	2013
Method of irrigation	Gravimetric	Gravimetric	Gravimetric	Gravimetric
Source of the irrigation water	River diversion	River diversion	Dam water intake	River pumping station
Production system				
Rice-growing area (ha)	350	1260	100	565
Number of rice farmers	950	1350	1120	390
Tillage	Oxen/Power tiller	Oxen/Power tiller	Manual/Oxen/Power tiller	Oxen/Power tiller
Crop establishment method	Transplanting	Transplanting	Transplanting	Transplanting
Rice varieties	Improved	Improved	Improved	Improved
Fertilizer and pesticide input use	Yes	Yes	Yes	Yes
Average rice grain yield (Mg ha^{-1})	4.5	4.9	4.3	5.5
Irrigation charge fee (€ per ha/season)	9.15	19.82	22.86	105.17

Average climatic data (1981 - 2017) were calculated based on NASA's POWER (Prediction Of Worldwide Energy Resource) database (Sparks 2018).
Soil chemical properties were retrieved from the iSDAsoil map (Hengl et al. 2021) using site-specific GPS coordinates.
Dominant soil type information was obtained from Harmonized World Soil Database (version 1.2) (FAO/IIASA/ISRIC/ISSCAS/JRC 2012).

We carried out household surveys using a structured questionnaire. The respondents were the household heads (i.e., principal male or female member) as they usually have the decision-making power for managing farm resources. The information collected using the questionnaire covered seven major sections:

Section 1: Geolocation (site name, GPS coordinates) and physical characteristics (soil texture) of the rice field. In each field, the soil texture was determined by the "feel method" (or "hand method") (Defoer *et al.*, 2009) and classified as sandy, loamy or clayey.

Section 2: Professional profile of the household head (gender, age, education level, rice farming experience)

Section 3: Household's socio-demographic (household size, farming association membership) and economic characteristics (number of farmworkers, total farmland size, rice field size, herd size, number of farm machines owned, main income source, and the ratio of rice production sold). The herd size was expressed in Tropical Livestock Units (TLU) of 250 kg.

Section 4: Rice productivity [rice cropping intensity i.e., the number of times rice is grown per year), estimated grain yield typically harvested in the wet and dry seasons by indicating the number of paddy bags harvested and the average weight of the bags over the past five years on the cultivated area].

Section 5: Current situation of perceived water scarcity and usage restriction during wet and dry seasons including the month of occurrence and the frequency of water scarcity encountered over the past five years. Respondents rated the water availability in their rice field in the wet and/or dry season following a 5-point Likert scale: 1 = "Very bad", 2 =

"Bad", 3 = "Fairly good", 4 = "Good", and 5 = "Very good". They also provided perceived water scarcity effects (yield reduction or complete crop failure).

Section 6: Farmers' water management practices and perception of the critical phases for irrigation including the irrigation frequency, factors influencing the irrigation frequency, and the amount paid for irrigation water per season. Additionally, farmers indicated the possible benefits of water-saving production strategies.

Section 7: Inventory of farmers' adaptation strategies to perceived water scarcity issues in their rice fields.

Before being administered to 572 randomly selected rice farmers, the questionnaire was tested with voluntary farmers, adjusted as required, and converted into Open Data Kit (ODK) collect application format. The forms were uploaded to a server and downloaded to android devices (smartphones or tablets) using the ODK collect App. Well-trained extension agents or BSc students conducted the interviews in local languages (Mooré or Dioula). Finalized data forms were sent to the server housing all the survey information.

Before and after the household survey, in each scheme, discussions with 5 to 8 local experts and key resource people were conducted to get descriptive and historical information on each irrigation scheme (**Table 2.1**) and experts' opinions on some quantitative observations from the household survey. Weather data (annual rainfall, minimum and maximum temperatures) from 1981 to 2017 were retrieved for each site/scheme from NASA's POWER (Prediction Of Worldwide Energy Resource) database (Sparks, 2018). Standardized Precipitation-Evapotranspiration Index (SPEI) data (Vicente-Serrano *et al.*, 2010) were retrieved from the SPEI Global Drought Monitor website (https://spei.csic.es/map/) (Beguería *et al.*, 2010) for each site, allowing for the assessment and monitoring of aridity over timescales from 1 to 48 months.

2.2.3. Data analysis

After cleaning, household survey data were analyzed using R. 4.0.5 (R Core Team, 2021) according to the objectives of this study.

- *Characterization of rice-based farming systems and farmers' water management practices*

Household characteristics, presented as continuous variables, were analyzed using descriptive statistics (mean, median, standard deviation, and interquartile range). Percentage shares were calculated on categorical variables such as gender, age group, and education level of the household head, belonging to a farming association, and main source of income. Similarly, the rice farmers' water management practices and perception of the critical phases for irrigation were analyzed using descriptive statistics. Percentage shares were calculated for categorical variables.

The diversity between households was apprehended by a farm typology based on resource endowment (Falconnier *et al.*, 2015). The farm type classification was derived from a cluster analysis based on five variables describing primary farm capital assets and potential labor availability: (i) total household size, (ii) number of full-time farmworkers (family members and hired people), (iii) total farmland size, (iv) herd size and (v) number of farm machines (plows, rice thresher, motor tricycles) (Falconnier *et al.*, 2015). After standardizing the data, the cluster analysis was performed using Agglomerative Hierarchical Clustering (AHC) (Köbrich *et al.*, 2003). The AHC grouped households into clusters based on their similarity using Euclidian distance and Ward’s minimum variance linkage method.

As all household characteristics presented were continuous variables and average rice yield did not meet the normality of residues and homogeneity of variance, the Kruskal-Wallis H tests were computed to identify significant differences across (i) irrigation schemes and (ii) farm types. Furthermore, to compare the distribution of the categorical variables between (i) irrigation schemes and (ii) farm types, the Fisher's exact tests or the approximation method, the Chi-squared (χ^2) tests of independence were computed. When more than 20% of cells had expected frequencies of < 5, we used Fisher's exact test as applying the approximation method (χ^2 test) is inadequate in such cases (Crawley, 2012).

- *Status of water scarcity*

Continuous and categorical variables explaining the perceived water scarcity were analyzed using descriptive statistics and percentage shares, respectively. As the residuals of cultivated rice field size data failed to meet the normality assumption, we run robust linear mixed-effects models (*Robustlmm* package; Koller, 2016), including farmer’s field as random effect and season as a fixed factor to test its effect on cultivated rice field size.

To link the farmers’ perception of months when water scarcity occurs with meteorological records, we plotted long-term (1981-2017) monthly rainfall and maximum temperature (T_{max}) data for each site. In addition, a long-term (1981-2017) temporal analysis of the seasonal water deficit was done using SPEI_3 (SPEI over a 3-month accumulation period) for each site. Thus, we estimated the basic potential impacts of aridity on soil moisture and streamflow, and the impacts of water balance on agriculture during the crop-growing season (Copernicus European Drought Observatory (EDO), 2020; World Meteorological Organization (WMO) & Global Water Partnership (GWP), 2016). Subsequently, the annual 12-month timescale accumulation SPEI (SPEI_12) was compiled, representing the precipitation deficit for the entire year and reflecting the hydrological consequences of the water deficit. The nonparametric Mann–Kendall test as described by Hirsch et al. (1982) was used to detect the possible existence of a monotonic trend of SPEI-12. The *Z*-value was used to test the statistical significance of the monotonic (upward/downward) trends whereas Sen's slope estimator was used to determine the magnitude of the trends (Sen, 1968). We used Pettitt's test to identify the point at which the values in the data change for each site (Pettitt, 1979). These analyses were done using the R package *trend* (Pohlert, 2020). Similar to Polong et al. (2019), the threshold of annual SPEI_12 ≤ −1.0 was inferred to stand for a dry year whereas annual SPEI_12 ≥ +1.0 represented a wet year over the study domain. The frequency of occurrence of dry years ($F_{\text{dry years}}$) was calculated according to equation 2:

$$F_{dry\ years} = \frac{n}{N} \times 100 \qquad (2)$$

where n is the number of dry years (annual SPEI_12 < −1.0) and N is the total of the years for a defined period.

- *Categorization of adaptation strategies to water scarcity*

The water scarcity-adaptation strategies adopted by farmers were aggregated into seven major categories by grouping closely related strategies based on function/effects (Smit *et al.*, 2001) and following the groups of adaptation strategies in the agricultural sector suggested by IPCC (2014). Rice farmers could use simultaneously several strategies to cope with water scarcity in their field, therefore these strategies were coded as binary variables (Yes or No), and were unordered and non-mutually exclusive. The percentage shares of "Yes" were calculated to assess the predominance of the utilization of the strategies. In addition, The Kendall rank correlation analysis was also performed to assess the monotonic association between the typical grain yield in the dry season and the number of water scarcity adaptation strategies implemented.

- *Analysis of farmers' decisions to adopt strategies counteracting water scarcity*

Our survey revealed that farmers use simultaneously several strategies to cope with water scarcity, thereby, excluding the multinomial logistic model (Greene, 2011). For each adaptation strategy, farmers' decision is a binary variable, y, comprising two possible outcomes coded as 1 (or "Yes") if the adoption and implementation take place or 0 (or "No") if no adoption. Therefore, given the binary nature of the response (dependent variable), we used binary logistic regression (Zhai *et al.*, 2018) to understand factors affecting the farmers' decision to adopt and implement each major category of water-scarcity strategy. To analyze the binary response, *logit* and *probit* functions are the most commonly used. Both functions are perfectly symmetric and sigmoid except at the tails and in most cases lead to similar results (Cameron & Trivedi, 2009). Therefore, we opted for the logit function partly because the coefficients can be more easily interpreted (Klieštik *et al.*, 2015).

Unlike linear regression models, the estimated regression coefficients by the logit model only provide the direction of the effect of the explanatory variables on the dependent variables but do not indicate the actual magnitude of change. Therefore, the marginal effects of the explanatory variables were also computed. Marginal effects measure how a change in response is related to a change in a covariate while all other variables are held constant. For categorical variables, the marginal effect evaluates discrete change, i.e., how predicted probabilities change as the independent variable changes from a reference modality to another one. For continuous variables, it measures the impact that an instantaneous rate of change of an independent variable has on the outcome variable (Leeper, 2021).

All dependent variables are related to the farmers' decision to implement an adaptation strategy. We modelled separately the seven aggregated adaptation strategies and not the single ones as the initial models failed to generate significant parameters. Moreover, for some strategies, the frequency is very low, yet, in the case of rare event data, logistic regression models can produce inaccurate estimates or fail to converge as maximum likelihood estimation is well known to suffer from small-sample bias sparse datasets (Allison, 2004; King & Zeng, 2001). The explanatory variables of the logistic regression models were selected according to literature and local expert knowledge. They covered five groups of factors: (i) climatic and environmental factors, (ii) institutional factors, (iii) socio-economic and demographic factors, (iv) irrigation scheme water supply, and (iv) farmers' perceptions of water scarcity. Therefore, these five groups of factors were hypothesized to influence the choices of farmers' adaptation strategies to water scarcity in their irrigated rice fields. **Table 2.2** describes all independent variables. At the outset of the fitting of the logit regression models, multi-collinearity issues of the explanatory variables were checked by computing the variance inflation factor (VIF). The smallest possible VIF value is 1, which indicates the complete absence of collinearity. On the contrary, as a rule of thumb, a VIF value that exceeds 10 indicates a serious issue of collinearity (James *et al.*, 2014). The estimated VIF values of our models ranged from 1.00 to 2.98. Therefore, we concluded that multi-collinearity is not an issue in our models. In the next step, regression coefficients and average marginal effects (AME) of the logistic regressions were estimated. Among three different parameters of interest derived from marginal effects, we calculated average marginal effect (AME) as it has the potential to convey an important amount of information about the effect of each covariate on the outcome variable (Leeper, 2021). The AMEs were computed using the package *margins* (Leeper, 2021). To assess the goodness of fit of the models, the overall significance of the models was evaluated by computing likelihood-ratio tests. These tests consist to compare the log-likelihood of the model with the predictors (the full model) to a restricted model where only an intercept is included (the null model). In addition, Nagelkerke Pseudo R^2 was estimated for each model.

We counted the number of active strategies implemented by each farmer to counteract water scarcity during the last years and assessed its key determinants by Poisson regression analysis. After checking the overdispersion issue and the variance inflation factor ($1.04 \leq VIF \leq 2.52$), the Poisson regression model was fitted, and the likelihood-ratio test and Nagelkerke Pseudo R^2 were computed.

Table 2.2 *Explanatory variables of the models explaining the choice of rice farmers' adaptation strategies to water scarcity in irrigated rice fields*

Explanatory variables	Type	Category
Climatic and environmental factors		
Climatic zone	Categorical	**Sudanian**; Sudano-Sahelian
Soil texture	Categorical	**Clayey**; Loamy; Sandy
Institutional factor		
Farming association membership	Categorical	Yes; **No**
Socio-economics factors		
Gender of the household head	Categorical	**Male**; Female
Age group of the household head	Categorical	Young adult (20-39 years of age); **Middle-aged adult (40-59 years)**; Senior adult (› 59 years)
Education level of the household head		**Illiterate**; Primary school; Secondary school &University
Farm type	Categorical	**LRE**; MRE; HRE
Rice field size (ha)	Quantitative	
Rice farming experience (years)	Quantitative	
Main income source	Categorical	**Agriculture**; Trade, Other
Ratio of rice production sold (%)	Quantitative	
Irrigation water paid (€)	Quantitative	
Irrigation scheme water supply		
Irrigation frequency in dry seasons	Categorical	**At less one a week**; Less than one a week; Erratic and very scarce
Irrigation water availability in dry seasons	Categorical	Very good & Good; **Fairly good**; Very bad & Bad
Water scarcity perception		
Frequency of water scarcity (in the previous five-year term)	Quantitative	

For each explanatory variable, the category in bold represents the reference or base category.
The three farm types are Low Resource Endowed (LRE), Medium Resource Endowed (MRE), and High Resource Endowed (HRE) farms.

2.3. Results

2.3.1. Characteristics of the farm households and farmers' water management practices

All environmental, institutional, socio-economic, and demographic characteristics of the rice farm households were significantly different among irrigation schemes and the descriptive statistics are presented in Table S1. Agriculture was the main income source for 94% of the households. On average, farmers cultivated 2.9 ha of land of which irrigated rice comprised 0.6 ha. Only about 40% of the rice production was sold on local markets, the largest share serving subsistence purposes. Some 58%, 34%, and 8% of households cultivated their irrigated rice on clayey, loamy, and sandy soils, respectively. About 31%, 56%, and 13% of the household heads were young adults (20-39 years), middle-aged adults (40-59 years), and senior adults (› 59 years), respectively. Thus, the mean household head age was 46 years while the mean farming experience was 22 years. Some 75% of the respondents were male and only 25% were female. About 66% of the respondents were illiterate whereas 26% and 8% of them attended primary school and higher schools, respectively. Illiteracy rates were much higher among female household heads (84%) in comparison to male household heads (60%). On average, the households had 14 members and 7 full-time employed farm workers. Less than 20% owned farm machines. Almost three quarters (74%) of the household belonged to farming groups or cooperatives.

The hierarchical cluster analysis differentiated three farm types based on households' resource endowment. The largest group of 57% having a low resource endowed (LRE) referred to as Type 1, 41% having medium resource endowed (MRE) referred to as Type 2, and only <3% were classified as having high resource endowed (HRE), being referred to as Type 3 (Table S2).

Type 1 (or LRE) farms are small households of 10 people on average who own a small farm size (on average 1.7 ha). Irrigated rice covers only 0.5 ha. Households are poor, owning no farm machinery and less than 2 TLUs.

Type 2 (or MRE) farms own 4.3 ha of farmland of which 0.7 ha are under irrigated lowland rice cultivation. These farms are characterized by mid-size households of about 17 persons with 8 employed farm labourers. Households own at least one farm machine and 2 TLUs.

Type 3 (or HRE) farms are those with a high resource endowed and are characterized by farm sizes of 8.3 ha as well as a large household size of on average 43 people with 24 employed farm workers. The share of irrigated rice land is 1.6 ha. Farmers own more capital and productive farm assets, owning on average 28 TLU and at least 2 farm machines.

Despite considerable and significant differences in household size, capital, and productive assets among farm types, there were no significant differences in terms of the age group, level of education, and rice farming experience of the household heads, and the income source and affiliation to farming associations.

Rice grain yields varied (CV=25%) across the irrigation scheme with an average of 4.7 Mg ha^{-1}, and were significantly affected by farm resource endowment. Farms belonging to type 1 (low resource endowment) tended to yield less (4.6 Mg ha^{-1}) than farms with medium (4.9 Mg ha^{-1}) or high resource endowment (5.6 Mg ha^{-1}) (Table S2).

Farmers' management practices differed both between schemes and among households within a scheme (Table S3). While during the wet season, rice farmers rely mainly on rainfall with some supplemental irrigation (data not shown), during the dry season, most farmers irrigated their field once a week (60%) and up to 2 times per week (27% of the surveyed farmers). The frequency of irrigation was determined by the scheme-management fixed water turn, the water availability in the canal, the soil water status, soil type (texture, organic matter, water-holding capacity), distance from the secondary/tertiary canal, and the topography. Among all these factors, more than half of the farmers explained that the water turn was the most important one (Table S3).

A water pricing mechanism is currently in force on all the studied irrigation schemes. Fixed by the local authority in charge of the water management in each scheme, the water price is a flat rate per unit of irrigated area per season that differs between schemes. On average, rice farmers paid € 33 per hectare and per season with a much higher price in Sourou Valley (€ 104 per hectare and season), a drier area, where water is provided by pumping stations, and the lowest price in Karfiguela (€ 9 per hectare and season), a less dry area, where water is supplied by river diversion through gravity.

When asked about the most drought-sensitive phenological stages of rice, and hence the period with the highest need for reliable water supply, most farmers (70% of the respondents) named the heading and flowering stages, though answers differed between schemes (Table S4). More than 90% of the household heads considered relevant and useful to save water in the rice fields. About 70% of them considered that the water saved could be used for growing legumes or other non-rice crops while 18% indicated that it could be used for livestock (Table S5).

2.3.2. Farmers' perceptions of water scarcity and analysis of its impact on rice production

The overall farmers' perceptions of water scarcity differed among schemes (Table S6). Nearly all farmers (97%) grow rice in the wet season and almost three quarters (73%) grow rice additionally in the dry season. In wet seasons, submergence and the lack of cropland represented about 60% of the causes explaining the absence of rice cropping. In contrast, in dry seasons, water shortage was the main cause (94%) (Table S7).

Most respondents reported that water scarcity is a real issue for their farming activities. More than three quarters (78%) declared having experienced water scarcity issues in their irrigated rice field over the last 5 years. The average frequency of occurrence of water scarcity issues in the rice fields was twice over 5 years. Water scarcity occurred mostly during dry seasons (Table S6) and extended from a few days up to two months. Rice farmers perceived April and March as the critical months when water scarcity is frequently experienced (Fig. S4). Their perceptions are in line with the weather data analysis of the period 1981-2017 in these regions showing that March and April are the months with the highest maximum temperatures (Fig. S5a), and are among those with the lowest rainfall (Fig. S5b). March and April are also among the months which show the lowest SPEI_3 (Fig. S6; Table S8). Moreover, from 1981 to 2017, at all the sites, annual SPEI_12 exhibits decreasing trends. From 2000 to 2017, the frequency of occurrence of drier years drastically increased in comparison with the period 1981-1999 (Fig. S7; Table S9). This observation of the climate getting drier supports a large number of farmers complaining about water scarcity.

The majority of respondents (83%) perceived that their access to irrigation water is restricted in dry seasons against 17% who reported no restriction (Table S6). Thus, irrigation water availability during wet seasons was scored by 90% of the respondents as being “Good” and “Very good” while only 28% of the respondents indicated good water availability in the dry season. About 39% scored “Bad” and “Very bad” on the irrigation water availability in their rice fields in dry seasons (**Figure 2.3**). The farmers’ complaints were higher (around 90% of the respondents) where rice farmer density is high and water provided by river diversion and dam water intake (Karfiguela, Kou valley, and Zoungou) but were less where rice farmer density is low and water provided by pumping station (Sourou Valley) (Table S6).

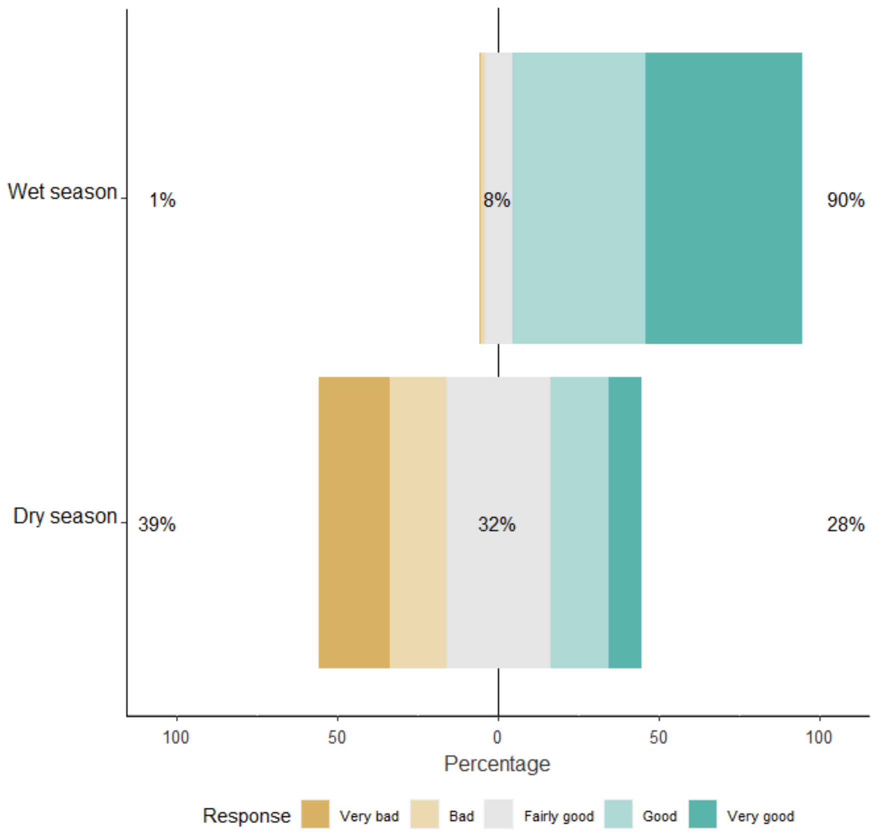


Figure 2.3. *Farmers’ perception and assessment of the irrigation water availability in the rice fields in wet and dry seasons.*

The question was: “Score the irrigation water availability in your rice field during the wet and dry seasons”. The coloring represents the proportion of each score (“Very bad”, “Bad”, “Fairly good”, “Good”, or “Very good”) for each season. The percentage on the left side is the combined proportion for “Very bad” and “Bad”, the one on the middle for “Fairly good”, and the one on the right side for “Good”, and “Very good”.

The majority of rice farmers (80%) claimed that water scarcity reduces their yield whereas a minority (20%) affirmed that it leads to complete crop failure (Table S6). This situation most likely led some farmers to stop rice cropping in dry seasons. Thus, the area cultivated with rice during the dry season (0.367 ha) was significantly smaller than in the wet seasons (0.534 ha) (n = 572; $p < 0.0001$).

2.3.3. Strategies adopted to counteract water scarcity

In response to the perceived water scarcity issues in their irrigated rice fields, farmers on the different sites have undertaken several adaptation strategies. From our survey, we inventoried seventeen adaptation measures that we grouped into seven main strategies differing in their aims and resource requirements (**Table 2.3**). The strategy group "Water and soil conservation practices" was the most adopted and implemented (80%), followed by "Crop rotation" (31%). Among "Water and soil conservation practices", field bunding and levelling predominate (**Table 2.3**). About 20% of the respondents reported using "Adjustment of the agricultural calendar", "Use of motor pump for supplemental irrigation", and "Use of more irrigation water from the scheme". About 40% abandoned rice cultivation during the dry season, while 29% opted for the reduction of their rice field size (**Figure 2.4**).

Table 2.3 *Categorization of water scarcity adaptation strategies adopted by rice farmers in irrigated lowland fields (in Burkina Faso in 2013-2018).*

Adaptation strategy	Frequency (%)	Category	Description	Land	Labor	Capital	Know-how
No rice cultivation	39.5	No rice cultivation	No cultivation of rice in critical seasons	0	0	0	0
Reduction of the share of the rice area cultivated	28.8	Reduction of the cultivated rice field size	Reducing rice field size in critical seasons	0	0	0	0
Night irrigation	0.2	Use of more irrigation water from the scheme	Increased use of water supplied by the irrigation scheme	0	+	0	0
Borrowing the water turn of neighbors & multiple irrigations per day	15.6						
Curing of canals	0.3						
Use of a motor pump	16.3	Use of motor pump for supplemental irrigation	Use of water for irrigation, as a secondary supply, once it becomes apparent that the primary supply will be unable to meet the full demand	0	0	+	+
Use of a tubewell	0.2						
Water retention pond	1.0						
Bunding	73.8	Water and soil conservation practices	Strategies aiming to control runoff and thus prevent loss of soil by erosion, improve soil water storage, and maintain or improve soil fertility and water use efficiency	0	+	+	+
Bund repairing	53.1						
Land leveling	21.2						
Organic fertilizer application	0.3						
Mulching with straw	0.2						
Farmers' system of rice intensification (transplanting of one or two young seedlings per hill, organic matter application, and reduction of irrigation water input)	0.3						
Delaying transplanting date	18.4	Adjustment of the agricultural calendar	Adjustment of the agricultural calendar	0	0	+	+
Use of short-duration rice varieties	0.2						
Water-saving non-rice and legumes crops	31.1	Crop rotation	Shift from rice to non-rice and legumes crops	0	+	+	0

About the demand for each factor of production (land, labor, capital, know-how), "+" means Yes; "0" means no effect.

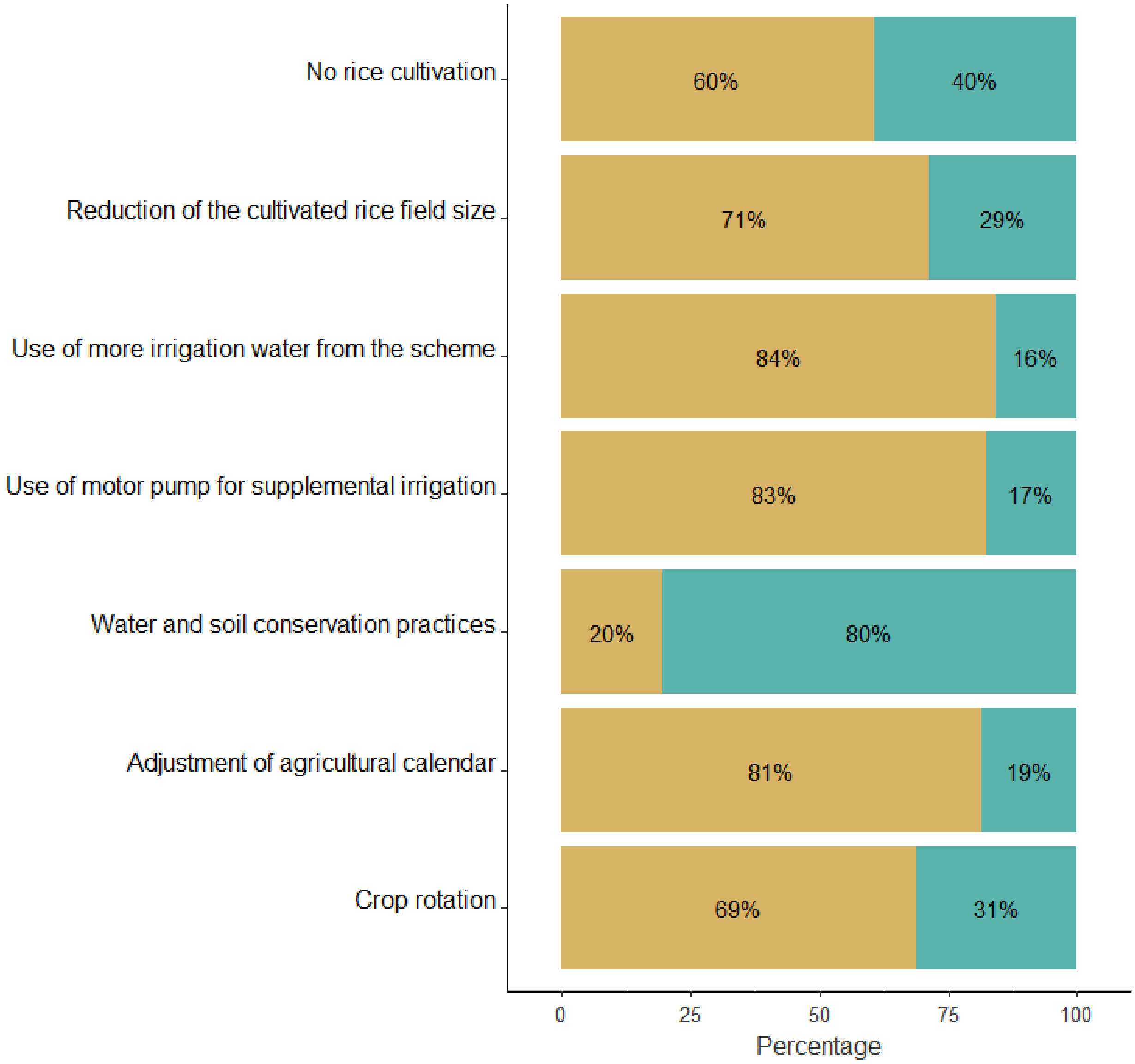


Figure 2.4. *Rice farmers' adaptation strategies to water scarcity.*

The coloring represents the proportion of each response ("No" or "Yes") for each adaptation strategy. The percentage on the left side is for "No" and the one on the right side for "Yes".

Among the farmers opting for "Crop rotation" as an adaptation strategy to water scarcity, almost half replaced rice with maize (*Zea mays*), a less water-demanding crop, during the dry season. After maize, other alternative crops to dry season rice comprised vegetables (31%), sweet potato (*Ipomea batatas*) (12%), and groundnut (*Arachis hypogaea*) (8%) (Fig. S8). However, the alternative crops to irrigated rice were site-specific. Thus, in Kou Valley, the most common alternative crop was sweet potato, whereas, in Zoungou, vegetables were the most common (Fig. S9).

To cope with water scarcity in their irrigated rice fields, farmers implemented up to six distinct adaptation strategies with an overage of two. There was a positive association between the typical grain yield and the number of active water scarcity adaptation strategies implemented. This means that as the number of adaptation strategies implemented on a farm increases, the typical rice yield tends to increase. Despite the small effect size ($\tau = 0.11$), the association was statistically significant ($p = 0.005$). Farmers implementing the maximum (5 and 6) adaptation strategies in their fields increased the typical rice yield in the dry season by 12% in comparison to those implementing one adaptation strategy.

2.3.4. Factors influencing smallholder farmers' choices of adaptation strategies

- *Analysis of the adaptation strategies*

Factors increasing or reducing the likelihood of farmers' decision to implement an adaptation strategy differed by site and household socio-economic attributes. Thus, non-association in farming groups and the perceived frequency of water scarcity in the rice fields negatively influenced the choice of the strategy "Use of more irrigation water from the scheme". Conversely, rice fields on light (loamy and sandy) soils, were positively associated with this adaptation strategy group (Table S10).

In comparison with rice farmers from wetter areas, and having agriculture as their main income source, those from drier zones and having trade as their main income source preferably selected the "Use of motor pump for supplemental irrigation" (Table S10).

Compared to farmers growing rice on clay soil, those on sandy soil were less likely to adopt "Water and soil conservation practices". Moreover, the probability of choosing and implementing this strategy group was lower for rice farmers in drier areas in comparison with those from wetter areas (Table S10).

Farmers complaining about irrigation water availability (scoring "Very bad" or "Bad") in the dry season were less likely to choose "Adjustment of the agricultural calendar" as an adaptation strategy to water scarcity. In contrast, compared to middle-aged adults, young adult-headed households were more likely to implement this strategy.

"Crop rotation" was a strategy more likely chosen by households belonging to a farming association, and having large rice field sizes (p = 0.06). Farmers complaining about the water availability from the irrigation scheme in the dry season were 18% more eager to implement this strategy. Female-headed households were 17% less likely to implement this strategy in comparison with male-headed households (Table S11). "Crop rotation" was more likely adopted on sandy soils in comparison with clayey soils.

Rice farmers from drier areas and those complaining about the water availability from the irrigation scheme in the dry season have a higher propensity to abandon rice cultivation. Our model failed to identify factors influencing the strategy "Reduction of the cultivated rice field size" (Tables S12 and S13).

- *Factors influencing the number of adaptation strategies implemented*

The climatic zone, the soil texture, the farming association membership, the gender of the household head, and the amount paid for irrigation water were key drivers explaining the number of adaptation strategies implemented by farmers (**Figure 2.5**).

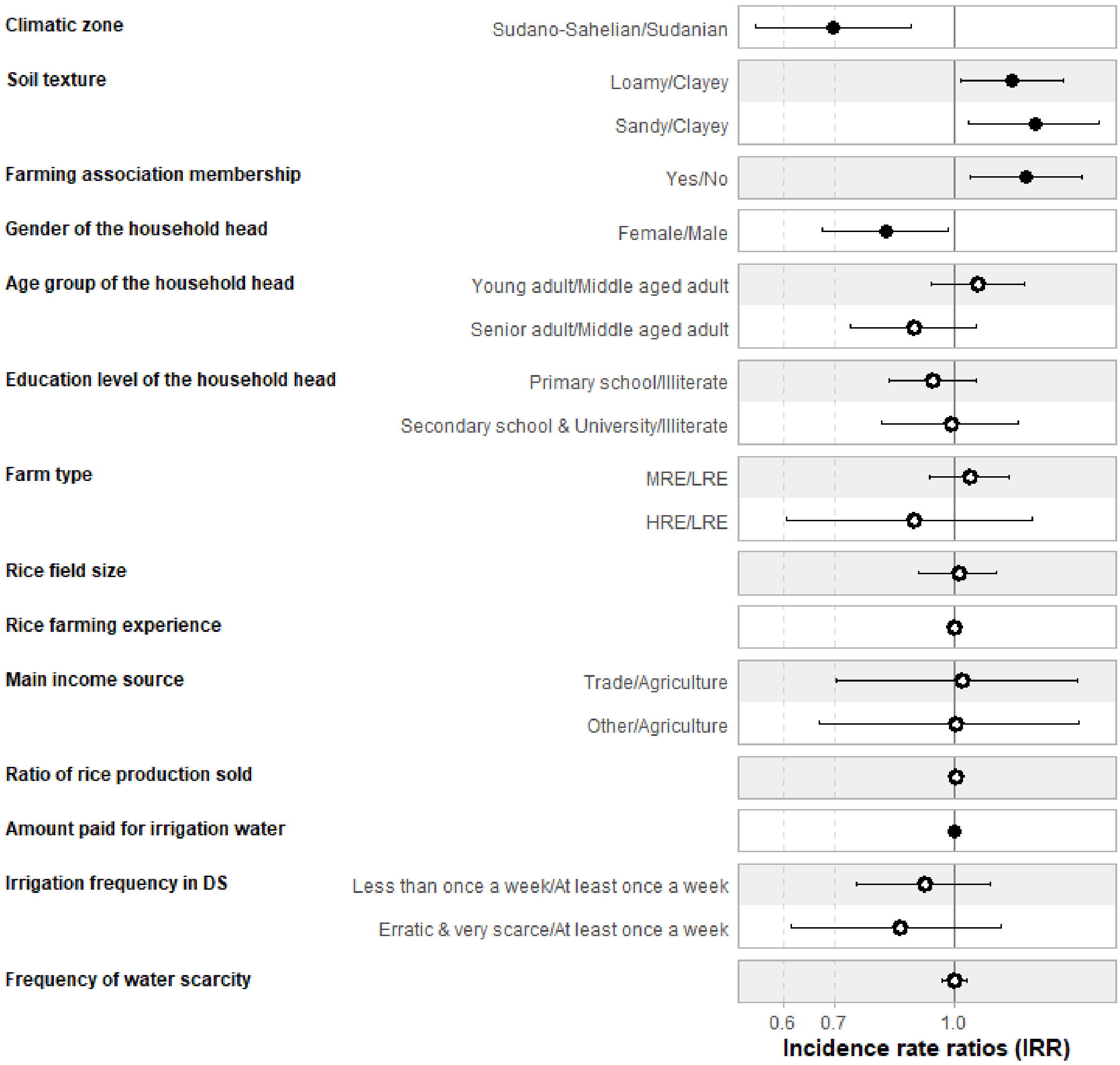


Figure 2.5. *Estimated Incidence Rate Ratio (IRR) (obtained by Poisson regression) and confidence intervals (95% CI) in the analysis of factors (climatic and environmental, institutional, socio-economics, and farmers' perceptions) associated with the number of water scarcity adaptation strategies (n = 572).*

Empty dot symbols mean the regression is not significant (p > 0.05). Filled dot symbol means the regression is significant (p < 0.05).

Farmers in drier areas (Sudano-Sahelian zone) were less likely to implement more adaptation strategies to water scarcity compared to farms in wetter areas (Sudanian zone). Male-headed households and farmers growing rice on loamy or sandy soils were more likely to adopt and implement several adaptation strategies compared to female-headed and those growing rice on heavy (clay) soils. Moreover, the farming association membership had a positive effect on the number of adaptation strategies adopted (**Figure 2.5**).

2.4. Discussion

2.4.1. Farm typology and effect of farm resource endowment on the yield

Smallholder farms differ in terms of capital assets, potential labor availability, land area, and investment capacity. Furthermore, we found that farm resource endowment had a significant effect on the grain yield with HRE and MRE farms obtaining higher rice yields than LRE farms (Table S4). This finding supports the conclusion of Falconnier et al. (2015) who showed that in the cotton zone of Southern Mali, LRE farms achieved lower land productivity for all crops than other farm types. In climbing bean farming systems in northern Rwanda, Franke et al. (2019) also reported the same conclusion by stating that poorer households achieved lower grain yields than wealthier households. Household resource endowment acts most likely as a proxy for the economic status of households. It affects a range of crop management factors such as access to mineral fertilizer and organic manure, ability to conduct crop management operations (land preparation and sowing/transplanting, weeding, fertilizer application, bird scaring) on time, and access to good quality seeds. In turn, those factors determine crop productivity.

2.4.2. Water management practices in irrigated lowland rice fields

Farmers' management practices in the dry climatic zones of West Africa were different among the irrigation schemes. During the wet season, farmers rely mainly on rainfall while irrigation is supplemental. However, in the dry season, due to the high pressure on water, the majority of farmers (59%) irrigated their fields once a week. Hence, most farmers did not practice strict continuous flooding which is still a popular water management practice in irrigated rice systems in Asia and America (Datta *et al.*, 2017; Singh *et al.*, 2017).

This study highlights two local perceptions, which could promote the implementation and adoption of water-saving technologies such as alternate wetting and drying (AWD) in rice fields. First, about 70% of survey rice farmers identify the periods around heading and flowering as the most sensitive phenological stages to drought, and hence during these periods, they take care to irrigate thoroughly their rice fields. This endogenous perception is in agreement with the current scientific insight which shows that the effect of drought stress on yield is most severe when drought occurs during panicle development (Boonjung & Fukai, 1996) and at the flowering stage (Cruz & O'Toole, 1984; Yang *et al.*, 2019). Second, although there is no economic incentive to implement water-saving technologies as farmers pay a fixed irrigation fee that is determined by the field size (but not on the amount of water used), about 90% of the surveyed household heads considered relevant and useful to save water in their rice fields. In the Philippines and Bangladesh, in both gravity-based and pumping irrigation systems, the lack of economic incentives was a key reason for the failure of scaling up AWD, a water-saving technology (Enriquez *et al.*, 2021).

2.4.3. Farmers' perceptions of water scarcity

This paper evidenced for the first time that water scarcity is currently a real issue in irrigated rice-based systems in dry (Sudanian and Sudano-Sahelian) climatic zones of West Africa. Indeed, more than three quarters declared having experienced water scarcity issues in their irrigated rice fields over the last five years. Water scarcity occurred essentially during dry seasons (April and March being the most critical months) (Fig. S4). This is congruent with the perception of the majority (83%) of respondents who felt that their access to irrigation water is restricted in dry seasons (Table S6). These perceptions are less subjective in comparison to those related to climate variability and climate change in other studies (Ayal & Leal Filho, 2017;

Ayanlade *et al.*, 2017). Indeed, sometimes the farmers' observations (e.g., rainfall trends) were inconsistent with the meteorological records (Ayal & Leal Filho, 2017). But, in this study, as farmers are witnesses and above all victims of water scarcity and its effect on the availability of irrigation water and productivity, their perceptions should be considered as solid empirical evidence. Thus, this is an additional evidence confirming that farmers in the Sahel are seriously concerned with the climate change and its corollary (drought) (Mertz *et al.*, 2009).

The current water scarcity in irrigated rice fields could be caused by several factors. The first cause could be the poor management and maintenance of the irrigation infrastructures. Indeed, the obsolescence of the irrigation infrastructure was noticeable in the oldest irrigation schemes: Karfiguela, Kou Valley, and Zoungou (Table S1). And these three irrigation schemes were those where we recorded more complaints about water scarcity (Table S6). Moreover, in these three irrigation schemes, we observed the illegal activity of water siphoning through bilge piping by farmers outside the irrigation schemes for the benefit of vegetable cropping. A second cause could be the adverse impact of climate change. Indeed, the trend analyses of the annual SPEI_12 from 1981 to 2017 showed that the climate is getting drier in our study sites. We found a decreasing pattern of the annual SPEI_12 and a drastic increase in the frequency of occurrence of dry years from 2000 to 2017 in comparison with the period 1981-1999. Thus, the severity and frequency of dryness events could explain the water scarcity situations. Therefore, adequate water-saving technologies should be tested, implemented, and adopted by farmers in that system. Finally yet importantly, the degradation of shared freshwater ecosystems, the competing demands for water resources, and the increasing population are other probable causes of water scarcity in these irrigated schemes.

2.4.4. Farmers' adaptation strategies to water scarcity

Most of the farmers' adaptation strategies to water scarcity listed have been also inventoried as farmers' strategies to cope with climate change effects and drought in paddy fields in drought-prone areas in Bangladesh (Alam, 2015; Alauddin & Sarker, 2014), China (Huang *et al.*, 2015), Iran (Esfandiari *et al.*, 2020), and Nepal (Khanal *et al.*, 2018). However, there are some water scarcity adaptation strategies listed in these studies that had not been explicitly mentioned by the rice farmers during our survey. Among those strategies appear: using high-yielding heat and drought-tolerant seed varieties (Alam, 2015), direct-seed rice (Alauddin & Sarker, 2014), crop insurance (Huang *et al.*, 2015), increasing seed rate, seed priming, reducing tillage, increasing the number of weeding and improving/increasing fertilizer use (Khanal *et al.*, 2018). While in drought-prone areas of Bangladesh, rice farmers preferred to increase the use of groundwater irrigation (Alam, 2015), our study revealed that the "Water and soil conservation practices" group was the most adopted and implemented water scarcity adaptation strategy, followed by the "Crop rotation". Similar to rice farmers in drought-prone regions in Bangladesh (Alam, 2015), rice farmers surveyed in this study implemented multiple adaptation strategies.

About 40% of the respondents declared abandoning rice cultivation during the challenging period. This proportion is very high in comparison with the one (5.6%) of rice farmers in drought-prone areas in Bangladesh (Alauddin & Sarker, 2014). This confirmed the previous findings showing that a large proportion of African smallholder farmers did not make any adjustments to their farming practices despite having perceived climate change adverse effects (Bryan *et al.*, 2009). Limited knowledge and lack of information about appropriate water scarcity adaptation strategies, inadequate irrigation facilities, or financial constraints could be the main barriers to adaptation

(Alauddin & Sarker, 2014; Bryan *et al.*, 2009). However, abandoning rice cultivation during dry seasons and focusing on other businesses could be a good risk adaptation strategy if income or any other key indicators of sustainability are improved.

In Nepal, Khanal et al. (2018) showed that the adoption of climate change adaptation strategies plays a significant role in enhancing rice yield. Our study supports this finding to some extent. It is also in line with Di Falco et al. (2011) and Huang et al. (2015) who showed the positive effects of adaptation on crop productivity in studies in Ethiopia and China, respectively. Moreover, we found that as the number of active adaptation strategies implemented on a farm increases, the rice yield tends to increase.

2.4.5. Determinants of smallholder farmers' choices of adaptation strategies

Empirical evidence showed that the decision-making drivers regarding farm-level adaptation strategies to water scarcity or climate change fall into five groups of factors: (i) climatic and environmental factors (Deressa *et al.*, 2009),(ii) institutional factors (Bryan *et al.*, 2009; Thoai *et al.*, 2018), (iii) socio-economic and demographic factors (Alam, 2015; Khanal *et al.*, 2018),(iv) irrigation scheme water supply (Aguilar *et al.*, 2022) and (v) farmers perceptions (Khanal *et al.*, 2018).

Climatic and environmental factors

Farmers in drier areas (Sudano-Sahelian zone) were less likely to adopt and implement multiple adaptation strategies to water scarcity (especially "Water and soil conservation practices") in comparison with farmers in wetter areas (Sudanian zone) (**Figure 2.5** and Table S10). This could be explained by the fact that water scarcity events in drier areas are more severe, risks are higher, and farmers who are willing to continue to grow rice find these strategies less relevant and inefficient in their context. This finding could also be a bias of our study. Indeed, in pump irrigation systems such as in Sourou Valley (a scheme in the Sudano-Sahelian zone), water is available and therefore there is no incentive to adopt and implement multiple adaptation strategies and “Water and soil conservation practices”. Although the water price in the Sourou Valley irrigation system was five times more expensive than in the others (that rely on surface water, e.g., river diversion), using this system positively influenced the farmers' resilience during the dry season.

In comparison with farmers growing rice on clayey soil, those growing rice on sandy soil were more likely to adopt and implement concomitantly several active adaptation strategies such as “Use of more irrigation water”, and “Crop rotation”. However, they have a lower propensity to adopt and implement “Water and soil conservation practices” (Table S10). This is understandable as they most likely consider this strategy group inappropriate for their soil. Indeed, bunding, the most popular strategy in this group, is challenging, as the construction of the bund requires moderate soil clay content. Viewed from another perspective, farmers growing rice on clayey soils implemented fewer adaptation strategies than those growing rice on sandy or loamy soil because the fine-textured soils have a higher water storage capacity that is adequate for paddy rice cropping. In addition, farmers perceived the bunding on clayey soils to be an effective water conservation practice.

Institutional factors

In general, farming association membership has a positive and significant effect on the number of active adaptation strategies adopted (**Figure 2.5**). More specifically, we found that it positively influenced the choice of the strategies “Use of more irrigation water from the scheme”, “Use of motor pump for supplemental irrigation” and adopt “Crop rotation” (Table S10). In other words, “free rider” farmers are less prone to adopt and implement more active adaptation strategies. Indeed, most of the time, public and private research and development organizations use farming associations as the main canal for sharing information concerning training on new agricultural technologies. And, by participating in the social activities of these associations, farmers can access useful information, knowledge, skills, and resources. Thus, farmers belonging to farming associations have generally a better knowledge of adaptation strategies. In turn, they are more eager and skilled to implement several strategies. This confirms, inter alia, the studies of Khanal et al. (2019) and Vo et al. (2021) (in Nepal and Vietnam, respectively) affirming that involvement in community-based organizations is an effective institutional instrument fostering the adoption of adaptation strategies.

Socio-economic and demographic factors

The gender of the household head significantly influenced the number and the type of active adaptation strategies adopted and implemented. In comparison with male-headed households, the lower propensity of female-headed households to implement "Crop rotation" could be explained by the fact that alternatives to rice such as vegetable crops are more labour-demanding (Brosseau *et al.*, 2021). Male-headed households have also a higher propensity to adopt and implement concomitantly several adaptation strategies. Several studies (Thoai *et al.*, 2018; Vo *et al.*, 2021) in other countries (Botswana and Vietnam) demonstrated similar findings. Part of the explanation likely lies in the comparative advantage of men to get information about new technologies. In addition, female farmers in developing countries generally have lower socio-economic resources (Arora-Jonsson, 2011) and are discriminated against access to farming associations, land, and farm equipment (Kinkingninhoun-Mêdagbé *et al.*, 2010) which most likely impede their adaptation propensity. Our results support also the hypothesis that males have generally higher natural risk-taking behaviour than females (Asfaw & Admassie, 2004).

Contrary to Deressa et al. (2009), we did not find a significant and positive effect of the age of the household head on the probability of adapting. However, we found that in comparison with middle-aged farmers, young farmers are more likely to adjust their agricultural calendar. This could be explained by their strong motivation in adapting to water scarcity and higher natural risk-taking behaviour.

Education is an important determinant in adopting adaptation strategies (Alam, 2015). However, contrary to Gebrehiwot and van der Veen (2013) and Vo et al. (2021), this study did not reveal a significant and positive effect of the level of education of the household head on the adaptation propensity to water scarcity-related risks.

The group strategy “Use of motor pump for supplemental irrigation” is resource-demanding as it requires holding a motor pump and buying fuel for irrigation. This explains that farmers having trade as their main income source in comparison with those relying solely on agriculture, have a higher propensity to implement it.

Irrigation scheme water supply

The water turn and availability on an irrigation scheme significantly influenced farmers’ choices of adaptation strategies. This supports previous studies showing that direct access to water sources is closely associated with overall farmers’ adaptation to water scarcity (Aguilar *et al.*, 2022) and points out the importance of good and timely maintenance of irrigation infrastructures for better scheme performance. In this sense, both national and local authorities in charge of water management on the schemes have key roles in helping farmers to cope with water scarcity.

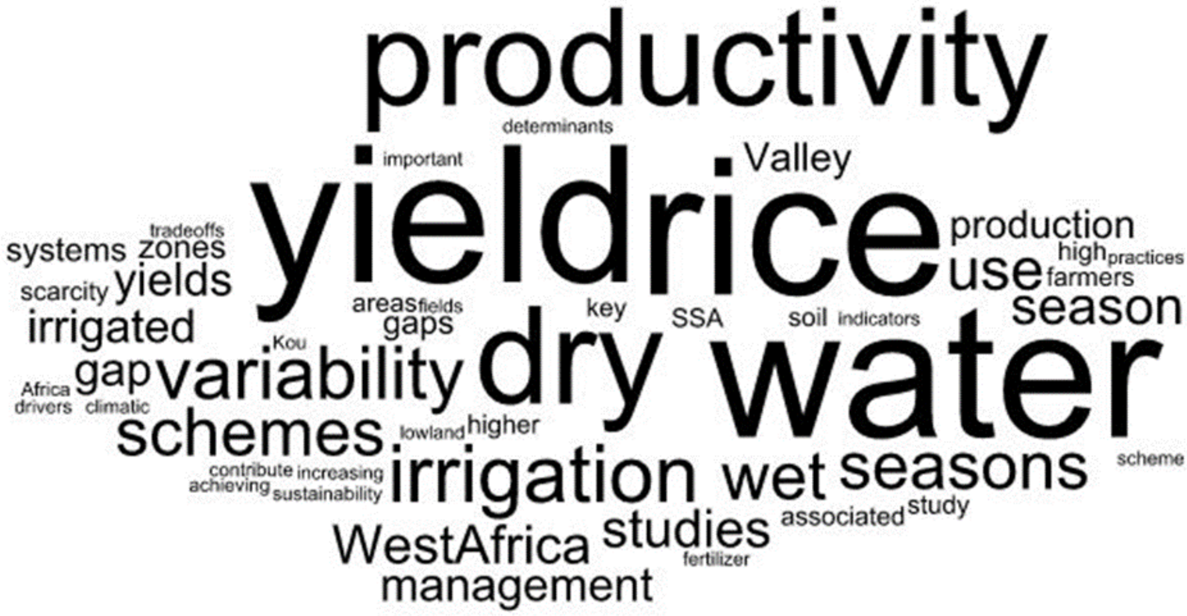
Farmers perceptions

The farmers' perception of water scarcity or other threats like global warming side effects shape their adaptation strategies (Alam, 2015; Mertz *et al.*, 2009). Indeed, we found that farmers' perception of the frequency of water scarcity events in the previous five-year term negatively influenced their likelihood to use more irrigation water from the scheme as an adaptation strategy. This could be explained by the fact they consider this strategy less efficient to cope with high climate-related risks.

2.5. Conclusion

Farmers in dry climatic zones of West Africa must rapidly adapt to emerging water scarcity to promote the sustainability of rice-based systems. To this end, studies on farmers' perceptions and on the factors driving decision-making and technology adaptation are fundamental. The present survey in contrasting irrigation schemes of Burkina Faso has provided a first inventory of the strategies adopted by rice farmers to counteract water scarcity and analyzed the determinants of adaptation strategies. Farmers' management practices differed both between schemes and among households within a scheme. While during the wet season rice farmers relied mainly on rainfall with some supplemental irrigation, during the dry season about half of the farmers irrigated their fields once a week and a quarter up to 2 times per week. Most respondents have experienced water scarcity in their irrigated rice fields and perceived access to irrigation water as a key limitation to rice production in dry seasons. Furthermore, increasing dryness trends have been visible since 2000 in some zones. To cope with and mitigate the adverse impacts of water scarcity, farmers implemented seven groups of adaptation strategies, the three most popular being "Water and soil conservation practices", "No rice cultivation" and "Crop rotation". However, farmers' choices of adaptation strategies varied with climatic zones, soil texture classes, farmers belonging to associations, gender, and irrigation water availability in dry seasons. Resource endowment had a significant effect on the yield. High and medium-resource endowed farms had higher rice yields. We thus advocate national policy interventions to aim at (1) improving households' livelihoods, (2) supporting the establishment and strengthening of farmer organizations, and (3) providing training on site- and system-specific adaptation to water scarcity and climate change, encouraging specifically the participation of female farmers. Such measures are expected to increase farmers' capacity to adapt to emerging water scarcity with positive impacts on crop productivity in the dry climatic zones of West Africa.

Chapter 3: Improving rice yield and water productivity in dry climatic zones of West Africa: Season-specific strategies [β]



Word cloud visualization of the 50 most frequent words in this chapter

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Abstract

Irrigated lowland systems contribute most to rice production in sub-Saharan Africa and play a critical role in meeting the increasing rice demand. However, in dry areas of West Africa, negative effects associated with climate change and widespread water scarcity hamper efforts to increase the productivity of irrigated rice. Quantifying rice yields and water productivity and identifying the drivers for the prevailing variability can aid in the targeting and dissemination of appropriate soil, water, and crop management practices.

The main objectives of this research were: (i) to quantify the rice yield gap in representative irrigated systems in dry areas of West Africa, both in wet and dry seasons, and identify factors that can contribute to narrowing the gap, and (ii) to assess the trade-offs or synergies between productivity and resource (water and fertiliser) use efficiency.

We monitored 203 and 192 smallholder farmers' fields in the wet and dry seasons, respectively, in four contrasting irrigation schemes in Burkina Faso from 2018 to 2020 and assessed key performance indicators (grain yield, water productivity, and nutrient use efficiency). We calculated rice yield gaps (difference between exploitable and actual farmer yields) and identified the drivers of yield and water productivity variability using machine learning and Shapley Additive exPlanations (SHAP) feature importance.

Indicators of productivity and sustainability differed between irrigation schemes and seasons. Rice yield was higher in wet (5.3 Mg ha^{-1}) than in dry seasons (3.7 Mg ha^{-1}), while the variability was higher in the dry (CV = 46%) than in the wet seasons (CV = 29%). In addition, the yield gap was slightly higher in the dry (36%) than in the wet seasons (31%). While differences in the number of seedlings per hill and the source of seeds were the key drivers of yield variability in wet-season rice, the split of N fertilizer applications, bird control, and the soil dryness index were the most important in dry-season rice. Furthermore, within seasons, high-yielding fields had higher water productivity, and N, P, and K use efficiencies.

These findings suggest that rice yields can be increased without trade-offs with water productivity and nutrient use efficiencies.

This is the first study highlighting the season-specificity of determinants of yield and yield variability in irrigated rice in West Africa. Improved water and fertilizer management can contribute to achieving the dual goal of narrowing the yield gap and improving water productivity, while increasing nutrient use efficiency, particularly in the dry season.

Keywords: Burkina Faso; machine learning; *Oryza spp.*; Shapley values; sub-Saharan Africa; water scarcity

3.1. Introduction

The population growth rate in sub-Saharan Africa (SSA) is the highest in the world, exceeding 2.6% per year since 2000 (The World Bank, 2022). This presents important advantages for the economy and commerce but also has downsides as it increases domestic food demand. Rice (*Oryza* sp.) is considered to play a key role in achieving the Sustainable Development Goals 1 – Zero Poverty and 2 – Zero Hunger. It is a traditional staple food in many parts of Africa and the second most important source of calories in SSA (Seck *et al.*, 2013). Moreover, demand for rice in SSA increases faster than anywhere else in the world. Thus, from 2008 to 2018, the annual rice consumption in SSA increased by 81% (FAO, 2020). However, domestic production in the predominating smallholder farms lags far behind consumption rates (Lowder *et al.*, 2016), entailing self-sufficiency rates as low as 60% (USDA, 2024). Over the last decades, efforts aimed at reversing this trend focused on expanding or rehabilitating rice irrigation schemes as the most productive environment for rice production. However, the yield gap (i.e., the difference between the potential and the actual yield obtained by farmers) is still large and estimated at around 4.96 Mg ha^{-1}, corresponding to an average relative yield gap of 55% (Dossou-Yovo *et al.*, 2020). Furthermore, in dry areas of West Africa, negative impacts related to climate change, such as heat waves and delayed onset of the rains with associated water scarcity, seriously hamper efforts to increase rice productivity in irrigated systems (Johnson *et al.*, 2023a). Narrowing yield gaps while increasing water productivity and minimizing environmental footprint is central to sustaining the irrigated lowland rice systems and in turn, achieving food security in SSA.

Quantifying the rice yield gap shows, how the lands are used in farmer conditions and identifying the causes for the prevailing variability can help in the development of appropriate soil, water, and crop management strategies for sustainably intensifying production. Likewise, yield gap studies contribute to designing research and development programs supporting progress toward the application of improved management practices that narrow yield gaps.

Most studies assessing on-farm rice yields, yield variability, and associated management practices (Becker *et al.*, 2003; Haefele *et al.*, 2002; Wopereis *et al.*, 1999) or profitability (Haefele *et al.*, 2000, 2001; Segda *et al.*, 2004) in dry areas of West Africa were conducted in the late 1990s. Only a few recent studies are available that were either based on field surveys (Niang *et al.*, 2017; Tanaka *et al.*, 2015) or on farmers' interviews (Arouna *et al.*, 2021a; Ibrahim *et al.*, 2022). Key determinants of low rice productivity in these studies were mainly related to inefficient weed control (Becker *et al.*, 2003; Haefele *et al.*, 2001) and poor nitrogen fertilizer management (Haefele *et al.*, 2002; Tanaka *et al.*, 2015; Wopereis *et al.*, 1999). Other agronomic constraints identified by these studies included the use of relatively old seedlings at transplanting, low or non-use of phosphorus fertilizers in P-deficient soils, unreliable irrigation water supply (Haefele *et al.*, 2001; Wopereis *et al.*, 1999), bird control (Tanaka *et al.*, 2015) and late harvesting (Haefele *et al.*, 2001; Wopereis *et al.*, 1999). Consequently, multiple split applications of N fertilizers, high weeding frequency, the use of certified seeds, and good land levelling have recently been shown to be associated with high grain yields across the West African region (Niang *et al.*, 2017).

Past studies (Niang *et al.*, 2017; Tanaka *et al.*, 2015) aiming to identify the factors explaining yield variability in dry climatic zones, were restricted to climatic, soil, and field management factors, but did not consider socioeconomic attributes of household, irrigation schemes and terrain attributes, and field water conditions. Although rice production in the dry season has an important share in global production and is seriously threatened by water scarcity (Johnson *et al.*, 2023a), most past studies focused on the wet season and very few assessed the yield gaps (Segda *et al.*, 2004) and identified determinants of yield variability in the dry season (Wopereis *et al.*, 1999). None of these studies compared performance indicators of productivity and sustainability between dry and wet seasons. Likewise, studies identifying the determinant of water productivity (Sawadogo *et al.*, 2023) or analyzing the trade-off between yield and water productivity in on-farm fields are scarce or even inexistent. We hypothesized that actual yields obtained by farmers in the dry zones of West Africa are higher in wet than dry seasons as the water scarcity impacts less the fields in wet seasons and that the determinants of variability of yield and water productivity are season-specific. We also surmised that increasing yields and narrowing yield gaps are associated with increased resource (water and fertilizer) use. Consequently, achieving both high yields and high resource-use efficiencies may present conflicting goals, potentially leading to trade-offs due to overuse and waste of resources. To investigate these hypotheses, we designed the present study, following four objectives: (i) describe current farmers' management practices in irrigated lowland rice systems, (ii) estimate yield variability and yield gaps during both dry and wet seasons, (iii) identify the key drivers of yield and water productivity variability, and (iv) assess trade-offs among sustainability indicators (grain yield, water productivity and partial factor productivity of N, P and, K) to provide season-specific recommendations for sustainable rice production.

3.2. Material and Methods

3.2.1. Description of the study area and site selection

The cross-sectional study of the rice productivity and sustainability performance indicators was conducted in irrigated rice-based farming systems in dry zones of West

Africa. Burkina Faso was selected as a case study of a Sahelian country in West Africa presenting contrasting dry climatic zones. Four sites were selected as being representative of irrigated lowland rice-growing areas in those zones, namely Karfiguela and Kou Valley irrigation schemes in the Sudanian zone, and Zoungou and Sourou Valley irrigation schemes in the Sudano-Sahelian zone (Fig. S1). Here, a “site” refers to an irrigation scheme, which is an area equipped with an organized system designed to deliver water, through any method, to agricultural land for crop cultivation. While the Kou Valley and Karfiguela irrigation schemes draw water from a river diversion headwork, the Zoungou and Sourou Valley schemes are supplied by a dam intake and a river pumping station, respectively. Thereafter, in all these irrigation schemes, water is conveyed gravitationally through a hierarchical irrigation canal system, and subsequently distributed to individual plots via bund breaks. The rice-growing area of the irrigation schemes ranges from 100 to 1,260 hectares, with Kou Valley being the largest and Zoungou the smallest. The irrigation schemes are divided into blocks for efficient water distribution and operational management. Drainage facilities are designed in every scheme but are not functional in every farmer's field. The background and history of these schemes differ; Kou Valley is the oldest scheme, commissioned in 1970, while Sourou Valley is the newest, commissioned in 2013. Due to poor maintenance of the infrastructures, the age of an irrigation scheme may serve as a proxy for its efficiency. These four sites cover diverse geographic and socio-economic conditions prevailing in West Africa [refer to Johnson et al. (2023) for a comprehensive description of the study area and sites].

3.2.2. Yield gap survey and data collection methods

From January 2018 to June 2020, farmers’ field surveys were conducted during both wet and dry seasons. We used stratified random sampling to accurately capture the variability in agricultural practices and yield outcomes within each study site (Tenorio *et al.*, 2024). This method of collecting survey and field data is considered reliable and cost-effective for assessing yield variability in both large- and small-scale systems while minimizing bias (Tenorio *et al.*, 2024). At each site (irrigation scheme), we selected all the blocks where rice was planned to be grown during the season. Thereafter, farmers' fields disposing of various resource endowments were purposely selected along different water access conditions (easy, intermediate or difficult access to the canal irrigation water), toposequence positions (flat, upper, middle, or lower parts) and soil texture (sandy, loamy, clayey). The aim was to cover a wide range of biophysical and socio-economic conditions. Data on (i) farm management practices (source of seeds, straw and residue management, tillage method, land levelling, sowing date, planting density, number of seedlings per hill, weed management, fertilizer management, pests control, irrigation frequency), (ii) pest incidence, (iii) field water status, and (iv) farmers' yield were collected using a standardized protocol [see Niang et al. (2017) and Tanaka et al. (2017)]. In brief, within each rice field, a survey plot of about 300 m^2 was established at the beginning of the season. Within each of these survey plots, three 12 m^2 harvesting areas were demarcated for assessing farmers' crop management practices and determining grain yield. At maturity, grain yield was measured in the three harvesting areas of 12 m^2, and averaged for the final estimation of yield per field. A total of 203 and 192 farmers' fields were surveyed in the wet and dry seasons, respectively (Table S1).

Nine soil cores were collected along diagonals from the surface layer (0–20 cm) in each surveyed field after ploughing and levelling but before basal fertilizer application. These cores were then combined to create a composite sample. The composite soil samples from each surveyed field were air-dried, sieved (2 mm), and analyzed for clay, silt, and sand contents (Robinson pipette method), pH H_2O (1:2.5), available P (Bray-2), total N and C contents (dry combustion method) according to analytical methods described by Niang et al. (2017) and Johnson et al. (2019). Elevation data was extracted from the Digital Elevation Model (DEM) of the Shuttle Radar Topography Mission (SRTM) at a 30 m resolution. Attributes of terrain and irrigation schemes (scheme age, source of the irrigation water, position on the toposequence, access to water, and drainage facilities) were collected either through field surveys and observation, or by interviews of key resource persons. In addition, we collected data on the socio-economic attributes of individual household heads (farmer characteristics and resource endowment) using a semi-structured questionnaire. The field and household surveys were carried out on an open-source suite of tools (Open Data Kit, ODK) that allows data collection using Android mobile devices, geo-location of plots (i.e. longitude and latitude) and data submission to an online server. We also retrieved 10-year weather data (solar radiation, maximum and minimum air temperature, relative air humidity and rainfall at daily time steps) for each site/scheme from the near real-time “aWhere” cloud-based data platform (aWhere, Inc., Broomfield, Colorado, United States). Information on the planting material (growth duration, variety type - i.e. tropical *japonica*, *indica*, upland NERICA or lowland NERICA, and potential yield of the variety) was obtained from published literature (Table S2).

Every three days, from two weeks after transplanting to maturity, the field water status was assessed visually and scored using a three-point scale (1: ponded water, 2: wet soil surface, 3: dry soil surface) by research technicians. The soil dryness index was calculated as the ratio between the number of days with the dry soil surface and the total number of recording days during the entire growing season. Similarly, the soil flooding index was calculated using the number of days with ponded water and expressed as a percentage. Thus, a soil dryness index of 0% indicates that the field has been continuously flooded or wet, while a soil dryness index of 100% indicates that the field has been continuously dry.

As recommended by Kool et al. (2020), we provided a comprehensive description of the farmers' fields and crop management practices. The final dataset consisted of 60 yield-determining variables classified into 8 groups: socio-economics factors, weather conditions, irrigation scheme and terrain attributes, soil fertility factors, planting material and genetics factors, farm management practices, pest incidence, and field water conditions. The full list and description of these variables are provided in **Table 3.1**.

3.2.3. Computation of sustainability performance indicators

To assess the productivity and sustainability of rice production, we computed, for each surveyed field, five performance indicators: (1) grain yield, (2) water productivity, (3-5) partial factor productivity of nitrogen, phosphorus, and potassium (PFPN, PFPP, and PFPK). Grain yield was expressed in Mg grain ha^{-1} at 14% moisture content. Water productivity (kg grain m^{-3} of water) was computed by dividing the grain yield by the total amount of water input (i.e., irrigation + rainfall) during the rice-growing period (from transplanting to crop harvest). The bucket method *(Trimmer, 1994)* was used to estimate the water flow rate in each field. The amount of water applied per irrigation was calculated by multiplying the water flow rate by the duration of the irrigation. During the growing season, this amount was estimated three to four times. For each field, the irrigation water input was calculated by multiplying the total number of irrigation events by the average water amount applied per individual irrigation. Partial factor productivity (kg grain kg^{-1} nutrient) of N (PFPN), P (PFPP), and K (PFPK) were calculated by dividing the measured grain yield by the respective amount of nutrient (N, P, and K) applied. The lower and upper benchmarks for water productivity (0.2 – 0.4 kg grain m^{-3} water), PFPN (30 – 100 kg grain kg^{-1} N applied), PFPP (100 – 300 kg grain kg^{-1} P applied), and PFPK (50 – 300 kg grain kg^{-1} K applied) were set as suggested by Bouman (2009) and (Devkota *et al.*, 2021). For water productivity, values < 0.2 kg grain m^{-3} of water were classified as wasteful water use, while values > 0.4 kg grain m^{-3} water were classified as efficient water use or even water saving *(Bouman, 2009)*. For PFP, values < the lower benchmarks (30 kg grain kg^{-1} N applied, 100 kg grain kg^{-1} P applied, and 50 kg grain kg^{-1} K applied) were considered inefficient, corresponding to a potential wasteful over-application. On the order hand, values > the upper benchmarks (100 kg grain kg^{-1} N applied, 300 kg grain kg^{-1} P applied, and 300 kg grain kg^{-1} K applied) suggest a potential risk of soil nutrient mining. The shares of farmer's fields presenting high water productivity and optimum partial factor productivities for N, P and K were calculated.

3.2.4. Data analysis and visualization

The field survey data submitted on a server were downloaded, cleaned, and gathered into an Excel spreadsheet. Then, the data was analyzed using R. 4.2.3 (R Core Team, 2023).

Descriptive statistics of production inputs and performance indicators

Household and weather characteristics, irrigation scheme, terrain and soil fertility attributes, farm management practices, pest incidence, and water input parameters presented as continuous variables were analyzed using descriptive statistics (means, medians, standard deviation, and interquartile range) while percentage shares were calculated on categorical variables. We compared those variables and productivity and sustainability performance indicators across (i) the seasons and (ii) the irrigation schemes by computing non-parametric tests (i.e., Mann-Whitney-Wilcoxon test for two independent groups or Kruskal-Wallis H test for more than two) as these continuous variables did not meet the normality of residues and homogeneity of variance. Furthermore, to compare the distribution of the categorical variables between (i) the seasons and (ii) the irrigation schemes, the Fisher's exact tests or the Chi-squared ($\chi2$) tests of independence were computed. When more than 20% of cells have expected frequencies < 5, we used Fisher's exact test because applying the approximation method ($\chi2$ test) is less accurate (Crawley, 2012).

Yield and water productivity gaps estimation

According to their yield level, farmers' fields were categorized into three groups: high- (top 10%), moderate- (middle 80%), and low- (bottom 10%) yielding fields for each unique combination of site, growing season, and year. Following Stuart et al. (2016), the absolute exploitable yield gap (YG) was defined as the difference between exploitable and actual yield, whereby exploitable yield (Ye) was calculated as the mean of the top-10% percentile farmers' yield and actual yield (Ya) was calculated as the mean grain yield of all farmers' fields for each site and season combination. The relative exploitable yield gap (YG) was calculated as the ratio between the absolute exploitable yield gap and the exploitable yield and expressed in percentage (Eq. 1).

$$YG = \frac{Ye-Ya}{Ye} \times 100 \quad (1)$$

Similarly, we calculated the field-level yield gap as the difference between exploitable and field-level yield. This method fits with our goal of identifying key drivers of yield variability and is robust as it prevents errors caused by single-field outliers (Tanaka *et* *al.*, 2017), and considers the bio-physical and socio-economic conditions (Stuart *et al.*, 2016). Using the same yielding field categories, relative gaps of water productivity, PFPN, PFPP, and PFPK were also calculated (Devkota *et al.*, 2019).

Machine learning techniques

Here, our focus is on grain yield and water productivity. Another study will specifically investigate the determinants of the variability of PFPN, PFPP, and PFPK. Preliminary statistical analyses indicated a difference in grain yield between wet and dry seasons. Therefore, to enhance our comprehension of the variability among growing seasons, separate models were fitted for both wet and dry seasons. To identify major determinants of the variability of yield and water productivity, the Random Forest (RF) algorithm (Breiman, 2001) was applied to (i) manageable factors i.e., factors associated with management practices (e.g., planting material, field-level management practices, pest incidence, and water input parameters), and to (ii) non-manageable factors i.e., factors describing general field attributes that are difficult to improve or regulate (e.g. socio-economic characteristics of households, weather conditions, irrigation scheme, terrain, and soil fertility attributes) (**Table 3.1**). We opted for Random Forest over multiple linear regression for four main reasons: (i) its nonparametric nature; (ii) it can handle multi-collinearity in the dataset and high dimensional data ($n \ll p$) (Boulesteix *et al.*, 2012); (iii) it can capture nonlinear association patterns between predictors and output (Strobl *et al.*, 2009); and (iv) its high predictive accuracy in agronomic data analysis (Jeong *et al.*, 2016; Nayak *et al.*, 2022).

Random forest models were built using the *RandomForest* package (Liaw & Wiener, 2002) with the leave-one-out cross-validation method and the algorithm parameters set as follows: number of trees to grow (n_{tree}) = 2500; number of variables randomly sampled as candidates at each split (m_{try}) = p/3; number of times the out-of-bag data are permuted per tree (m_{Perm}) = 3. The Lin's concordance correlation coefficient (CCC), along with the coefficient of correlation R^2, was used to quantify the agreement and goodness-of-fit (between observed and predicted values) of each Random Forest fitted model. Accuracy was assessed using the root mean square error (RMSE). Splitting a small modelling dataset into training and testing sets for evaluating model predictive ability presents certain limitations (Molinaro *et al.*, 2005). To overcome this issue, we applied the Random Forest algorithm to the entire dataset using the 10-fold cross-validation method repeated five times using the *caret* package (Kim, 2009; Kuhn, 2023) and computed the coefficient of determination (R^2).

To identify the key drivers of the variability of dependent variables, we calculated the Shapley values of each explanatory variable using the *fastshap* package (Greenwell, 2023). SHapley Additive exPlanations (SHAP) is a method intending to explain individual predictions of machine learning models (Lundberg & Lee, 2017). The idea of SHAP is to decompose a model prediction into additive contributions of the explanatory variables, and repeating this process for many observations provides a powerful means for explaining the model as a whole. We averaged the absolute Shapley values per explanatory variable across the observations to determine the global (or SHAP feature) importance [number of Monte Carlo repetitions (nsim) = 100]. According to this concept, an explanatory variable with large absolute Shapley values is important as his changing greatly affects the dependent variable. For the interpretation of the random Forest models, partial dependent plots were built (using *pdp* package; Greenwell, 2017) for the most influential independent variables to assess their effects on yield and water productivity in wet and dry seasons, allowing the visualization of the partial contribution and relationship (linear, monotonic, or nonmonotonic) of each independent variable when accounting for the average effect of the other variables (Friedman & Meulman, 2003).

Trade-off and synergy analysis of performance indicators

We compared production inputs and sustainability performance indicators between the three yielding categories (high-, moderate-, and low-yielding fields) of farmers in the wet and dry seasons using the Kruskal-Wallis H test. In addition, Spearman's correlation coefficients were calculated to examine the relationships between yield gaps and resource- (water and fertilizer) use efficiency indicators (Yuan *et al.*, 2021).

Table 3.1 *Independent variables used to explain the variability of yield and water productivity*

N°	Explanatory variables	Units	Type	Modalities	Data collection method
	Socio-economics factors				
1	Gender of the household head		Categorical	Female; Male	Survey
2	Education level of the household head		Categorical	Illiterate; Primary school; Secondary school	Survey
3	Number of farm workers		Quantitative		Survey
4	Rice field size owned	ha	Quantitative		Survey
5	Herd size	TLU#	Quantitative		Survey
6	Number of farm machines		Quantitative		Survey
7	Rice farming experience	years	Quantitative		Survey
8	Main income source		Categorical	Agriculture; Trade, Other	Survey
9	Irrigation water paid	€	Quantitative		Survey
	Weather conditions				
10	Cumulative solar radiation	kWh m^{-2}	Quantitative		aWhere data platform
11	Average maximum air temperature	°C	Quantitative		aWhere data platform
12	Average minimum air temperature	°C	Quantitative		aWhere data platform
13	Average relative air humidity	%	Quantitative		aWhere data platform
14	Rainfall volume	mm	Quantitative		aWhere data platform
	Irrigation scheme and terrain attributes				
15	Commissioning date (or scheme age)		Quantitative		Interview
16	Source of the irrigation water		Categorical	Dam water intake; River diversion; River pumping station	Interview
17	Elevation	m	Quantitative		DEM/NASA's STRM (30 m)
18	Position on the toposequence		Categorical	Flat; Upper; Middle; Bottom	Field survey & observation
19	Access to the irrigation water		Categorical	Easy; Intermediate; Difficult	Field survey & observation
20	Functional drainage facilities		Categorical	No; Yes	Field survey & observation
	Soil fertility factors				
21	pH H_2O (1:2.5)	-	Quantitative		Laboratory analyses
22	Total N	%	Quantitative		Laboratory analyses$

23	Total C	%	Quantitative		Laboratory analyses[$]
24	C:N ratio	-	Quantitative		Laboratory analyses
25	Available P (Bray-2)	mg kg^{-1}	Quantitative		Laboratory analyses
26	Clay content	%	Quantitative		Laboratory analyses[$]
27	Silt content	%	Quantitative		Laboratory analyses[$]
28	Sand content	%	Quantitative		Laboratory analyses[$]
	Genetic factors of the planting material				
29	Growth duration of the variety	days	Quantitative		Literature review
30	Yield potential of the variety	Mg ha^{-1}	Quantitative		Literature review
31	Variety type		Categorical	Tropical *japonica*; *indica*; Upland NERICA; Lowland NERICA	Literature review
	Farm management practices				
32	Source of the seeds		Categorical	Non-certified; Certified	Field survey & observation
33	Straw management		Categorical	Removing; Burning; Grazing *in-situ*; Mulching; Incorporation	Field survey & observation
34	Residue management		Categorical	Removing; Burning; Mulching; Incorporation	Field survey & observation
35	Tillage method		Categorical	No-tillage; Manual; Animal; Mechanical	Field survey & observation
36	Land levelling		Categorical	Poor; Good	Field survey & observation
37	Sowing date in the nursery		Quantitative		Field survey & observation
38	Age of the seedlings at transplanting	days	Quantitative		Field survey & observation
39	Planting density	hills m^{-2}	Quantitative		Field survey & observation
40	Number of seedlings per hill		Quantitative		Field survey & observation
41	Weeding frequency		Quantitative		Field survey & observation
42	Herbicide use		Categorical	No; Yes	Field survey & observation
43	Mechanical weeding		Categorical	No; Yes	Field survey & observation
44	Application of organic manure in the main field		Categorical	No; Yes	Field survey & observation
45	Application of mineral fertilizer in the nursery		Quantitative	No; Yes	Field survey & observation
46	Split of N fertilizer application		Quantitative		Field survey & observation
47	N application rate	kg N ha^{-1}	Quantitative		Field survey & observation

48	P application rate	kg P ha^{-1}	Quantitative		Field survey & observation
49	K application rate	kg K ha^{-1}	Quantitative		Field survey & observation
50	Insect and disease control frequency		Quantitative		Field survey & observation
51	Birds control		Categorical	No; Yes	Field survey & observation
52	Irrigation frequency		Quantitative		Field survey & observation
53	Irrigation water input	m^3 ha^{-1}	Quantitative		Field survey & observation
	Pest incidence				
54	Weed infestation above the canopy at flowering		Quantitative	0 = No weed; 1 = Weed cover ≤ 10% of ground cover; 2 = Weed cover > 10% and ≤ 30% of ground cover; 3 = Weed cover > 30% and ≤ 60% of ground cover; 4 = Weed cover > 60%	Field survey & observation
55	Weed infestation below canopy at flowering		Quantitative	0 = No weed; 1 = Weed cover ≤ 10% of ground cover; 2 = Weed cover > 10% and ≤ 30% of ground cover; 3 = Weed cover > 30% and ≤ 60% of ground cover; 4 = Weed cover > 60%	Field survey & observation
56	Insect damage at maturity		Categorical	No; Mild; Moderate	Field survey & observation
57	Disease damage at maturity		Categorical	No; Mild; Moderate; Severe	Field survey & observation
	Field water conditions and total water input				
58	Total volume of water input (Rainfall + Irrigation)	m^3 ha^{-1}	Quantitative		Field survey & aWhere
59	Soil flooding index	%	Quantitative		Field survey & observation
60	Soil dryness index	%	Quantitative		Field survey & observation

[#] The herd size was expressed in tropical livestock units (TLU) of 250 kg.

[$] Clay, silt, and sand contents were assessed using the Robinson pipette method, and total N and C contents by dry combustion.

3.3. Results

3.3.1. Characteristics of irrigated rice production systems

Weather conditions during the rice growing period differed substantially between sites (Table S3) and seasons (Table S4). On average, the relative air humidity was 68% and 36% and the cumulative rainfall volume during the rice-growing period was 353 and 51 mm in the wet and dry seasons, respectively. Cumulative solar radiation and average maximum air temperature during the growing period were higher in dry (611 kWh m^{-2} and 38 °C) than in wet (558 kWh m^{-2} and 34 °C) seasons (Table S4). Soil fertility attributes varied highly (CV = 16 – 99%) across farmers' fields, with available P (Bray-2) showing the highest coefficient of variation. Soil pH (H_2O) ranged from 4.5 (strongly acid) to 8.5 (strongly alkaline) with an average of pH 6.2. Total N and total organic C ranged from 0.02 to 0.22 with an average of 0.08% and from 0.18 to 2.13 with an average of 0.95%, respectively (Tables S5 and S6). The soil fertility attributes in the wet and dry seasons were in the same range (Table S6).

The mean size of rice fields owned by households (0.63 ha) varied across irrigated schemes, ranging from 0.12 (Zoungou) to 1.58 ha (Sourou Valley) (Table S7). Rice straw from the previous season was removed in half of the studied fields for use as animal feed and burned in 20% of the fields. In 15% of the fields, straw was grazed *in-situ*, and in 15% of the fields, it was returned by either mulching or incorporation (Table S8). These proportions were similar in both seasons (Table S9). Field residues (rice stubbles and weeds) were incorporated into the soil in 70% of fields. More than 70% of all farmers tilled their fields with animal traction. Mechanical tillage, using a power tiller, was practised in only 13% of the cases. Manual tillage was more frequent in dry (28%) than in wet seasons (2%). While all farmers used bunds around their paddy fields, only half of the fields were well-levelled, irrespective of the season. Non-certified seeds were used in almost 60% of the surveyed fields. Farmers used more frequently certified seeds in the wet (51%) than in the dry seasons (33%). The average growth duration of varieties was 118 ± 12 days and almost similar in the wet (120 ± 11) and dry seasons (115 ± 13). Transplanting was the main crop establishment method in both seasons. Across schemes, the mean sowing date in the nursery was July 26th (day 207 ± 23) in the wet, and January 12th (day 12 ± 29) in the dry season. Wet season rice was seeded the earliest (day 195 ± 12) in Sourou Valley, and the latest (day 213 ± 17) in Karfiguela. Similarly, in the dry season, rice was seeded earliest (day -20 ± 11) in Sourou Valley, and latest (day 67 ± 14) in Karfiguela. On average, farmers transplanted 24-day-old seedlings. Seedling age and the number of seedlings per hill at transplanting were similar in both seasons (Table S9). During the rice-growing period, farmers weeded their rice fields between one and five times with an average of two, and in three-quarters of cases, they used herbicides at least once (Table S8). The weeding frequency was almost similar in both seasons. However, herbicide use was more frequent in the wet (97%) than in dry seasons (54%) (Table S9).

While organic manure was applied in less than a quarter of fields, mineral fertilizer was usually used (99%). Mineral fertilizer application rates differed between schemes with 1 to 4 applications (average of 2). Thus, N, P, and K were applied at average rates of 126, 17, and 25 kg ha^{-1}, respectively (CV ranging between 39 and 49%). The N and K rates were similar in the wet (124 kg N ha^{-1} and 26 kg K ha^{-1}) and the dry seasons (128 kg N ha^{-1} and 24 kg K ha^{-1}). The P fertilizer application rates tended to be higher in wet seasons (19 kg P ha^{-1}) than in dry seasons (16 kg P ha^{-1}) (Table S9). Application of mineral fertilizer in the nursery was not a common practice (29% of cases).

Insects and diseases were controlled in all four irrigation schemes, however at different frequencies. Bird control measures were taken in 37% of surveyed fields and were more frequent in Sourou Valley (91% of cases) than in Zoungou (9%) and Karfiguela (16%) (Table S8) and more so in the dry than in the wet seasons (Table S9).

Although irrigation systems were available and operational in all sites, irrigation frequency and water inputs differed between schemes and seasons. On average across schemes, during the dry season, fields were irrigated 16 times, providing 3916 m^3 ha^{-1}, and 5 times in the wet season, supplying 1190 m^3 ha^{-1} (Table S9). Irrigation water input was the highest in Sourou Valley (14 irrigation events and 5146 m^3 ha^{-1}) and the lowest in Karfiguela (5 irrigation events and 944 m^3 ha^{-1}) (Table S8).

Pest incidence differed between irrigation schemes. Only 17% of all fields were completely weed-free at the flowering stage of rice. Weed infestation below the rice canopy was the highest in Karfiguela and the lowest in Sourou Valley, while disease damage at maturity was frequent in Kou Valley and almost non-existent in Sourou Valley (Table S10). Dominant plant disease symptoms were indicative of Brown Spots, Leaf Blasts, and Bacterial Leaf Streak with the highest incidences during the wet season (Table S11).

Field water conditions varied across schemes and seasons. Across schemes, soil dryness and flooding indices ranged from 0 to 56% and from 0 to 100%, with an average of 3% and 60%, respectively. Continuous flooding irrigation was strictly implemented only in 2% of the surveyed fields and only in the wet season. The soil flooding index was higher in the wet (65% ± 21%) than in the dry (54% ± 22%). On average, fields in Sourou Valley had the highest soil flooding index (78 ± 14) while Kou Valley (54 ± 20) and Zoungou (55 ± 22) had the lowest. The total water input (irrigation

+ rainfall) was highly variable (CV=48%) with an average of 4062 m^3 ha^{-1} $season^{-1}$. It varied between schemes but not between seasons. On average, the total seasonal water input to rice fields was highest in Sourou Valley (6386 ± 3243 m^3 ha^{-1}) and lowest in Karfiguela (4069 ± 1811 m^3 ha^{-1}) and Kou Valley (4128 ± 1776 m^3 ha^{-1}) (Table S12). Total water input was comparable between seasons with 4620 ± 1761 m^3 ha^{-1} in the wet and 4577 ± 2661 m^3 ha^{-1} in the dry season (Table S13).

3.3.2. Seasonal and spatial variation of productivity, sustainability indicators, and yield gaps

Productivity (grain yield) and sustainability indicators (WP, PFPN, PFPP, and PFPK) differed significantly among irrigation schemes and seasons. Grain yields varied (CV = 40%) from 0.8 to 10.9 Mg ha^{-1} with an average of 4.6 Mg ha^{-1} (**Figure 3.1**).

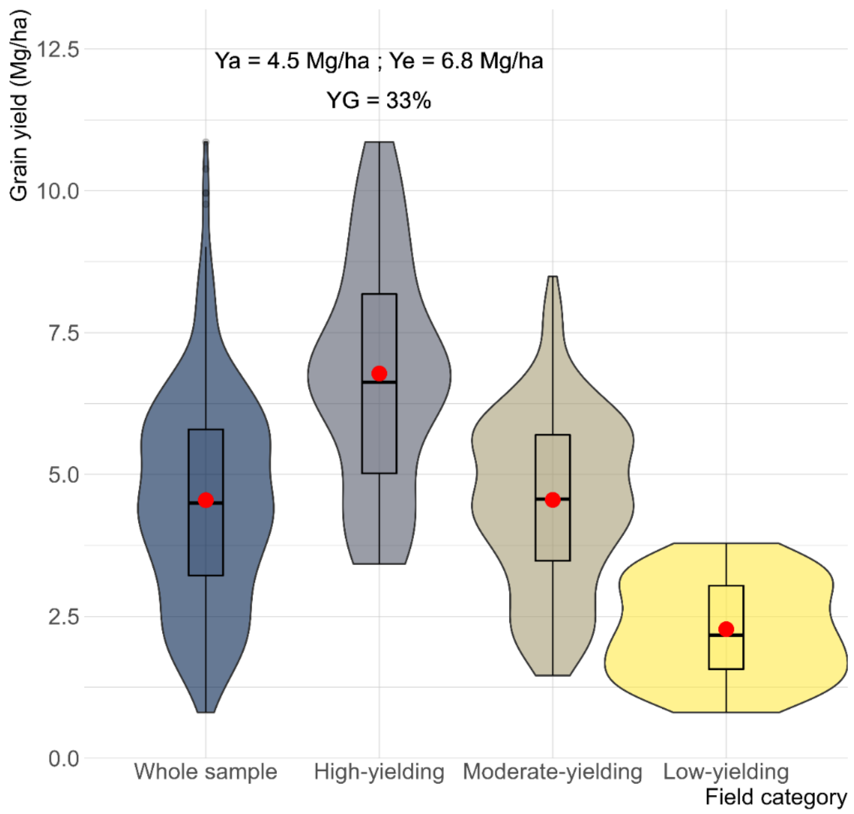


Figure 3.1. *Actual grain yield (i.e., mean of all fields) (Ya), "exploitable" yield (Ye) (i.e., mean of the high-yielding fields), and exploitable yield gap (YG) across sites and seasons in irrigated lowland systems in Burkina Faso in 2018-2020.*

High-yielding, moderate-yielding, and low-yielding fields cluster the top 10%, middle 80%, and bottom 10% percentile fields, respectively, for each unique combination of site, growing season, and year. The black solid line inside a box plot indicates the median and the red dot, the mean.

Over half of the fields had a yield lower than the overall average (4.6 Mg ha^{-1}). Yields were lowest in Zoungou (3.9 Mg ha^{-1}), where 71% of the farmers obtained less than the overall mean yield (**Figure 3.2**). Highest mean yield was obtained in Sourou Valley, with an average of 5.2 Mg ha^{-1}. Kou Valley and Kafiguela took an intermediate position with mean yields of 4.9, and 4.7 Mg ha^{-1}, respectively (Table S14). Irrespective of the irrigation scheme, yields tended to be higher in wet (5.3 Mg ha^{-1}) than in dry seasons (3.7 Mg ha^{-1}) but more variable in the dry (CV = 46%) than in the wet seasons (CV = 29%) (Table S15), except for Kou and Sourou Valleys where the yields in wet and dry seasons were similar (Fig. S2).

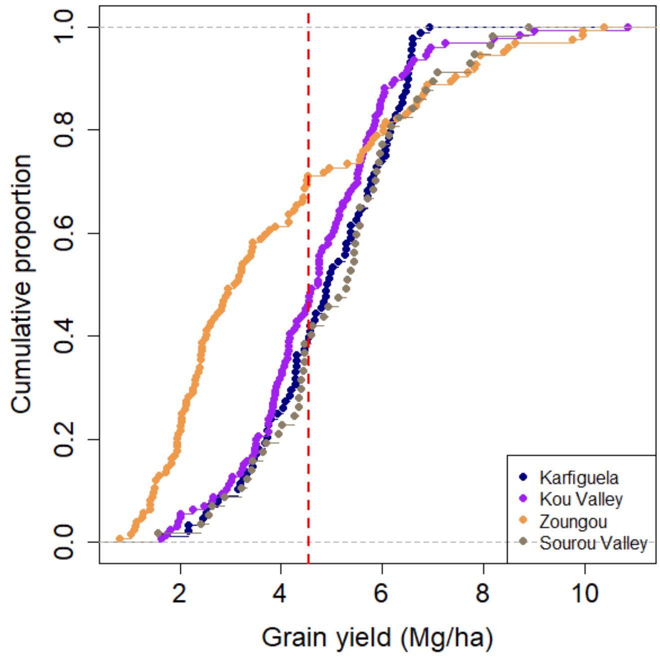


Figure 3.2. *Cumulative distribution probability of grain yield (Mg ha^{-1}) in Karfiguela, Kou Valley, Zoungou, and Sourou Valley irrigation schemes in 2018-2020.*

The dashed vertical red line indicates the global average yield (4.55 Mg ha^{-1}).

Irrespective of the seasons and schemes, the yield gap was 2.3 Mg ha^{-1} accounting for 33% of the exploitable yield (Ye) (**Figure 3.1**). The highest yield gap (37%) occurred in the schemes at Zoungou and Kou Valley and the lowest in Karfiguela (20%) (**Figure 3.3**). Mean yield gaps tended to be higher in dry (36%) than in wet seasons (31%) (**Table 3.2**; Fig. S3), except in Kou Valley (Fig. S4).

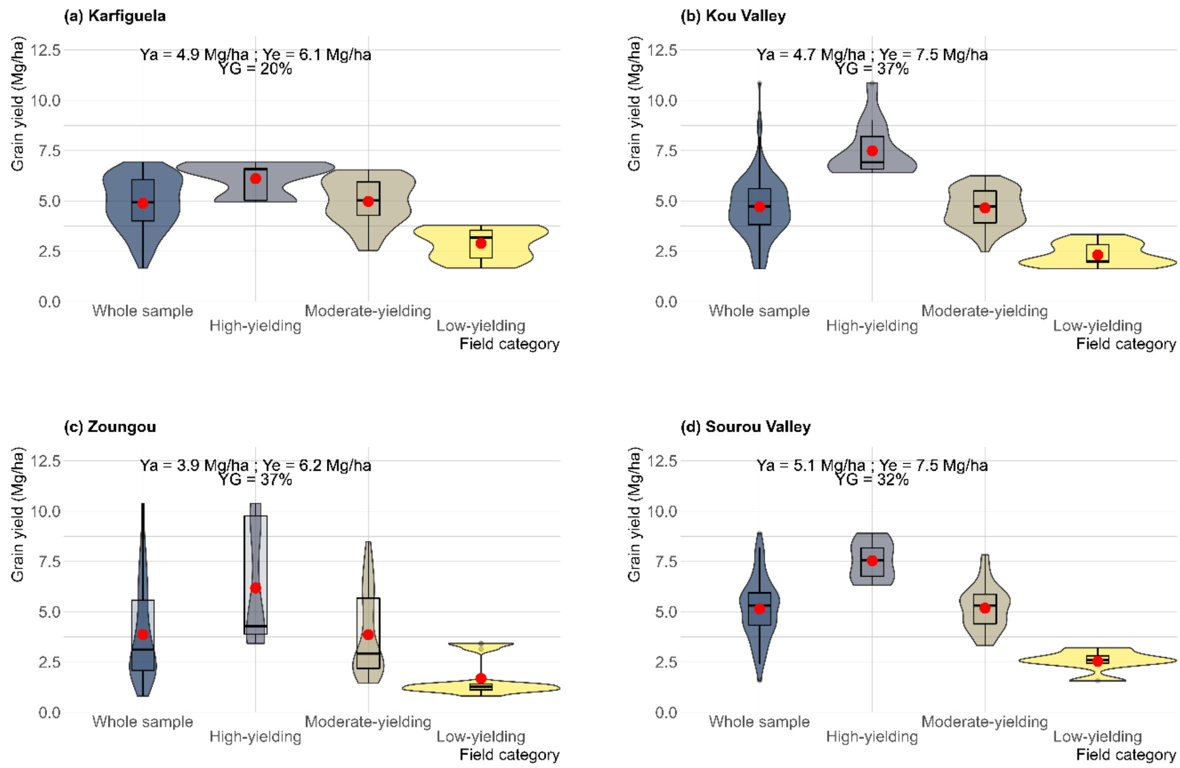


Figure 3.3. *Actual grain yield (i.e., mean of all fields) (Ya), "exploitable" yield (Ye) (i.e., mean of the high-yielding fields), and exploitable yield gap (YG) in* ***(a)*** *Karfiguela,* ***(b)*** *Kou Valley,* ***(c)*** *Zoungou, and* ***(d)*** *Sourou Valley irrigation schemes in 2018-2020.*

High-yielding, moderate-yielding, and low-yielding fields cluster the top 10%, middle 80%, and bottom 10% percentile fields, respectively, for each unique combination of site, growing season, and year. The black solid line inside a box plot indicates the median and the red dot, the mean.

Water productivity strongly varied between schemes and seasons, and also among farmers within each scheme (CV = 66%). Most farmers used the available water resources efficiently [i.e., had water productivity > 0.4 kg grain m^{-3} water] (**Table 3.3**). On average, water productivity was higher in Karfiguela, Kou Valley, and Zoungou (1.53, 1.38, and 1.23 kg grain m^{-3} of water, respectively) than in Sourou Valley (0.94 kg grain m^{-3} of water). Across schemes, water productivity was higher in the wet (1.40 kg grain m^{-3} of water) than in the dry season (1.19 kg grain m^{-3} of water) (Tables S15 and S16), a trend that was evident in all irrigation schemes except in Kou Valley (Fig. S5). The water productivity gap was also higher in the wet (35%) than in the dry seasons (23%) (**Table 3.2**).

Table 3.2 *Productivity and sustainability indicators (mean ± standard deviation) of irrigated rice in Burkina Faso in wet (n = 203) and dry (n = 192) seasons (2018-2020)*

Indicators	Wet season			Dry season		
	Whole sample	Top 10% (Target)	Exploitable gap (%)	Whole sample	Top 10% (Target)	Exploitable gap (%)
Grain yield (Mg ha^{-1})	5.32 ± 1.56	7.72 ± 1.38	31	3.73 ± 1.73	5.79 ± 2.05	36
Water productivity (kg grain m^{-3} water)	1.40 ± 0.86	2.17 ± 0.98	35	1.19 ± 0.83	1.55 ± 1.39	23
Partial factor productivity of N (PFPN) (kg grain kg^{-1} N)	49 ± 27	73 ± 21	33	36 ± 38	53 ± 27	33
Partial factor productivity of P (PFPP) (kg grain kg^{-1} P)	322 ± 165	528 ± 279	39	286 ± 206	475 ± 403	40
Partial factor productivity of K (PFPK) (kg grain kg^{-1} K)	229 ± 127	378 ± 230	39	177 ± 109	270 ± 208	35

The partial factor productivity of applied N, P, and K fertilizers varied between seasons and among farmers within each scheme with averages of 43, 305, and 204 kg grain per kg of N, P, and K, respectively (Table S14). Nearly one-third of farmers were likely wasting N fertilizer due to high application rates of N and low yield resulting in very low PFPN (PFPN < 30 kg grain kg^{-1} N). On the other hand, almost half of the farmers (43%) were mining P stocks due to low P application rates and high yield, resulting in very high productivity of applied P (PFPP > 300 kg grain kg^{-1} P) (**Table 3.3**). Across schemes, the productivities of applied N, P, and K were higher in the wet (49 kg grain kg^{-1} N, 322 kg grain kg^{-1} P, and 229 kg grain kg^{-1} K) than in the dry seasons (36 kg grain kg^{-1} N, 286 kg grain kg^{-1} P, and 177 kg grain kg^{-1} K) (Table S15). The partial factor productivity gaps of applied N, P, and K in the wet (33%, 39%, and 39%, respectively) and dry seasons (33%, 40%, and 35%, respectively) were in the same range (**Table 3.2**).

3.3.3. Main drivers of rice yield and water productivity variability and their impact

Regardless of the seasons, the agreement and goodness-of-fit between the observed grain yields and the predicted yields from the random forest models were excellent (CCC ≥ 0.9; R^2 ≥ 0.85). The RMSE was about 0.6 Mg ha^{-1}. However, the predictive ability of the models was moderate. The random forest models fitted with the manageable factors explained 30% of the yield variability, while those fitted with the non-manageable factors explained 15% to 25% of the yield variability (**Table 3.4**).

Table 3.3 *Proportion (%) of rice farmers implementing optimum levels of water productivity and partial factor productivity of N, P, and K in different irrigation schemes in Burkina Faso (2018-2020)*

Indicators threshold levels	Karfiguela	Kou Valley	Zoungou	Sourou Valley	Overall
Water productivity (kg grain m^{-3} water)					
Low (wasteful water use)	0.0	0.0	0.0	1.8	0.3
Optimum range	1.1	2.5	10.1	3.5	4.1
High (water saving)	98.9	97.5	89.9	94.7	95.6
Partial factor productivity of N (PFPN) (kg grain kg^{-1} N)					
Too low (wasteful application)	23.9	31.2	45.5	33.3	34.3
Optimum range	75.0	67.2	49.6	64.9	63.2
Too high (risk of soil mining)	1.1	1.6	5.0	1.8	2.6
Partial factor productivity of P (PFPP) (kg grain kg^{-1} P)					
Too low (wasteful application)	3.4	0.8	16.5	1.8	6.2
Optimum range	73.9	43.2	49.6	36.8	51.2
Too high (risk of soil mining)	22.7	56.0	33.9	61.4	42.6
Partial factor productivity of K (PFPK) (kg grain kg^{-1} K)					
Too low (wasteful application)	0.0	0.8	8.7	1.8	3.2
Optimum range	97.6	88.0	76.5	80.7	85.5
Too high (risk of soil mining)	2.4	11.2	14.8	17.5	11.3

For Water productivity, Too low (wasteful water use, < 0.2); Optimum range (0.2 - 0.4); High (water saving, > 0.4);
For PFPN, Too low (wasteful application, < 30); Optimum range (30 - 100); Too high (risk of soil mining, > 100)
For PFPP, Too low (wasteful application, < 100); Optimum range (100 - 300); Too high (risk of soil mining, > 300)
For PFPK, Too low (wasteful application, < 50); Optimum range (50 - 300); Too high (risk of soil mining, > 300)

Irrespective of the irrigation scheme, the main determinants of yield variability were season-specific. Thus, in the wet season, the number of seedlings per hill, the source of seeds, and disease damage at maturity were the three most influential manageable factors (**Figure *3.4a***). On the other hand, in the dry season, split of N fertilizer application, bird control and the soil dryness index were the most important (**Figure *3.4b***).

In the wet season, reducing the number of seedlings from three to one per hill increased yield by 550 kg (~10%). Using certified seeds led to higher yields compared with the use of non-certified ones. Moderate disease damages at maturity reduced yield by 300 kg (~5%) compared with disease-free field status (**Figure *3.4a***). In the dry season, grain yields increased by 500 kg (~13%) in the absence of water stress (soil dryness index = 0%) compared to fields with a soil dryness index of 20%. Also, controlling birds provided a net yield increase. Mineral N fertilizers splitting increased grain yields by 350 kg when increasing the frequency of split applications from 2 to 3 times per season (**Figure *3.4b***).

Table 3.4 *Evaluation of the goodness-of-fit and predictive ability of the random forest models*

	Wet season (n = 203)		Dry season (n = 192)	
	Grain yield (kg ha^{-1})	Water productivity (kg grain m^{-3} water)	Grain yield (kg ha^{-1})	Water productivity (kg grain m^{-3} water)
Manageable factors				
R^2 (leave-one-out cross-validation)	0.28	0.79	0.31	0.44
R^2 (10-fold cross-validation)#	0.34	0.83	0.42	0.62
Goodness-of-fit (R^2)$	0.86	0.96	0.87	0.90
Lin's concordance correlation coefficient (CCC)$	0.91	0.98	0.92	0.94
Model accurarcy (RMSE)$	539	0.15	616	0.25
Non-manageable factors				
R^2 (leave-one-out cross-validation)	0.14	0.72	0.25	0.23
R^2 (10-fold cross-validation)#	0.26	0.75	0.35	0.40
Goodness-of-fit (R^2)$	0.85	0.95	0.87	0.86
Lin's concordance correlation coefficient (CCC)$	0.89	0.97	0.92	0.91
Model accurarcy (RMSE)$	559	0.17	628	0.30

Values computed based on 10-fold cross-validation.

$ Values computed from a model based on the full dataset.

Among the yield and yield variability-affecting factors that cannot be controlled by agronomic management practices, the rainfall amount was the most influential in the wet season, followed by the functional drainage facilities, and solar radiation. Grain yields decreased when the rainfall amount exceeded 500 mm. Surprisingly, fields equipped with functional drainage facilities exhibited lower yields (Fig. S6a). In the dry season, solar radiation, and relative air humidity were the prominent non-manageable factors explaining the yield variability (Fig. S6b). Highest yields were achieved when cumulative solar radiation reached 1000 kWh m^{-2}, or when relative air humidity was approximately 40% (Fig. S6b).

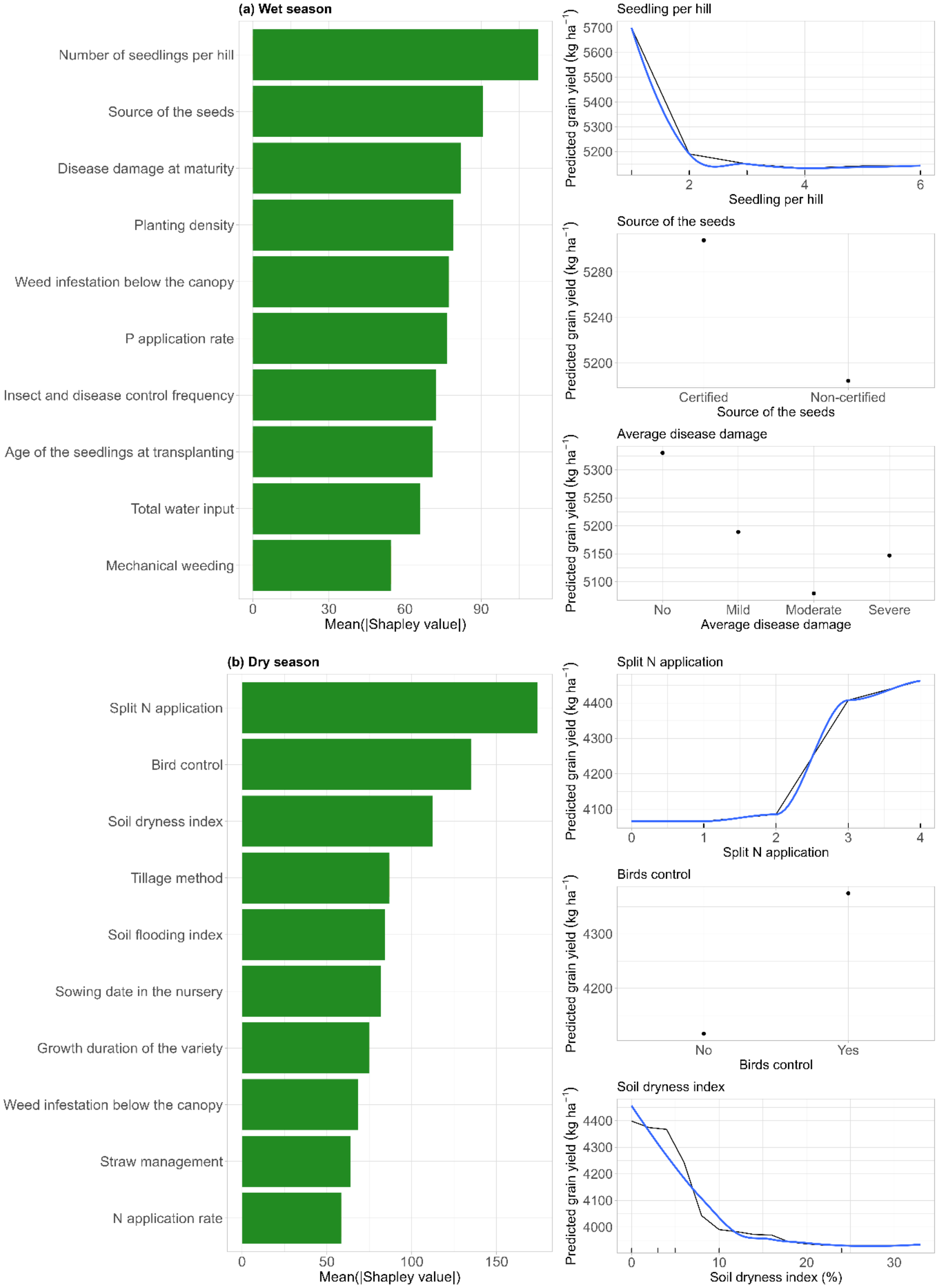


Figure 3.4. *Manageable factors explaining yield variability and their effect on the variation of yield in* ***(a)*** *wet season, and* ***(b)*** *dry season in irrigated lowland systems in Burkina Faso in 2018-2020.*

Results are from random forest models. Only the top 10 most important factors are displayed. The variable importance is expressed as the mean of the absolute Shapley values. Only partial dependence plots (PDPs) of the three top-ranked predictor variables of yield variability are displayed. Each PDP (black line) is overlaid by a Locally Estimated Scatterplot Smoothing (LOESS) curve (blue line). The Y-axis of each plot indicates the average effect of different values or categories of the X predictor on the predicted yield (kg ha^{-1}).

The agreement and goodness-of-fit of the fitted models for water productivity were consistently excellent across seasons (CCC ≥ 0.9; $R^2 \geq 0.85$). The RMSE ranged from 0.15 to 0.3 kg grain m^{-3} of water. However, the predictive ability of the models varied between seasons, with stronger performance in the wet season and moderate performance in the dry season. In the wet season, the random forest models explained 70% to 80% of the variability in water productivity, while in the dry season, 20% to 45% of the variability is explained (**Table 3.4**).

In the wet season, among the factors that farmers can influence through management practices, total water input was by far the most influential factor determining water productivity variability, followed by the sowing date. Specifically, total water input exceeding 5000 m^3 ha^{-1} resulted in very low water productivity. Additionally, sowing around mid-August (Julian data 225) was associated with higher water productivity in the wet season (**Figure 3.5*a***).

In the dry season, total water input and irrigation water input were the two most important ones. Here also, excessive water input led to reduced water productivity (**Figure 3.5*b***). While in the wet season, rainfall and solar radiation were the two most influencing non-manageable factors explaining the variability of water productivity (Fig. S7a), in the dry season, the scheme age and relative air humidity were the most important ones. In the dry season, water productivity was higher in older schemes but lower in recent ones (Fig. S7b).

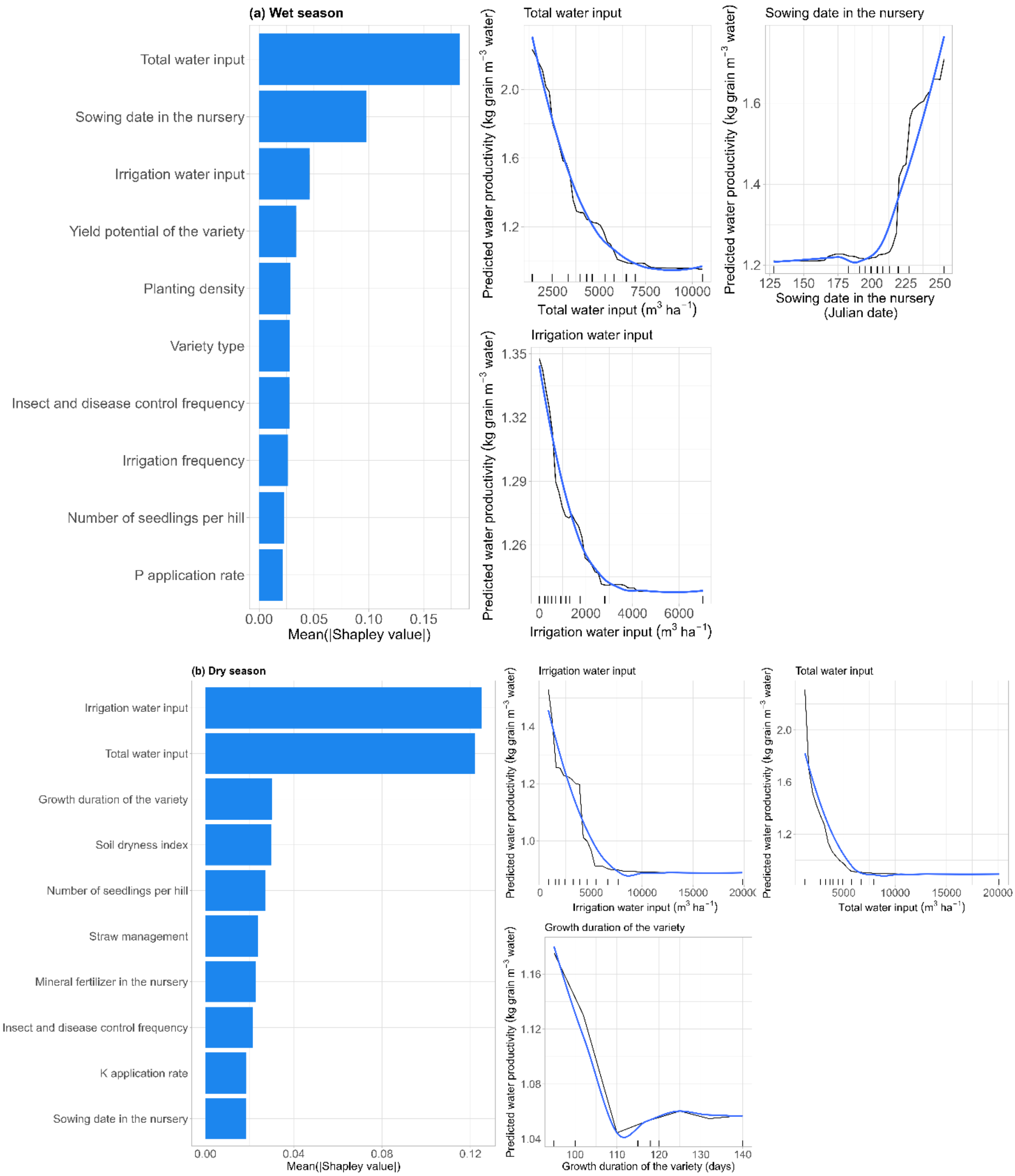


Figure 3.5. *Manageable factors explaining water productivity variability and their effect on the variation of water productivity in* ***(a)*** *wet season, and* ***(b)*** *dry season in irrigated lowland systems in Burkina Faso in 2018-2020.*

Results are from random forest models. Only the top 10 most important factors are displayed. The variable importance is expressed as the mean of the absolute Shapley values. Only partial dependence plots (PDPs) of the three top-ranked predictor variables of water productivity variability are displayed. Each PDP (black line) is overlaid by a Locally Estimated Scatterplot Smoothing (LOESS) curve (blue line). The Y-axis of each plot indicates the average effect of different values or categories of the X predictor on the predicted water productivity (kg grain m^{-3} water).

3.3.4. Trade-offs among rice production input and sustainability indicators

Across seasons and schemes, there were no significant differences between farmers' fields yielding categories in terms of socio-economic characteristics (Tables S16 and S17) and soil fertility attributes of the rice fields except for soil N content which was higher in high-yielding fields in the dry season (Tables S18 and S19). Similarly, there were no significant differences in production inputs between the three yielding field categories (**Table 3.5**). The differences between yielding categories were mainly attributed to crop and water management practices. Mineral N fertilizers were applied three times in high-yielding fields against two times in low-yielding fields (Tables S20 and S21; Figs. S8a and S8c). During the wet season, high-yielding fields were transplanted with an average of 2 seedlings per hill, compared to 3 in low-yielding ones (Table S20). During the dry season, the soil flooding index was also higher in high-yielding fields (60% ± 22%) than in low-yielding ones (37% ± 24%) (Table S21). In both seasons, high-yielding fields had higher water productivity, and partial productivities of applied N, P, and K than the two other categories (moderate- and low-yielding fields) thus, indicating no trade-offs between productivity and sustainability indicators (**Table 3.6**; Figs. S8b and S8d). During the wet season, the high-yielding fields demonstrated a 234% increase in water productivity and a significant improvement in the efficiency use of N and P fertilizers, with a 232% and 174% increase, respectively, compared to the average of low-yielding fields. Similarly, in the dry season, the high-yielding fields exhibited a 210% increase in water productivity and improved efficiency of N and P fertilizers by 130% and 176%, respectively (**Table 3.6**). Furthermore, we found a negative linear relationship between the relative yield gap and the resource (water and fertilizer) use efficiencies ($-0.60 \leq \rho \leq -0.40$; $p < 0.001$) in both seasons, suggesting that lower yield gaps were associated with higher resource-use efficiencies (**Figure 3.6**).

Figure 3.6. *Linear correlations between the relative yield gaps at farmers' field level, grain yield and the indicators of resource-use efficiency (WP- Total water productivity; PFPN – Partial factor productivity of applied N; PFPP – Partial factor productivity of applied P; PFPK – Partial factor productivity of applied K) in irrigated lowland systems in Burkina Faso in 2018-2020.*

*The values displayed in the matrix are Spearman's rank correlation coefficients (ρ). *** indicates that the correlation coefficient is significant at $p < 0.001$.*

Table 3.5 *Production inputs in various rice-yielding fields in the wet and dry seasons in irrigated lowland systems in Burkina Faso (2018-2020).*

	Wet season				Dry season			
	Low-yielding	Moderate-yielding	High-yielding	Test statistic	Low-yielding	Moderate-yielding	High-yielding	Test statistic
N application rate (kg N/ha)				0.06				0.108
Mean (SD)	144 (71)	123 (40)	112 (29)	Kruskal-Wallis	101 (63)	132 (53)	122 (50)	Kruskal-Wallis
Median (IQR)	136 (34)	121 (38)	119 (30)		120 (86)	128 (48)	118 (74)	
P application rate (kg P/ha)				0.326				0.759
Mean (SD)	19 (13)	19 (8)	18 (8)	Kruskal-Wallis	14 (9)	16 (8)	15 (6)	Kruskal-Wallis
Median (IQR)	13 (7)	20 (7)	20 (7)		13 (12)	16 (10)	16 (9)	
K application rate (kg K/ha)				0.626				0.494
Mean (SD)	26 (16)	26 (10)	23 (9)	Kruskal-Wallis	22 (14)	24 (12)	26 (10)	Kruskal-Wallis
Median (IQR)	25 (4)	25 (6)	23 (2)		23 (14)	23 (14)	23 (13)	
Irrigation water input (m^3/ha)				0.441				0.288
Mean (SD)	1060 (832)	1217 (1082)	1118 (1555)	Kruskal-Wallis	4256 (3828)	3608 (2222)	5435 (4761)	Kruskal-Wallis
Median (IQR)	805 (1081)	948 (1275)	690 (1292)		2580 (2480)	2834 (3416)	4190 (3987)	
Total water input (m^3/ha)				0.499				0.244
Mean (SD)	4802 (1956)	4641 (1709)	4285 (1973)	Kruskal-Wallis	5061 (3494)	4282 (1942)	5925 (4626)	Kruskal-Wallis
Median (IQR)	4014 (2438)	4622 (2628)	4180 (2718)		3853 (2338)	3781 (2606)	4592 (3165)	

SD: Standard deviation. IQR: Interquartile range

Table 3.6 *Grain yield and the indicators of resource-use efficiency (WP- Total water productivity; PFPN – Partial factor productivity of applied N; PFPP – Partial factor productivity of applied P; PFPK – Partial factor productivity of applied K) of various rice-yielding fields in the wet and dry seasons in irrigated lowland systems in Burkina Faso (2018-2020).*

	Wet season				Dry season			
	Low-yielding	Moderate-yielding	High-yielding	Test statistic	Low-yielding	Moderate-yielding	High-yielding	Test statistic
Grain yield (Mg/ha)				**<0.001**				**<0.001**
Mean (SD)	2.81 (0.75)	5.33 (1.08)	7.72 (1.38)	Kruskal-Wallis	1.71 (0.55)	3.72 (1.45)	5.79 (2.05)	Kruskal-Wallis
Median (IQR)	3.04 (0.93)	5.38 (1.55)	6.93 (2.12)		1.64 (0.78)	3.48 (2.27)	5.00 (2.48)	
WP (kg grain/m^3 of water)				**<0.001**				**<0.001**
Mean (SD)	0.65 (0.25)	1.40 (0.81)	2.17 (0.98)	Kruskal-Wallis	0.50 (0.28)	1.21 (0.70)	1.55 (1.39)	Kruskal-Wallis
Median (IQR)	0.60 (0.23)	1.14 (0.84)	1.97 (1.30)		0.49 (0.35)	1.04 (0.95)	1.13 (1.05)	
PFPN (kg grain/kg N)				**<0.001**				**<0.001**
Mean (SD)	22 (8)	49 (26)	73 (21)	Kruskal-Wallis	23 (16)	35 (41)	53 (27)	Kruskal-Wallis
Median (IQR)	22 (6)	44 (19)	71 (32)		16 (16)	29 (19)	46 (18)	
PFPP (kg grain/kg P)				**<0.001**				**<0.001**
Mean (SD)	193 (108)	312 (124)	528 (279)	Kruskal-Wallis	172 (152)	274 (152)	475 (403)	Kruskal-Wallis
Median (IQR)	186 (104)	292 (124)	397 (330)		127 (117)	249 (183)	355 (228)	
PFPK (kg grain/kg K)				**<0.001**				**<0.001**
Mean (SD)	134 (79)	222 (94)	378 (230)	Kruskal-Wallis	102 (79)	173 (82)	270 (208)	Kruskal-Wallis
Median (IQR)	110 (79)	208 (91)	298 (100)		72 (99)	164 (88)	214 (118)	

Significant effects ($p < 0.05$) are indicated in bold. SD: Standard deviation. IQR: Interquartile range

3.4. Discussion

This study showed that all performance indicators for productivity and sustainability were lower and more variable in the dry season than in the wet season. Also, drivers of management factors, explaining the variability of yields and water productivity differed substantially between seasons in dry zones of West Africa. Therefore, the synopses of this study will be discussed in four strands: (i) variability of performance indicators, (ii) determinants of variable yields and water productivity, (iii) assessment of yield gaps, and (iv) recommendations for improving grain yield and resource use efficiency.

3.4.1. Variability of yield, water productivity, and nutrient use efficiency

The mean yield in this study (4.6 Mg ha^{-1}) was slightly lower than the yield levels reported from farmers' interviews (5.0 – 5.8 Mg ha^{-1}) at the same sites in Burkina Faso in 2018-2019 (Ibrahim *et al.*, 2022). These differences may well be linked to the methods used, with the direct assessment and correction for grain moisture (as in the present study) being more accurate than farmers' estimation. The comparison of the average yields of the present study and those conducted about 20 years ago in the same location (Kou Valley, 1995-1996 - Wopereis et al., 1999) or locations belonging to the same climatic zones (Bagré scheme, 1999-2000 - Segda et al., 2004) seems to indicate that irrigated rice yields have stagnated around 4.5 Mg ha^{-1}. The national statistics of the global rice productivity in Burkina Faso support this trend of yield stagnation (Ray *et al.*, 2012). However, in other Sahelian countries such as Mali, facing similar constraints as Burkina Faso, rice yields have increased in the past decades (Ray *et al.*, 2012). Further studies aiming to unravel the causes of rice yield trends in different West African countries are required to provide country-specific guidelines for governments and international agencies for increasing rice productivity and in turn, reducing the dependence on food imports.

The average farmer yields in irrigated rice in Burkina Faso were in similar ranges to the yield levels in Nakhon Sawan (Thailand) and Polonnaruwa (Sri Lanka), higher than those in Bago (Myanmar), and lower than those in Yogyakarta (Indonesia) and Guangdong (China) (Devkota et al., 2019). These comparisons with top rice-producing countries show that irrigated rice systems in Burkina Faso have an average productivity at the global scale.

In many parts of the world (e.g., Vietnam, Sri Lanka, Indonesia, China), irrigated crop yields are reportedly higher in the dry than wet seasons (Devkota *et al.*, 2019), due to higher radiation levels in the dry season (van Oort & Zwart, 2018). In the present study in semi-arid environments, this trend was reversed. This result aligns with the climatic yield potential trend in farmers' fields, confirming the higher yielding potential in the wet season compared to the dry season (van Oort & Zwart, 2018). The negative impact of water scarcity could explain the lower yield performance in the dry season, which was most evident in the severely water-strapped irrigation schemes of Karfiguela and Zoungou. Indeed, a baseline survey conducted in 2018-2019 in the same areas, showed that nearly 80% of the rice farmers have experienced water scarcity during the past 5 years, and the vast majority of these farmers claimed that water scarcity reduced their rice yields (Johnson *et al.*, 2023a). Similarly, in 1995-1996 in Kou Valley, Wopereis et al. (1999) reported reduced rice yields in the dry season due to unreliable irrigation water supply. This highlights that the water scarcity in irrigation schemes in Burkina Faso is not a recent phenomenon, but started already more than 20 years ago. However, the problem aggravated from 2000 to 2017, with drastic increases in the frequency of drier years in most regions of Burkina Faso (Johnson *et al.*, 2023a). In addition, high temperatures, approaching the 37°C tipping point, combined with limited availability of water in the dry season compared to the wet season, also negatively affect the potential yield of dry-season irrigated rice (van Oort & Zwart, 2018). All this could also explain the high observed yield variability between farmers (CV = 46%), reflecting a risk or uncertainty in the outcome of farmers' investments, particularly during the dry season.

Despite large variations in water productivity (CV = 66%), the mean of 1.3 kg grain m^{-3} of water suggests a generally efficient use of water in Burkina Faso, a value which was largely above the critical benchmark threshold of 0.2 - 0.4 kg grain m^{-3} of water suggested by Bouman (2009). On the other hand, the large variability of water productivity highlights large differences between farmers of the same scheme regarding their crop and water management practices. Data assessing water productivity in farmers' fields in dry climatic zones are not available, or they are restricted to on-station trials or the sub-humid zones of West Africa (Dossou-Yovo and Saito, 2021), limiting comparison of our findings with those of other sites or countries. However, our findings on water productivity are within the range of results reported from on-station trials in the Senegal River Valley, Senegal (0.7 – 1.4 grain m^{-3} of water) (Djaman *et al.*, 2018). However, they are higher than other on-station reports from Burkina Faso (0.60 – 0.70 kg grain m^{-3} of water) (Dembelé *et al.*, 2005) and from Senegal (~0.70 grain m^{-3} of water) (Krupnik *et al.*, 2012b). These differences are likely related to different site characteristics (soil texture, water management practices, level of the groundwater table) but also by the methods used for assessing water input (bucket method in our study vs. V-notched weirs in on-station trials). The bucket method may be less accurate than the weirs method (Saito *et al.*, 2023a; Trimmer, 1994), however, it is easy to implement, especially when measurements have to be done in many farmers' fields scattered in remote locations. In addition, contrary to the study by Krupnik et al. (2012), we only accounted for water use from transplanting to crop harvest and did not quantify and include water used for seedbeds and land preparation, resulting in relatively high water productivity.

Given the growing importance of water conservation in agriculture, measuring the current water input in farmers' fields is a prerequisite to improve water management and use in the future. Thus, developing standardized operation procedures for assessing water productivity in rice fields must account for both accuracy and ease of implementation. Further studies including water productivity as a key performance indicator, and its monitoring across schemes and seasons, are recommended to fill the gap of such data for the dry zones of SSA. During the last decades, water-saving technologies have been introduced in irrigated fields with the system of rice intensification and alternate wetting and drying being the most popular and promising (Ishfaq *et al.*, 2020).

The partial factor productivity of applied N, P, and K varied widely across schemes and seasons and among farmers (CV ≈ 60 - 75%) with average values of 43, 305, and 204 kg grain per kg of N, P, and K, respectively. The average values of observed N and P efficiencies were comparable to those reported from on-station experiments at the same sites in the wet season of 2018-2019 (Ibrahim *et al.*, 2022), and slightly lower than those reported in Bagré, Burkina Faso in the 1999-2000 wet and dry seasons (Segda *et al.*, 2004). The large variability of nutrient use efficiencies both across and within sites underlines the importance of field-specific crop management. Additionally, the lower efficiency of applied mineral N in the dry season compared to the wet season (Wopereis *et al.*, 1999) emphasizes the necessity of season-specific fertilizer management in the semi-arid and arid regions of SSA. The identification of determinants of the variability of partial factor productivity of applied mineral nutrients was not addressed in this study. Therefore, further research should investigate these factors and extend the analysis to other key indicators of nutrient use efficiency, such as agronomic use efficiency, apparent recovery efficiency, and physiological use efficiency.

In about one-third of all fields, we observed wasteful use of N fertilizers with excessively high N application rates being associated with very low N use efficiency (PFPN < 30 kg grain kg^{-1} N). On the other hand, almost half of the farmers were mining P nutrient stock due to low P application rates and relatively high yields (PFPP > 300 kg grain kg^{-1} P). Therefore, it is paramount to train farmers in integrated and site-specific nutrient management to avoid wasting expensive mineral N and further soil P mining (Johnson *et al.*, 2019; Saito *et al.*, 2019). Using solely partial factor productivities and empirical benchmarks (Devkota *et al.*, 2021) to point out such risks to policymakers may be appropriate. However, calculating actual nutrient budgets may well be a stronger approach to assessing the extent of losses and nutrient mining (Dobermann, 2005). It may also be required to consider nutrition inflows from irrigation water (Dobermann *et al.*, 1998), contributions from biological N_2 fixation, and the slowed-down decomposition of organic carbon under constantly flooded field conditions (Pampolino *et al.*, 2008).

3.4.2. Determinants of yield and water productivity variability

The yields predicted by the Random Forest algorithm fit well with the observed values, confirming its ability to explain yield variability accurately at regional levels. However, as demonstrated in this study and previous ones focused on rice production systems in Uruguay (Tseng *et al.*, 2021), Nepal (Devkota *et al.*, 2021), and sub-Saharan Africa (Niang *et al.*, 2017), the results of cross-validation were consistently low to moderate

(15%-40% of the variability explained). This raises questions regarding the effectiveness of this analytical approach in accurately capturing the intricate interactions among multiple factors. This also highlights the potential challenge of extrapolating an existing model to new locations, especially when predicting on-farm yields across different regions and growing seasons (Silva *et al.*, 2023b). Consequently, extrapolation to other irrigated rice systems of any insights into the determinants of yield variability and recommendations for increasing grain yield under on-farm conditions from this study should be made with caution.

In dry zones of West Africa, drivers of yield variability are season-specific. This was a key and novel finding of this study. Therefore, policy interventions and strategies aiming at reducing yield variabilities and yield gaps must also be season-specific. In the wet season, among the manageable factors, the number of seedlings transplanted per hill and the source of the seeds were the two most important drivers of yield variability. Most previous studies conducted in SSA (Ibrahim *et al.*, 2022; Tanaka *et al.*, 2017) did not take the number of seedlings transplanted per hill into consideration. On the other hand, past studies in The Philippines (Sanico *et al.*, 2002), Japan (San-oh *et al.*, 2004), Pakistan (Baloch *et al.*, 2006), and China (Wang *et al.*, 2010) highlighted the importance of seedling numbers and densities on rice yield. Thus, in the wet season, reducing the number of seedlings from three to one per hill increased yields by 10% (present study) to 12 % (San-oh et al., 2004). Similarly, Baloch et al. (2006) showed also that the use of a single seedling per hill reduced production costs without yield penalty for timely sowing. It has been surmised that under favourable edaphic and hydrological conditions, the use of single seedling is associated with a higher crop growth rate after panicle initiation which, in turn, is associated with a higher leaf area index, higher N and RuBisCo contents in the leaf, and particularly a larger number of roots per unit area. Since the growth of rice roots is supported by assimilates supply from lower (older) leaves, and that the shading of lower leaves by upper ones is less with a single seedling per hill, more assimilates can be supplied to developing roots, contributing to higher N uptake at later growth stages of rice and in turn, to higher yield (San-oh et al., 2004). However, other studies showed that under unfavourable conditions two seedlings (Hasanuzzaman *et al.*, 2009) or increasing the number of seedlings per hill in the dry season (Sanico *et al.*, 2002) leads to higher yield. To sum up, increasing the number of seedlings per hill decreases or increases yield depending on many factors such as the seedling age, season (Sanico *et al.*, 2002), and probably the fertilizer application rates. There is a need for more research as to determine the climatic and hydro-edaphic conditions for the outperformance of transplanting single seedlings.

Our findings highlight the importance of using certified seeds to increase yields during the wet season in irrigated lowland systems across West Africa (Niang *et al.*, 2017). In the dry season, about half of the farmers in our sample used non-certified seeds, originating either from their harvests or obtained from other farmers. Rigorous seed certification and seed quality control by governmental organizations and eventually subsidies to facilitate a continuous and wide use of high-quality seeds are strongly recommended.

Unexpectedly, we found that fields lacking functional drainage facilities in the wet season out yielded those having drainage infrastructures. This could be explained by the nutrient losses through drainage systems. Indeed, although beneficial, drainage systems are also significant loss routes for dissolved nutrients, particularly during the wet season. Therefore, better management (i.e., rate, timing, and method) of fertilizer applied and drainage control during the wet season could help mitigate nutrient losses via surface runoff and leaching. Fertilization application before high-intensity rainfall should be avoided (He *et al.*, 2020b).

In the dry season, we found that reducing the soil dryness index and splitting of N fertilizer application are important management practices that contribute to reducing yield variability and improving yield (Dossou-Yovo & Saito, 2021; Niang *et al.*, 2017). Splitting N fertilizer applications from 2 to 3 incurs an average additional cost of €4 but can yield a profit gain of €69. Therefore, implementing this recommendation is beneficial.

In the dry season, solar radiation was by far the most important non-manageable factor influencing yield variability. It increases biomass production (Huang *et al.*, 2016), thus resulting in higher yields (Islam & Morison, 1992).

As water productivity is calculated based on water input and yield, the drivers of its variability were thus strongly linked with the total water input and then with the determinants of yield variability. In the dry season, water productivity is higher in older schemes but lower in recent ones. This highlights the waste of water in young irrigation schemes characterized by higher relative water availability in comparison with old ones (Johnson *et al.*, 2023a). Given the high importance of better water management for sustainable rice production, incentives to save water should be designed and promoted in all irrigation schemes.

3.4.3. Rice yield gaps across dry climatic zones in West Africa

Across schemes and seasons, the yield gap was 33% of the exploitable yield. Thus, despite irrigated lowlands being the most productive system in SSA (Diagne *et al.*, 2013), there is still scope for yield improvement. Furthermore, the exploitable yield gap exceeds those reported in some leading rice-producing countries, such as Sri Lanka, Vietnam, Thailand, and China (Devkota *et al.*, 2019; Stuart *et al.*, 2016). As 53% of the domestic rice production is provided by irrigated lowlands in Burkina Faso (MAHRH, 2011) and as the annual rice imports in 2020 accounted for 67% of domestic consumption (USDA, 2024), closing this yield gap could increase domestic production by 26% while reducing rice imports by 9%. This would require assisting farmers with low- and moderate yields to shift from their common practices to those followed by farmers in the high-yielding category.

Our estimations of the yield gap are in similar ranges (between 20% and 46% of Ye) to those previously published in the semi-arid (Gaya and Tillaberi, Niger; Kouroumari, Mali; and Malanville, Benin) and the sub-humid zones (Navrongo and Savelugu, Ghana) (Tanaka *et al.*, 2017). Also, yield gap estimates from the same zones in Burkina Faso as the present study (Ibrahim *et al.*, 2022) indicate similar ranges (between 25% and 43%). However, our estimations are lower than those reported from the semi-arid [Kouroumari, Mali; Tillaberi, Niger; and Kano, Nigeria (43%) and the sub-humid zones [Navrongo, Ghana (35%)] published by Arouna et al. (2021). Although we used the same method for calculating the yield gaps, the difference could come from the quality of the data used. Indeed, Arouna et al. (2021) assessed yield levels based on farmers' interviews while we applied the more accurate direct sampling in the field at harvest. In addition, distinctive farm management practices in these irrigation schemes could explain the differences observed.

In Kou Valley, the average rice yield gap in 2018-2020 (37%) was slightly lower than the one in 1995-1996 (40%) (Wopereis *et al.*, 1999). This comparison suggests either that the research and development and policy actions over the last twenty-five years have not fully achieved their goal, or that new constraints arose that shadow any progress made. To assess and monitor the benefits of agricultural research and development and policy actions, we recommend conducting national-level yield gap surveys regularly (e.g., every 3, 5 or 10 years), contingent upon resource availability.

3.4.4. Intervention priorities for improving yield and resource use efficiency

In both the wet and dry seasons, when yields are lower than 2.8 Mg ha^{-1}, it is challenging to cover all production costs, including labour. Therefore, while farmers in the low-yielding category just covered production costs in the wet season, they did not generate any profit in the dry season. Within seasons, most socio-economic household characteristics and soil fertility attributes did not differ significantly between the three yielding categories, and the amounts of water and mineral fertilizer applied were similar. However, the field water conditions and the number of fertilizer splits were different between yielding categories. Thus, high-yielding fields exhibited also higher water productivity and nutrient use efficiencies than moderate- and low-yielding fields. Similarly, we found that higher resource (water and fertilizer) use efficiencies were associated with narrowing the yield gaps. Consequently, achieving both high yields and high resource-use efficiencies are not conflicting goals. The difference between high-yielding and low-yielding fields is likely not primarily due to the amount of input, but rather to crop management, particularly water and fertilizer management. Therefore, the dissemination of improved nutrient management practices (Chivenge *et al.*, 2021a) along with good agricultural practices could increase yields and improve nutrient use efficiencies. In our context, implementing strategies for sustainable rice intensification is feasible and likely to be beneficial in the vast majority of farmers' fields, without the need for additional inputs.

3.4.5. Limitations of the study and future directions

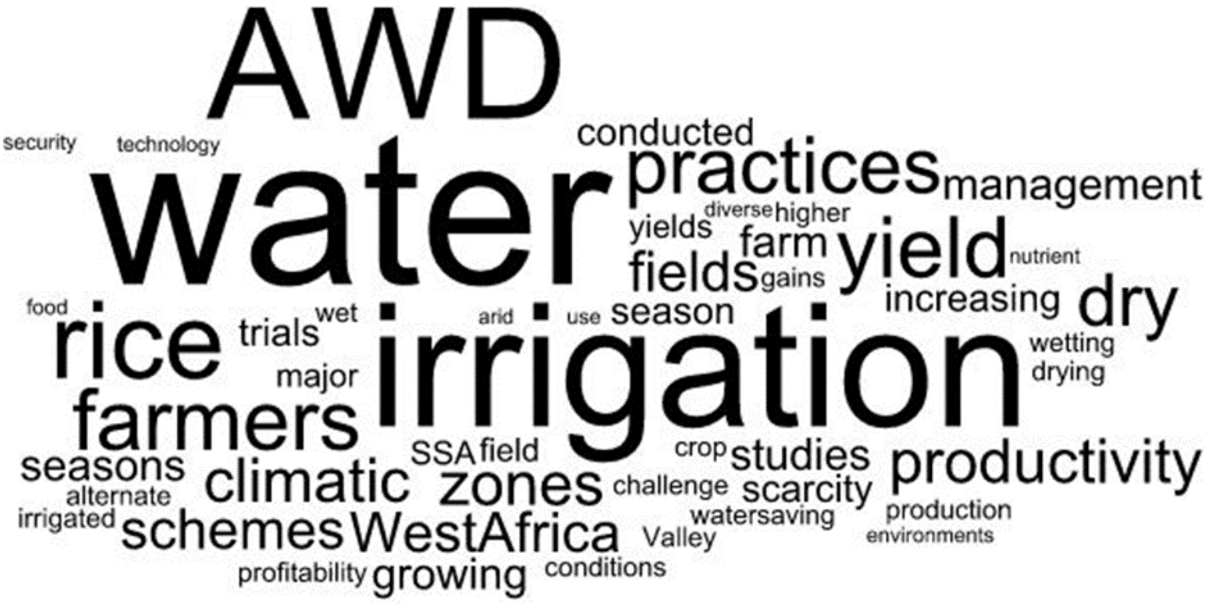
We used Random Forest, known for consistently outperforming other algorithms in identifying drivers of yield variability (Silva *et al.*, 2023b) and being more robust against overfitting compared to individual decision tree methods (Breiman, 2001). However, Random Forest models can be affected by high-cardinality features (i.e., features with many unique values) when using built-in variable importance measures (Strobl *et al.*, 2007). To address this concern, we used SHAP (SHapley Additive exPlanations), a widely-used and powerful tool for model interpretation. While SHAP offers significant improvements over traditional feature importance measures (Lundberg *et al.*, 2020), it may produce misleading results for correlated features (Loecher, 2024). To address this limitation, we employed tree SHAP, a method that effectively handles feature dependencies (Lundberg *et al.*, 2020). Furthermore, we enhanced the accuracy of SHAP value estimates by increasing the number of simulations. Consequently, this enables a more precise assessment of feature importance and more reliable rankings. Future studies could explore testing multiple machine learning algorithms. Additionally, increasing the sample size to enhance the training set and obtain additional data for external validation could be beneficial in further evaluating the model's predictive performance on new data.

Finally, there are likely underlying economic, social, or policy-related factors that explain the variability in yield. However, unlike studies conducted in Southeast Asia (Philippines, Indonesia, Thailand, and Vietnam) from 1966 to 2007 (Laborte *et al.*, 2012), this study did not identify any socio-economic factors as key drivers of yield variability. Additionally, we did not investigate policy-related factors such as water allocation, land tenure, irrigation infrastructure management, price support, market access, and extension services. Including these factors in future larger-scale studies could provide new insights into the root causes of rice yield variability.

3.5. Conclusion

This study quantified for the first time rice yield and water productivity gaps in both the wet and the dry seasons and identified determinants of their variability in irrigated lowlands in dry climatic zones of West Africa. Unlike previous studies, we combined climatic, hydro-edaphic, and field management factors with socio-economic characteristics of households, irrigation schemes, and terrain attributes. We found that the dry-season rice was less productive and showed higher yield variability than the wet-season rice. While rice yield gaps were larger in the dry than in the wet seasons, the scope for improving water productivity was larger in the wet than in the dry season. The drivers of yield variability were also season-specific. While the number of seedlings per hill and the source of seeds were the most influential manageable factors explaining the yield variability of wet-season rice, splitting application of N fertilizer, bird control and soil dryness index were the most important for dry-season rice. These findings confirm the large and growing impact of water scarcity on rice yields in the dry climatic zones of West Africa. Water productivity variability was linked with the drivers of yield variability. Within seasons, narrowing the yield gaps was associated with higher water productivity, and N, P, and K use efficiencies suggesting that yield improvement can be achieved without trade-offs with the sustainability performance indicators. Therefore, the diffusion of improved water and fertilizer management practices could help to achieve the dual goal of narrowing the yield gap and improving water productivity and N, P, and K use efficiencies. The decomposition of the yield gaps into efficiency, resource, and technology components, using a combination of frontier analysis and crop modelling (Silva *et al.*, 2017), could further improve the season-specific analysis and identify relevant management recommendations and policy interventions for sustainable intensification of rice production in the region.

Chapter 4: Enhancing rice yields, water productivity, and profitability through alternate wetting and drying technology in dry climatic zones of West Africa [γ$±]



Word cloud visualization of the 50 most frequent words in this chapter

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Abstract

Irrigated rice farming is crucial for meeting the growing rice demand and ensuring global food security. Yet, its substantial water demand poses a significant challenge in light of increasing water scarcity. Alternate wetting and drying irrigation (AWD), one of the most widely advocated water-saving technologies, was recently introduced as a prospective solution in the semi-arid zones of West Africa. However, it remains debatable whether AWD can achieve the multiple goals of saving water while increasing yield, farmer income, and nutrient use efficiency in diverse edaphic and climatic growing environments. We carried out participatory on-farm trials in four major irrigation schemes of Burkina Faso, (i) to assess the effects of AWD on yield, water productivity, partial factor productivity of applied nutrients, and profitability in comparison to farmers' irrigation practices, and (ii) to identify the environmental conditions and cropping practices determining yield gain of AWD over farmers' irrigation practices. During the 2018 and 2019 dry and wet seasons, we conducted 154 pairwise comparisons of AWD at the threshold level of -15 cm, and farmers' irrigation practices (fields being submerged as frequently as water availability allowed according to the scheme-dependent water provision schedule). We identified the drivers of yield gains associated with AWD using brute force and random forest machine learning algorithms. Across irrigation schemes and seasons, AWD reduced irrigation water input by 30%, while increasing grain yield by 6% ($p < 0.05$). Consequently, AWD increased the irrigation water productivity by 64% and profit by 5% over farmers' irrigation practices. Partial factor productivity of applied N, P, and K improved with AWD during the wet but not during the dry season. The AWD-associated yield gains were higher in fields with poor access to irrigation water, and higher for *indica* than for tropical *japonica* varieties. Overall, AWD appears to be an effective strategy to improve yields, water productivity, and profitability in rice irrigation schemes in dry climatic zones in West Africa. This study suggests a need for reshaping rice irrigation practices, involving a systematic monitoring of field water levels in the region.

Keywords: Burkina Faso, *Oryza* spp., profit gain, Random Forest, water-saving technology.

4.1. Introduction

Demographic growth, industrialization, and poor land, water and crop management put increasing pressure on available water resources. Climate change corollaries such as higher temperatures, erratic rainfall, and drought have become widespread in recent decades and exacerbate competing water demands (Seneviratne *et al.*, 2021). By 2025, over one-fifth of the global population is expected to be living with absolute water scarcity (i.e., disposing of less than 500 m^3/person per year) (FAO, 2012). Sub-Saharan Africa (SSA) is the region with the largest number of water-stressed countries, with the Sudanian and Sahelian climatic zones being the most vulnerable to water scarcity (UN-Water & FAO, 2007).

Agriculture uses 72% of water withdrawals worldwide (UN-Water, 2021), and irrigated lowland rice, providing 75% of the total rice production, uses between 34-43% of the world's total irrigation water (Bouman *et al.*, 2007). At the field level, irrigated rice requires two to three times more water than other major cereals such as wheat and maize because rice fields are generally flooded from the transplanting to the harvest (Tuong & Bouman, 2003). As a main staple food and the second most important source of calories in many parts of SSA, rice plays a major role in contributing to regional food security (Seck *et al.*, 2013). The rapid expansion of the rice-growing area and the 81% increase in regional rice consumption between 2008 and 2018 (FAO, 2021), highlight its crucial importance in SSA.

Given its large water footprint, a major challenge in rice production is to increase both production and resource (water and nutrient) use efficiency in the face of the growing scarcity of water resources. To tackle this challenge, many climate-smart rice technologies have been advocated (Surendran *et al.*, 2021). Among these options, the alternate wetting and drying irrigation regime (AWD), has shown promise as a water-saving technology, and it is widely promoted, especially in Asia (Lampayan *et al.*, 2015b; Li & Barker, 2004) and America (Linquist *et al.*, 2015). Under AWD, aerobic cycles are periodically introduced during the growing season, allowing fields to dry down to a threshold water table depth before re-flooding. However, it remains debatable whether AWD can achieve the multiple goals of saving water while increasing rice yield, farmer income, and nutrient use efficiencies in diverse edaphic and climatic environments.

While most studies confirm the water-saving ability and higher water productivity of AWD compared to the continuous flooding regime, conclusions on yields are highly variable and site-specific. Few studies reported an increase in yield with AWD (Liu *et al.*, 2013a; Maneepitak *et al.*, 2019), others presented a reduction (Islam *et al.*, 2018), while many others showed no yield penalty (Lampayan *et al.*, 2015b; Liao *et al.*, 2020). A meta-analysis of studies published between 1898 and 2015 showed that moderate AWD (i.e., when soil water potential ≥ −20 kPa or when field water tables do not drop below 15 cm from the soil surface) reduced water input by 23% relative to continuous flooding without significant yield penalty in most circumstances (Carrijo *et al.*, 2017). The vast majority (>80%) of these studies were from Asia, with only few (5%) being from SSA. Among the few studies assessing the effect of AWD on grain yield and water productivity in dry climatic zones of West Africa, most were conducted as researcher-managed trials on experimental stations (de Vries *et al.*, 2010; Djaman *et al.*, 2018), and they did not account for the large variability in management and edapho-climatic conditions encountered in farmers' fields. Moreover, these studies compared AWD to continuous field submergence which is not the predominant water management practice in irrigated rice schemes of West Africa, where water is made available on a scheme-depended irrigation schedule (Johnson *et al.*, 2023a). To the best of our knowledge, only few studies (Dossou-Yovo & Saito, 2021) compared AWD with current farmers' irrigation practices, and these were conducted in the sub-humid zone of West Africa. To date, no on-farm evaluation of the performance of AWD is available from the dry climatic zones. Therefore, we conducted on-farm trials to evaluate AWD across various biophysical environments, with the aim of facilitating its dissemination throughout the arid and semi-arid zones of SSA. We addressed the following objectives: (i) compare grain yields, water productivity, partial productivity of applied nutrients, and profitability of AWD and farmers' irrigation practices (FP), (ii) determine environmental conditions and crop management practices that favour the yield gains of AWD over FP, and (iii) identify the most important crop management practices for improving yields and reducing yield variability, regardless of the irrigation regime. We hypothesized that biophysical conditions, crop management practices, varietal choice, and the growing season may differentially influence the potential yield gains associated with AWD in dry climatic zones of West Africa.

4.2. Material and Methods

4.2.1. Study area and sites

Burkina Faso is a Sahelian country in West Africa, facing recurrent drought events and increasing water scarcity in the last decades. Water scarcity is also a major challenge in most irrigation schemes, particularly during the dry season (Johnson *et al.*, 2023a). This poses an important threat to rice production. We selected four priority intervention sites for the national research and extension programs, representing diverse irrigated lowland rice-growing areas across various agroecological zones and irrigation management types within the dry regions of West Africa. These sites include Karfiguela (10°40'29''N, 4°48'20''W) and Kou Valley (11°23'7''N, 4°24'20''W) irrigation schemes in the Sudanian zone, and Zoungou (12°7'0''N, 0°30'48''W) and Sourou Valley

(13°13’47’’N, 3°25’9’’W) irrigation schemes in the Sudano-Sahelian climatic zone (Fig. S1). In all schemes, irrigation water is conveyed by gravity through earthen or concrete-lined canals and released into individual plots via bund breaks. A detailed description of the study area and the irrigation schemes are presented in Johnson et al. (2023a).

4.2.2. Description of the on-farm trials and settings

A series of participatory on-farm trials was conducted for two years (2018–2019) in both the wet (from June to October) and dry (from December to May) seasons comparing alternate wetting and drying irrigation (AWD) to farmers’ irrigation practices (FP). After explaining the purpose of the experiment during cooperative group meetings, farmers were selected based on their willingness to participate in the experiment. In each scheme, we targeted 15 participating farmers per cropping season and conducted on-farm trials over two seasons in Sourou Valley, three seasons in Karfiguela and Zoungou, and four consecutive seasons in Kou Valley (Table S1). Due to logistic reasons, security issues, and some on-farm trial setbacks (non-cooperative farmers, farmers’ non-compliance with harvesting data collection instructions, cattle grazing fields), we ended up with a total sample of 154 farmers’ fields (78 in the wet and 76 in the dry seasons) (Table S1). The selected fields were different from one season to another.

Farmers’ fields were differentiated based on their relative position within each irrigation scheme into three categories: “head-end”, “middle reaches”, and “tail-end”. In each field, two plots of about 300 m^2 each, with comparable cropping histories, were delimited by 30 cm high consolidated bunds with a width of 50 cm to prevent seepage. These plots hosted two water irrigation regimes, consisting of (i) farmer’s practices of irrigation (FP) and (ii) AWD irrigation. The plots were irrigated using the scheme’s irrigation system. In all schemes, FP differs from “conventional continuous flooding irrigation" due to the non-permanent availability of water in the canals. Irrigation frequency was further determined by both individual farmers' water management decisions and the scheme-dependent water supply schedule, with water provision varying from every 3 to 5 days. Generally, in FP, for each irrigation event, farmers intensively irrigate their fields to reach standing water of 10-15 cm depth to prevent any water shortage before the next irrigation turn. In each AWD plot, a 40 cm-long perforated PVC tube, marked at 5 cm and -15 cm was installed to monitor water above and below the ground (Lampayan *et al.*, 2015b). We trained farmers on alternate wetting and drying irrigation, with a threshold water level in the field at 15 cm below the surface. In AWD irrigation treatment, farmers were requested to keep as much as possible 3-5 cm ponded water for the first 15 days after transplanting to ensure the recovery of seedlings and to suppress weeds. Afterwards, the intermittent irrigation was imposed. As water stress at flowering can induce spikelet sterility, farmers were requested to suspend the drying phase in the AWD plot and maintain ponded water at a depth of 3-5 cm, 7 days before and 7 days after this sensitive stage (Bouman *et al.*, 2007). We provided farmers with variety-specific time windows for the respective flowering stages. Thereafter, AWD irrigation was resumed until 2 weeks before rice harvest. Apart from the irrigation management, all plots were managed from land preparation to rice harvest according to farmers' cropping practices, with each farmer selecting the rice variety, deciding on seed source, and selecting the type, the quantity, and the application of inputs (herbicides, pesticides, and fertilizer).

4.2.3. Soil sampling and analysis

Before the onset of the trials in both the wet and dry seasons, nine soil cores were collected from each field at a depth of 0-20 cm within each field along the diagonals and combined. These composite samples from each field were air-dried, sieved, and analyzed for the determination of soil physical (clay, silt, and sand contents), and chemical attributes [pH (1:2.5 dry soil: water ratio), total organic C, total N, and available P (Bray-2)] following the analytical methods described by Johnson et al. (2019).

4.2.4. Field survey, observations, and data collection

Weather data (solar radiation, maximum and minimum air temperatures, relative air humidity, and rainfall at daily time steps) were retrieved for each scheme from "aWhere", a cloud-based real-time data platform (aWhere, Inc., Broomfield, Colorado, United States). We assessed the field attributes associated with the irrigation scheme, considering factors such as the position within the scheme and access to irrigation water (Table S2). Information on the variety type of the planting material (tropical *japonica*, *indica*, or lowland NERICA – interspecific hybrids of *Oryza glaberrima* x *O. sativa indica*) and growth duration was obtained from published literature and is presented in Table S3.

Using a standardized protocol [see Niang et al. (2017) and Tanaka et al. (2017)], we collected data on (i) farm management practices, (ii) weed infestation, and (iii) grain yield. Management practices included the source of seeds, straw and residue management, tillage method, land levelling, sowing date, planting density, number of seedlings per hill, weed management, fertilizer management, pest control, and irrigation frequency. The level of weed infestation was visually assessed at the flowering stage, both below and above the rice canopy, and was categorized and scored into four levels: 0 = no weed; 1 = weed cover ≤ 10%; 2= weed cover > 10% and ≤ 30%; 3 = weed cover > 30% and ≤ 60%; and 4 = weed cover > 60%) (Gongotchame *et al.*, 2014). Three harvest areas, each measuring 12 m², were demarcated within both the FP and AWD plots to assess farmers' land and crop management practices and determine grain yield. These areas were positioned along a diagonal to capture the variability in productivity within the fields. The grain yields and field observations were based on three harvest areas of 12 m^2 each, demarcated within both FP and AWD plots. At the flowering stage, we measured the number of tillers from 10 randomly selected hills following the rice-standard-evaluation system (International Rice Research Institute, 2022). At maturity, grain yield was measured within each harvest area, adjusted to 14% moisture content, and averaged for the final yield estimation across the three replicates (Table S2). In addition, tiller and panicle number, weight of straw, and grain biomass were recorded from six randomly sampled hills for both FP and AWD plots. After drying the total shoot (straw + grain) biomass at 60 °C for 72 h, the harvest index (HI) was computed.

Every three days, the field water condition, in each plot was assessed visually and scored using a three-point scale [1: ponded water (i.e., standing water table with a depth of more than 1 cm); 2: wet soil surface (i.e., fully saturated or partially saturated soil without standing water table); 3: dry soil surface (i.e., soil surface does not exhibit any visible signs of moisture)] (Haefele *et al.*, 2006). In addition, the frequency of irrigation (the number of irrigations during the growing season) for each irrigation management treatment was recorded. The water flow rate was measured in each plot using the bucket method (Trimmer, 1994). The bucket method involves placing a bucket of known capacity at the plot's inlet to capture all the water flowing through the bund breaks while using a stopwatch to time how long it takes for the bucket to fill. The flow rate is then calculated by dividing the bucket's volume by the filling time. The quantity of water applied per irrigation event was calculated by multiplying the water flow rate by the irrigation duration. The quantity of water applied per irrigation was estimated three to four times during the growing season. Subsequently, for each plot, the irrigation water input was calculated by multiplying the total number of irrigation events by the average water quantity applied per individual irrigation event.

4.2.5. Calculation of indices, performance indicators, and effect sizes

The soil dryness index was calculated as the ratio between the number of days with a dry soil surface and the total number of recorded days during the growing season (from two weeks after transplanting to maturity) (Equation 1).

$$Soil\ dryness\ index = \frac{Number\ of\ days\ with\ a\ dry\ soil\ surface}{Total\ number\ of\ recorded\ days\ during\ the\ growing\ season} \times 100 \qquad (1)$$

Similarly, the soil flooding index was calculated using the number of days with ponded water (Niang *et al.*, 2018).

$$Soil\ flooding\ index = \frac{Number\ of\ days\ with\ a\ ponded\ water}{Total\ number\ of\ recorded\ days\ during\ the\ growing\ season} \times 100 \qquad (2)$$

Both indices are expressed as percentage shares. Therefore, a soil dryness index of 0% indicates a permanent ponded water layer in the plot or wet soil, whereas a soil dryness index of 100% indicates consistently dry conditions. Conversely, a soil flooding index of 0% indicates the absence of ponded water, meaning the soil surface is consistently dry or occasionally wet, while a soil flooding index of 100% reflects consistently ponded water conditions.

Water productivity (WP, in kg grain m^{-3} water), irrigation water productivity (IWP, in kg grain m^{-3} water), and partial factor productivity of applied N (PFPN, in kg grain kg^{-1} N), P (PFPP, in kg grain kg^{-1} P), K (PFPK, in kg grain kg^{-1} K) (Fixen *et al.*, 2015; Sharma *et al.*, 2015) were further computed as follows:

$$WP = \frac{Grain\ yield}{Total\ volume\ of\ water\ input} \qquad (3)$$

$$IWP = \frac{Grain\ yield}{Volume\ of\ irrigation\ water\ input} \quad (4)$$

$$PFP_x = \frac{Grain\ yield}{Rate\ of\ \ nutrient\ _x\ applied} \quad (5)$$

where grain yield is expressed in kg ha^{-1}, the total volume of water input (i.e., irrigation + rainfall) during the rice-growing period (from transplanting to crop harvest) is expressed in m^3 ha^{-1}, and the rates of N, P, and K applied are expressed on an elemental basis (i.e., kg N, P or K ha^{-1}).

To assess the impact of applying AWD over FP irrigation, the effect size of AWD on yield, water productivity, and irrigation water productivity was calculated for each field using the natural logarithm of the response ratio (RR).

$$RR_X = \ ln\frac{X_{AWD}}{X_{FP}} \quad (6)$$

where X is a response variable (yield, water productivity, or irrigation water productivity).

The mean effect sizes of AWD were calculated as the average of the effect sizes from the observations.

The percentage change or gain due to AWD treatment compared to the FP treatment was computed following Equation (7):

$$Percentage\ change = \ (e^{lnRR_X} - 1) \times 100 \quad (7)$$

4.2.6. Economic analysis

Based on post-harvest interviews with farmers, we conducted an economic analysis by comparing the total costs of cultivating rice and the gross income under each irrigation regime (FP and AWD). All production costs and income were reported on a per-hectare basis and are expressed in Euros (XOF 656 ≈ €1). The total cost was computed by summing up the cost of all inputs (seed, organic and inorganic fertilizer, pesticide, herbicide, irrigation water), labour (nursery, tillage, harrowing, ploughing, levelling, transplanting, fertilizer application, pesticide and herbicide application, manual or mechanical weeding, bird scaring, irrigation, harvesting, and threshing), oxen or machinery rental, and packaging and transportation. While fields within the irrigation schemes are owned by the respective cooperatives, most farmers hold usufruct rights to their individual fields. Therefore, the land rental was not included in the production costs; instead, cooperative membership fees were considered if applicable. For production tasks (such as weeding, or irrigation) performed by household members, the labour cost was estimated based on the equivalent to be paid to casual or permanent farm workers. Regarding irrigation labour costs, most farmers indicated that they did not pay based on the number of irrigation events. Instead, they typically negotiated a lump-sum payment for the entire growing season. Fixed by the local authority in charge of the water management in each scheme, the water price constituted a flat rate per unit of irrigated area per season. As a result, the same water fees were applied to both FP and AWD irrigation, leading to identical irrigation water costs for both water management regimes. The gross income was calculated from the sales of paddy (per kg) and straw (if applicable) at local market prices at the time of harvest. Paddy prices slightly varied between schemes, ranging from €0.2 (in Sourou Valley) to €0.3 (in Zoungou). During the wet season, the majority of farmers in Zoungou sold their paddy to a seed company at an exceptional price of €0.5. In addition, we calculated three economic performance metrics: the net income (in € ha^{-1}), benefit-cost ratio, and profit gain (%) for each irrigation regime following the equations below. The results were averaged per season and scheme.

$$Net\ income = Gross\ income - Total\ production\ cost \quad (8)$$

$$Benefit - Cost\ ratio = \frac{Gross\ income}{Total\ production\ cost} \quad (9)$$

$$Profit\ gain = \frac{\frac{Total\ cost\ of\ production_{FP}}{Yield_{FP}} - \frac{Total\ cost\ of\ production_{AWD}}{Yield_{AWD}}}{\frac{Total\ cost\ of\ production_{FP}}{Yield_{FP}}} \times 100 \quad (10)$$

4.2.7. Statistical analyses and visualization

The field survey data collected using Android mobile devices were submitted on a server, downloaded, cleaned, compiled into an Excel spreadsheet, and analyzed using R. 4.3.2 (R Core Team, 2023).

Descriptive statistics of farm management practices and AWD effects

Climatic and soil fertility attributes, and farm management practices presented as continuous variables were analyzed using descriptive statistics (mean and standard deviation), while percentage shares were calculated on categorical variables. We computed the Chi-squared ($\chi 2$) tests of homogeneity to assess the similarity in the distributions of categorical variables among two or more independent groups (e.g., wet and dry seasons) (Franke *et al.*, 2012). We compared the continuous variables featuring farm management practices and the effect of alternate wetting and drying irrigation (AWD) on yield, total water productivity, and irrigation water productivity between seasons by computing either Student's t-test when the normality of residues and homogeneity of variance were met or the non-parametric alternative, Mann-Whitney-Wilcoxon test, otherwise. Similarly, the effects of AWD on yield, total water productivity, and irrigation water productivity between schemes were assessed using either one-way analysis of variance (ANOVA) or the non-parametric alternative, the Kruskal-Wallis H test.

Mixed-effects models

We visualized 154 pairwise comparisons of AWD and FP for yield, total water productivity, and irrigation water productivity using scatterplots and determined the proportion of fields where AWD outperformed FP.

Linear mixed-effects models [LMMs, *lme4* package; Bates et al. (2015)] were applied with irrigation management as fixed factors and field nested in irrigation scheme as a random factor (1| Irrigation scheme/Field) to compare the overall performance of AWD and FP on different response variables (weed infestation, plant growth parameters, straw biomass, grain yield, water productivity, partial factor productivity of applied nutrients, water input and soil water condition indices) for both wet and dry seasons. For grain yield, the same analysis was performed additionally for the Season × Irrigation scheme combination, with the field considered as a random factor. The field was considered as a random effect to capture the clustering or repeated measurements (two plots in one farmer’s field). P-values of the fixed effect (irrigation management) with type-III analysis of variance were estimated according to Satterthwaite's method using *lmerTest* package (Kuznetsova *et al.*, 2017). When assumptions for the application of LMMs were severely violated (i.e., heteroscedasticity and strong deviance of residuals from normality), robust linear mixed-effects models [with *Robustlmm* package; Koller (2016)] were alternatively run, and p-values of the fixed effect were obtained using the *emmeans* package (Lenth, 2022). For modeling count variables (such as tillers or panicles number, and frequency of irrigation), Poisson generalized linear mixed-effects models [GLMMs, *lme4* package; Bates et al. (2015)] with the log-link function were implemented. After checking overdispersion issues in the Poisson model, p-values of the fixed effect were estimated according to the Wald test.

Model selection and machine learning techniques

To identify the conditions when AWD out-yielded farmers' irrigation practices, we performed a model selection analysis based on the generalized linear model by using the *glmulti* package (Calcagno, 2020). In contrast to the stepwise selection, the brute force algorithm, automated model selection and multi-model inference, implemented in *glmulti*, builds all possible models with all possible combinations of predictors and selects the best ones based on information criteria. The AWD effects (percentage change due to AWD) on yield were considered as the response variable and twenty-one predictors, including irrigation scheme characteristics, soil fertility attributes, planting material, and crop management practices were used as independent variables (Table S2). This analysis was conducted across all seasons, as the AWD effect on yield did not differ between the wet and dry seasons. Akaike's Information Criterion with small-sample correction (AICc) was used for the models' comparison and selection.

To deepen the investigation and capture non-linear patterns, we applied the Random Forest classification algorithm using the *ranger* package (Breiman, 2001; Wright & Ziegler, 2017) to the selected variables. The AWD effect was classified as positive when the yield gain or percentage of change was > 0 and as negative otherwise. We used the classification algorithm approach over the regression one as the accuracy of the regression model was poor (out-of-bag $R^2 < 0$). The relative importance of each explanatory variable was calculated as the mean of the absolute Shapley values of all observations using the *fastshap* package

(Greenwell, 2023). The concept behind SHapley Additive exPlanations (SHAP) is to decompose a model's prediction into additive contributions from individual explanatory variables. Applying this process to all observations provides a powerful method for comprehensively explaining the model (Lundberg & Lee, 2017). To interpret the Random Forest classification model, partial dependent plots were constructed using the *pdp* package (Greenwell, 2017) for the two most influential independent variables. The partial dependent plots provide a visual representation of the partial contributions and relationships of each independent variable while accounting for the average effects of the other variables (Friedman & Meulman, 2003). These plots display the effects of these variables on the probability of yield gain of AWD over FP.

Similarly, the Random Forest regression algorithm (Breiman, 2001) was applied to factors associated with management practices (e.g. planting material, crop management practices, pest incidence, and soil water condition and water input parameters) (Table S2) to determine the drivers of yield variability in wet and dry seasons irrespective of the irrigation regime (FP or AWD). We visualized the partial contributions and relationships of the most influential explanatory variables using partial dependent plots.

4.3. Results

4.3.1. Weather conditions, soil attributes, and farmers' management practices

Weather conditions during the rice-growing period differed between sites and seasons. On average, the relative air humidity was 69% and 37% and the rainfall volume during the rice-growing period was 370 and 70 mm in the wet and dry seasons, respectively. Cumulative solar radiation and average maximum air temperature during the growing period were higher in the dry (678 kWh m^{-2} and 37 °C) than in the wet (583 kWh m^{-2} and 34 °C) seasons (Tables S4 and S5). Across seasons, Karfiguela recorded the highest relative humidity and rainfall volume, while Sourou Valley experienced the highest cumulative solar radiation (Table S5).

With the exception of available P (Bray-2), which exhibited very high variability (CV = 101%) across farmers' fields, most soil fertility attributes showed moderate to high variation (CV = 16 – 40%). Soil pH (H_2O) ranged from 4.5 (strongly acidic) to 8.5 (strongly alkaline) with an average pH of 6.4. Overall, soils from Karfiguela, Kou Valley, and Zoungou were within the optimal pH range (pH H_2O 5.5-6.5), whereas those from Sourou Valley were slightly alkaline (pH H_2O 7.6). Total N content ranged from 0.02% to 0.15% with an average of 0.07% and organic C content ranged from 0.27% to 1.90% with an average of 0.85%. The soil clay content varied between 4 and 45% with an average of 22% (**Table 4.1**).

Table 4.1 *Soil fertility attributes (mean ± standard deviation) of the rice fields across irrigation schemes*

	Karfiguela (n = 48)	Kou Valley (n = 29)	Zoungou (n = 23)	Sourou Valley (n = 51)	Overall
pH H_2O	5.4 ± 0.5	5.8 ± 0.4	6.5 ± 0.7	7.6 ± 0.4	6.4 ± 1.1
Total N (%)	0.063 ± 0.026	0.092 ± 0.024	0.096 ± 0.027	0.053 ± 0.014	0.070 ± 0.028
Total C (%)	0.783 ± 0.353	1.107 ± 0.285	1.139 ± 0.298	0.634 ± 0.142	0.847 ± 0.342
Available P (Bray-2) (mg kg^{-1})	10.7 ± 7.8	17.0 ± 16.6	8.7 ± 6.1	5.1 ± 3.5	9.7 ± 9.8
Clay content (%)	13 ± 5	25 ± 7	28 ± 7	26 ± 6	22 ± 8
Silt content (%)	10 ± 4	15 ± 3	16 ± 4	8 ± 2	11 ± 5
Sand content (%)	77 ± 9	60 ± 8	56 ± 10	66 ± 6	67 ± 11

In 70% of all cases, rice straw from previous seasons was removed, either for use as animal feed (49%) and by burning (21%). In 12% of the cases, straw was grazed *in-situ* by animals, and in 18%, it was returned by either mulching or incorporation. These proportions were similar in both seasons (Table S6). Other crop residues (rice stubbles and weeds) were mostly incorporated into the soil. More than 60% of all farmers tilled their fields by animal traction. Mechanical tillage by power tiller was practised in 30% of the cases. Manual tillage was more frequent in the dry (14%) than in the wet seasons (3%). About 60% of the fields were well-levelled, irrespective of the season. Non-certified seeds were used in almost 70% of the surveyed fields. Certified seeds were used more frequently in the wet (49%) than in the dry season (21%). The average growth duration of varieties was 123 ± 14 days and was similar between the wet (124 ± 12 days) and dry seasons (122 ± 15 days). Transplanting was the main crop establishment method in both seasons. Across schemes, the mean sowing date in the nursery was July 22nd (Julian date 204 ± 16 days) in the wet, and January 12th (Julian date 12 ± 36 days) in the dry season. Wet season rice was seeded earliest in Sourou Valley (July 13th ± 11 days), and latest in Kou Valley (August 7th ± 11 days). Similarly, in the dry season, rice was seeded earliest in Sourou Valley (December 11th ± 11), and latest in Karfiguela (March 7th ± 12) (Table S7). On average, farmers transplanted 27-day-old seedlings (Table S6). During the rice-growing period, farmers weeded their rice fields between one and five times with an average of two weeding operations, and in 80% of the cases, they used herbicides at least once. While the weeding frequency was similar between seasons, herbicides were applied more frequently in the wet (96% of the cases) than in the dry season (64% of the cases) (**Table 4.2**).

While organic manure was applied in approximately 20% of the fields, mineral fertilizers were most widely used (99%). Farmers applied mineral fertilizer between 1 to 4 times, with an average of 3 split applications. Nitrogen, P, and K were applied at average rates of 128, 18, and 25 kg ha^{-1}, respectively (**Table 4.2**). Fertilizer application rates differed between schemes, with highest N rates being applied in Sourou Valley (150 kg N ha^{-1}) and highest P rates in Karfiguela (22 kg P ha^{-1}).

Table 4.2 *Farm management practices in the rice fields in wet and dry seasons across irrigation schemes in Burkina Faso, in 2018-2019*

	Wet season	Dry season	Overall	Test statistic
(Row %)(Col %)				
Land leveling				Chi-square
Poor	41 (61%) (53%)	26 (39%) (32%)	67 (100%) (42%)	**0.012**
Good	37 (40%) (47%)	56 (60%) (68%)	93 (100%) (58%)	
Weeding frequency				Wilcoxon rank-sum
Mean (SD)	3 (1)	2 (1)	2 (1)	0.551
Herbicide use				Chi-square
No	3 (10%) (4%)	28 (90%) (34%)	31 (100%) (19%)	**<0.001**
Yes	75 (58%) (96%)	54 (42%) (66%)	129 (100%) (81%)	
Application of organic manure				Chi-square
No	62 (48%) (79%)	68 (52%) (83%)	130 (100%) (81%)	0.723
Yes	16 (53%) (21%)	14 (47%) (17%)	30 (100%) (19%)	
Mineral fertilizer application frequency				Wilcoxon rank-sum
Mean (SD)	3 (1)	3 (1)	3 (1)	0.851
N application rate (kg N ha^{-1})				Wilcoxon rank-sum
Mean (SD)	121 (35)	134 (49)	128 (43)	0.101
P application rate (kg P ha^{-1})				Wilcoxon rank-sum
Mean (SD)	19 (6)	16 (7)	18 (7)	**0.003**
K application rate (kg K ha^{-1})				Wilcoxon rank-sum
Mean (SD)	25 (9)	25 (10)	25 (9)	0.776

Significant effects ($p < 0.05$) are indicated in bold. SD: Standard deviation

4.3.2. Productivity performance indicators

Grain yield, irrigation water productivity, and the partial factor productivity of applied mineral N and K differed between seasons and schemes (Tables S8 and S9). Yields ranged from 1.2 to 10.9 Mg ha^{-1}, with a mean of 4.9 Mg ha^{-1}, and were higher in the wet (5.2 ± 1.5 Mg ha^{-1}) compared to the dry season (4.5 ± 1.8 Mg ha^{-1}). Similarly, PFPN and PFPK were higher in the wet than in the dry season, while PFPP (average 311 ± 144 kg grain kg^{-1} P) showed no difference between the seasons (Tables S8). Total water productivity ranged from 0.19 to 5.6 kg grain m^{-3} of water, with a mean of 1.2 ± 0.7 kg grain m^{-3} of water.

4.3.3. Farmers' irrigation practices vs. AWD irrigation

Farmers' irrigation practices differed from AWD in the frequency of irrigation and the amounts of water inputs. AWD reduced irrigation water and total water inputs by 22% and 7% in the wet, and by 32% and 29% in the dry seasons, respectively. As a result, the soil flooding index was lower in AWD than in FP plots in both the wet (56% vs. 71%) and the dry (44% vs. 62%) seasons. However, the soil dryness index was comparable in AWD and FP plots in both seasons (**Table 4.3**).

AWD outperformed FP irrigation in terms of grain yield in 62% of the cases, water productivity in 88% of the cases, and irrigation water productivity in 92% of the cases (**Figure 4.1**). Overall, AWD increased grain yields over FP irrigation by 6% in the wet and by 4% in the dry season ($p < 0.05$) (**Table 4.4**).

Table 4.3 *Water input and soil water stress indices under two water management practices: farmers' practices (FP) and alternate wetting and drying (AWD) across irrigation schemes in Burkina Faso in 2018-2019*

	Wet season			Dry season		
	FP	AWD	Test statistic	FP	AWD	Test statistic
Irrigation frequency			GLMM			GLMM
Mean (SD)	7 (3)	5 (3)	**<0.001**	17 (5)	14 (4)	**<0.001**
Irrigation water input (m^{-3} ha^{-1})			LMM			LMM
Mean (SD)	1,645 (1,394)	1,274 (1,324)	**<0.001**	4,717 (3,442)	3,188 (2,061)	**<0.001**
Total water input (m^{-3} ha^{-1})			LMM			LMM
Mean (SD)	5,341 (1,550)	4,970 (1,456)	**<0.001**	5,314 (3,197)	3,784 (1,860)	**<0.001**
Soil flooding index (%)			LMM			LMM
Mean (SD)	71 (19)	56 (16)	**<0.001**	62 (22)	44 (20)	**<0.001**
Soil dryness index (%)			Robust LMM			LMM
Mean (SD)	1 (3)	1 (6)	1.000	2 (4)	3 (5)	0.147

SD: Standard deviation

LMM: Linear mixed effect model

GLMM: Generalized linear mixed effect model

Significant effects (p < 0.05) are indicated in bold.

Table 4.4 *Grain yield, water productivity, and partial factor productivity of applied nutrients under two water management practices: farmers' practices (FP) and alternate wetting and drying (AWD) irrigation in Burkina Faso in 2018-2019*

Key performance indicators	Wet season			Dry season		
	FP	AWD	Test statistic	FP	AWD	Test statistic
Grain yield (Mg ha^{-1})			LMM			LMM
Mean (SD)	5.07 (1.38)	5.35 (1.51)	**0.005**	4.44 (1.80)	4.61 (1.83)	**0.046**
Water productivity (kg grain m^{-3})			LMM			LMM
Mean (SD)	1.05 (0.48)	1.19 (0.54)	**<0.001**	1.08 (0.76)	1.49 (1.01)	**<0.001**
Irrigation water productivity (kg grain m^{-3})			LMM			LMM
Mean (SD)	6.13 (5.73)	10.22 (9.02)	**<0.001**	1.45 (1.21)	2.10 (1.75)	**<0.001**
Partial factor productivity of applied N (kg grain kg^{-1} N)			LMM			LMM
Mean (SD)	48 (32)	52 (38)	**0.007**	35 (14)	37 (19)	0.080
Partial factor productivity of applied P (kg grain kg^{-1} P)			LMM			LMM
Mean (SD)	284 (102)	305 (130)	**0.003**	321 (160)	334 (171)	0.093
Partial factor productivity of applied K (kg grain kg^{-1} K)			LMM			LMM
Mean (SD)	211 (75)	226 (93)	**0.002**	190 (81)	197 (86)	0.101

SD: Standard deviation

LMM: Linear mixed effect model

Significant effects ($p < 0.05$) are indicated in bold.

Table 4.5 *Weed infestation and plant growth parameters under two water management practices: farmers' irrigation practices (FP) and alternate wetting and drying irrigation (AWD) in Burkina Faso in 2018-2019*

	Wet season			Dry season		
	FP	AWD	Test statistic	FP	AWD	Test statistic
Weed infestation above the canopy#			GLMM			GLMM
Mean (SD)	0 (0)	0 (0)	0.467	0 (1)	0 (1)	0.758
Weed infestation below the canopy#			GLMM			GLMM
Mean (SD)	1 (1)	1 (1)	0.941	1 (1)	1 (1)	0.942
Average number of tillers at flowering			GLMM			GLMM
Mean (SD)	14 (4)	15 (4)	**<0.001**	16 (4)	17 (4)	**0.007**
Tiller number$ from 6 hills at harvest			GLMM			GLMM
Mean (SD)	83 (24)	87 (24)	**0.003**	95 (27)	100 (30)	**<0.001**
Panicle number from 6 hills at harvest			GLMM			GLMM
Mean (SD)	82 (24)	86 (24)	**0.005**	88 (26)	92 (27)	**<0.001**
Dry straw weight from 6 hills (g) at harvest			LMM			LMM
Mean (SD)	161 (78)	170 (80)	0.209	145 (44)	156 (49)	**<0.001**
Dry grain weight from 6 hills (g) at harvest			LMM			LMM
Mean (SD)	152 (62)	164 (55)	**0.039**	156 (55)	163 (55)	**0.043**
Dry biomass weight from 6 hills (g) at harvest			LMM			LMM
Mean (SD)	298 (111)	316 (104)	0.073	302 (93)	319 (98)	**0.002**
Harvest index			LMM			LMM
Mean (SD)	0.50 (0.06)	0.51 (0.05)	0.145	0.51 (0.06)	0.50 (0.04)	0.240

0 = No weed; 1 = Weed cover ≤ 10% of ground cover; 2 = Weed cover > 10% and ≤ 30% of ground cover; 3 = Weed cover > 30% and ≤ 60% of ground cover; 4 = Weed cover > 60%

$ This count includes both stems and tillers.

SD: Standard deviation; LMM: Linear mixed effect model; GLMM: Generalized linear mixed effect model

Significant effects (p < 0.05) are indicated in bold.

This increase was associated with a larger number of tillers and panicles under AWD (**Table 4.5**). However, we observed differences between schemes and seasons, whereby AWD irrigation was associated with yield increases in Karfiguela and Sourou Valley during the wet season and in Zoungou during the dry season (**Table 4.6**).

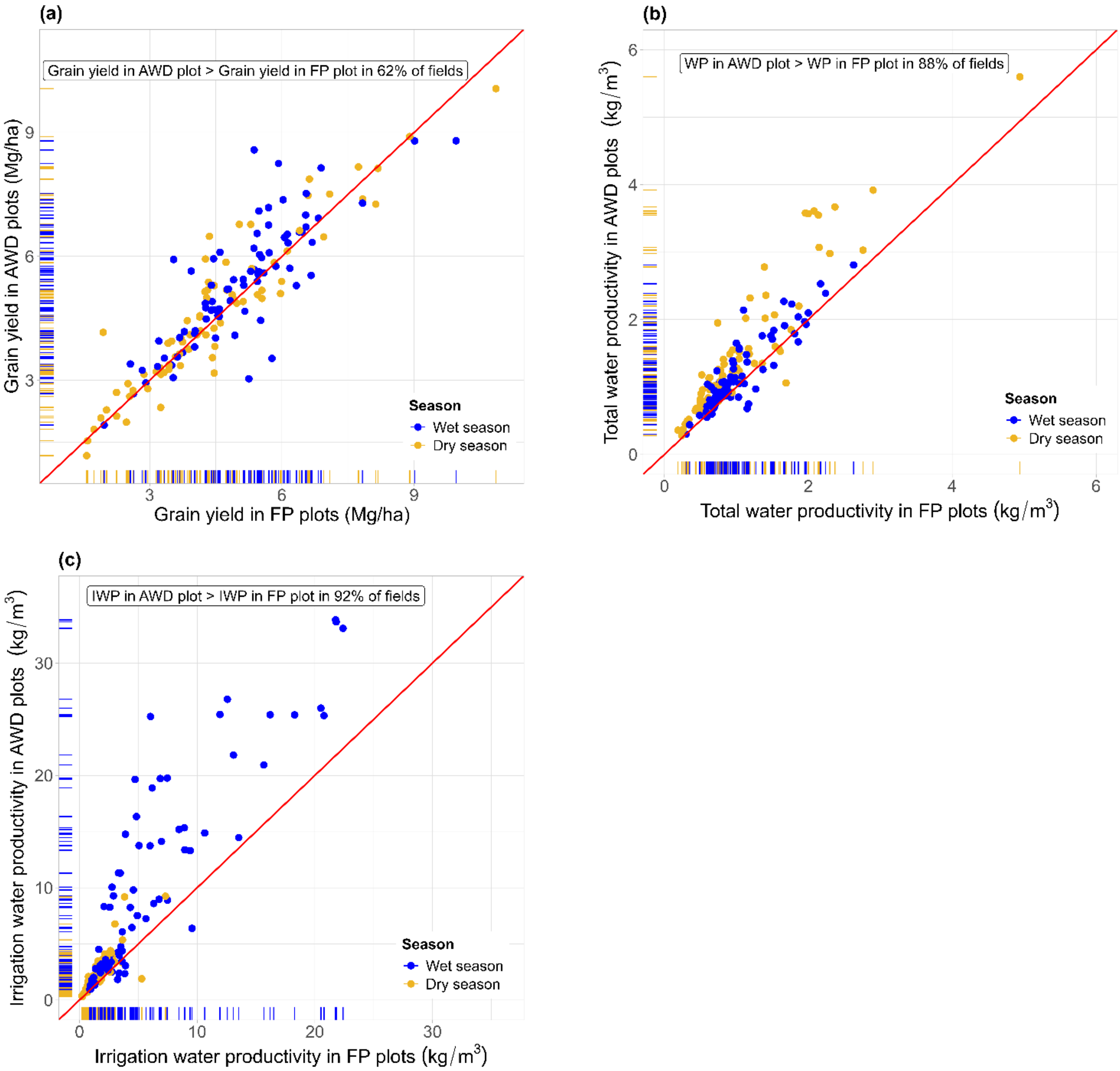


Figure 4.1. *Scatter plots of **(a)** grain yield, **(b)** water productivity, and **(c)** irrigation water productivity of plots under farmers' irrigation practices (FP) and alternate wetting and drying (AWD) irrigation in different schemes in Burkina Faso in 2018-2019.*

The red solid line is the identity line or line of equality.

Table 4.6 *Grain yield (mean ± standard deviation) under two water management practices: farmers' irrigation practices (FP) and alternate wetting and drying (AWD) in different irrigation schemes in Burkina Faso in 2018-2019*

Season	Irrigation schemes	Grain yield (Mg ha^{-1})		Test statistic
		FP	AWD	
Wet season				LMM
	Karfiguela (n=31)	5.02 ± 0.98	5.22 ± 1.08	**<.0001** [a]
	Kou Valley (n=13)	4.16 ± 1.79	4.15 ± 1.79	0.899
	Zoungou (n=11)	6.46 ± 1.55	6.65 ± 1.53	0.640
	Sourou Valley (n=23)	4.98 ± 1.04	5.59 ± 1.33	**0.008**
Dry season				LMM
	Karfiguela (n=13)	3.89 ± 0.74	4.04 ± 0.82	0.075
	Kou Valley (n=22)	4.61 ± 2.03	4.85 ± 1.99	0.214
	Zoungou (n=13)	3.12 ± 0.96	3.32 ± 1.13	**0.047**
	Sourou Valley (n=28)	5.22 ± 1.86	5.29 ± 1.96	0.609

LMM stands for linear mixed effect model

[a] Result (*p*-value) is from the robust linear mixed effect model.

Significant effects ($p < 0.05$) are indicated in bold

Partial factor productivities of applied N, P, and K (PFPN, PFPP, and PFPK) were generally higher with AWD during the wet season ($p < 0.05$), while no differences to FP irrigation were observed during the dry season ($p > 0.05$) (**Table 4.4**). Furthermore, in both wet and dry seasons, the weed infestation did not differ between AWD and FP plots (**Table 4.5**).

Across schemes, the production cost per hectare ranged from €582 to €862 in the wet and from €660 to €916 in the dry season. The net income varied between €252 and €2,179 in the wet season and between €229 and €569 in the dry season. The resulting benefit-cost ratios ranged from 1.3 to 3.5 in the wet season and from 1.3 to 1.9 in the dry season. AWD irrigation provided profit gains ranging from 1 to 11%, with an average of 5%, except in the Kou Valley during the wet season (**Table 4.7**).

Table 4.7 *Average total production costs, water input, yield, and income of rice production associated with the implementation of farmers' irrigation practices (FP) and alternate wetting and drying (AWD) irrigation in four schemes in Burkina Faso in 2018-2019*

	Karfiguela		Kou Valley		Zoungou		Sourou Valley	
	FP	AWD	FP	AWD	FP	AWD	FP	AWD
Wet season								
Total cost (€ ha^{-1})	752	742	584	582	862	862	811	813
Grain yield (Mg ha^{-1})	5.02	5.22	4.16	4.15	6.46	6.65	4.98	5.59
Gross income (€ ha^{-1})	1,149	1,194	984	981	2,956	3,041	1,062	1,192
Net income (€ ha^{-1})	397	452	399	399	2,093	2,179	252	379
Benefit cost-ratio	1.5	1.6	1.7	1.7	3.4	3.5	1.3	1.5
Profit gain (%)	5		0		3		11	
Total water input (m^3 ha^{-1})	5,727	5,310	4,805	4,507	4,568	4,256	5,491	5,113
Saving on total water input (%)	7		6		7		7	
Irrigation water input (m^3 ha^{-1})	766	349	909	611	1,764	1,453	3,189	2,811
Saving on irrigation water input (%)	54		33		18		12	
Dry season								
Total cost (€ ha^{-1})	661	660	667	667	666	664	910	916
Grain yield (Mg ha^{-1})	3.89	4.04	4.61	4.85	3.12	3.32	5.22	5.29
Gross income (€ ha^{-1})	890	924	1,174	1,236	1,019	1,080	1,194	1,211
Net income (€ ha^{-1})	229	265	507	569	353	416	285	294
Benefit cost-ratio	1.3	1.4	1.8	1.9	1.5	1.6	1.3	1.3
Profit gain (%)	4		5		6		1	
Total water input (m^3 ha^{-1})	3,559	3,375	3,362	2,421	5,588	4,063	7,535	4,917
Saving on total water input (%)	5		28		27		35	
Irrigation water input (m^3 ha^{-1})	1,700	1,515	2,833	1,892	5,387	3,862	7,288	4,670
Saving on irrigation water input (%)	11		33		28		36	

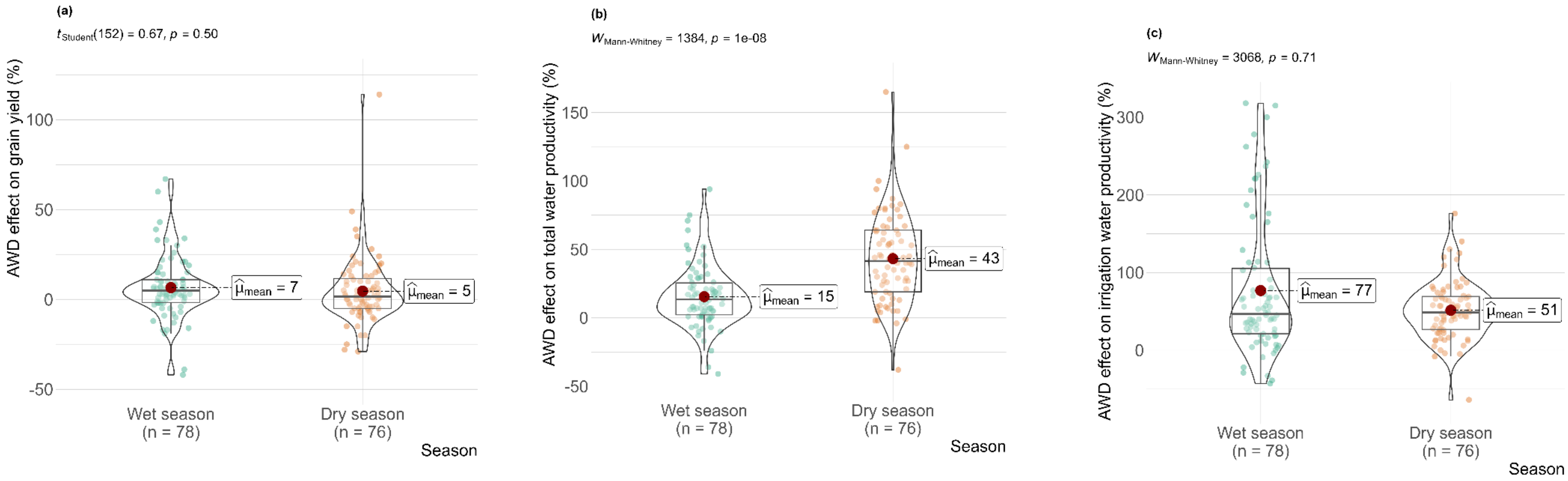


Figure 4.2. *Effect of alternate wetting and drying (AWD) irrigation (or percentage change in comparison with farmers' irrigation practices) on* ***(a)*** *grain yield,* ***(b)*** *water productivity, and* ***(c)*** *irrigation water productivity in wet and dry seasons in irrigated lowland systems in Burkina Faso in 2018-2019.*

The black solid line inside a box plot indicates the median and the red dot, the mean. n = 154.

4.3.4. Factors affecting the effects of AWD on yield and water productivity

Gains in yield and irrigation water productivity due to AWD over FP were 6% ± 18% and 64% ± 69%, respectively, and were comparable between seasons and irrigation schemes (**Figure 4.2a** and **c**; Table S10). The total gain in water productivity was higher (43% ± 33%) in the dry than in the wet season (15% ± 23%) (**Figure 4.2b**), and it reached 40% in the Sudano-Sahelian environment of Sourou Valley, but only 12% in the Sudanian environment of Karfiguela (Table S10).

It appears that various aspects related to the water supply and its in-field distribution (access to the irrigation water, land levelling), planting material (variety type), weeding control (weeding frequency and herbicide use), and P fertilizer application were key drivers affecting the yield gain of AWD over FP irrigation. Thus, the yield gains due to AWD were higher in fields with poor access to irrigation water than in those with good access to irrigation water and higher for *indica* than for tropical *japonica* genotypes. Similarly, yield gains due to AWD were higher in poorly levelled and weedy fields (**Figure 4.3**). In the same vein, the probability of yield gain due to AWD was higher in fields located at the middle reaches or tail-end with higher rates of P application (> 20 kg P ha^{-1}) (**Figure 4.4**).

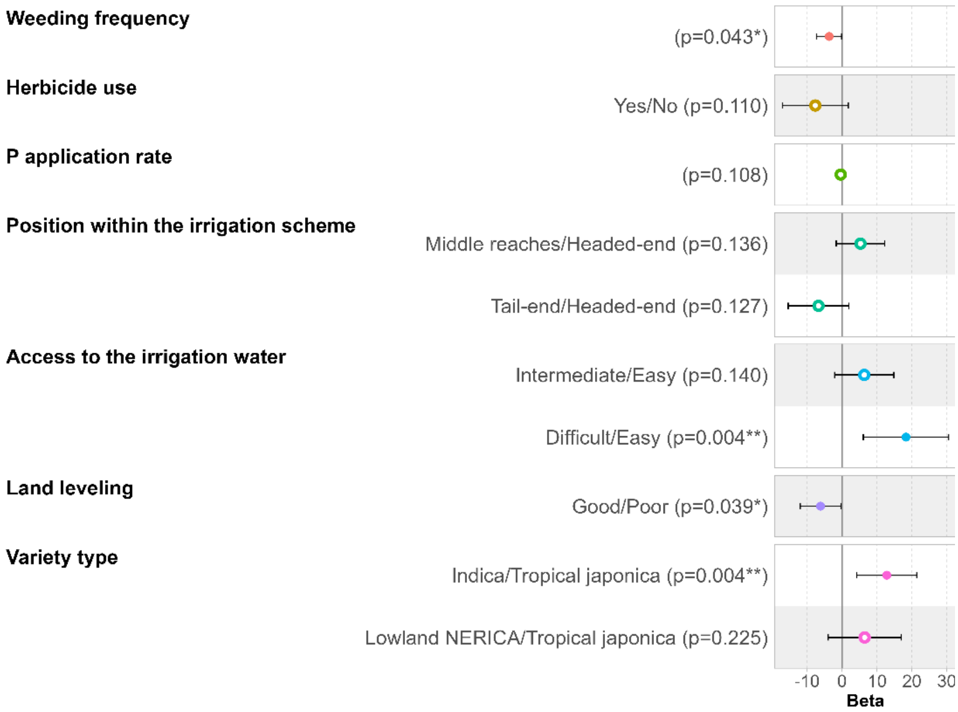


Figure 4.3. *Effects of key terrain attributes, variety type, and crop management practices on the effect size of alternate wetting and drying (AWD) over farmers' practices irrigation across seasons in Burkina Faso in 2018-2019.*

The slope coefficient for each explanatory variable was estimated using multiple linear regression (adjusted $R^2 = 0.14$; $p < 0.001$*). Empty dot indicates that the regression coefficient is not significant (*$p > 0.05$*), while filled dots indicate that the regression coefficient is significant (*$p < 0.05$*).*

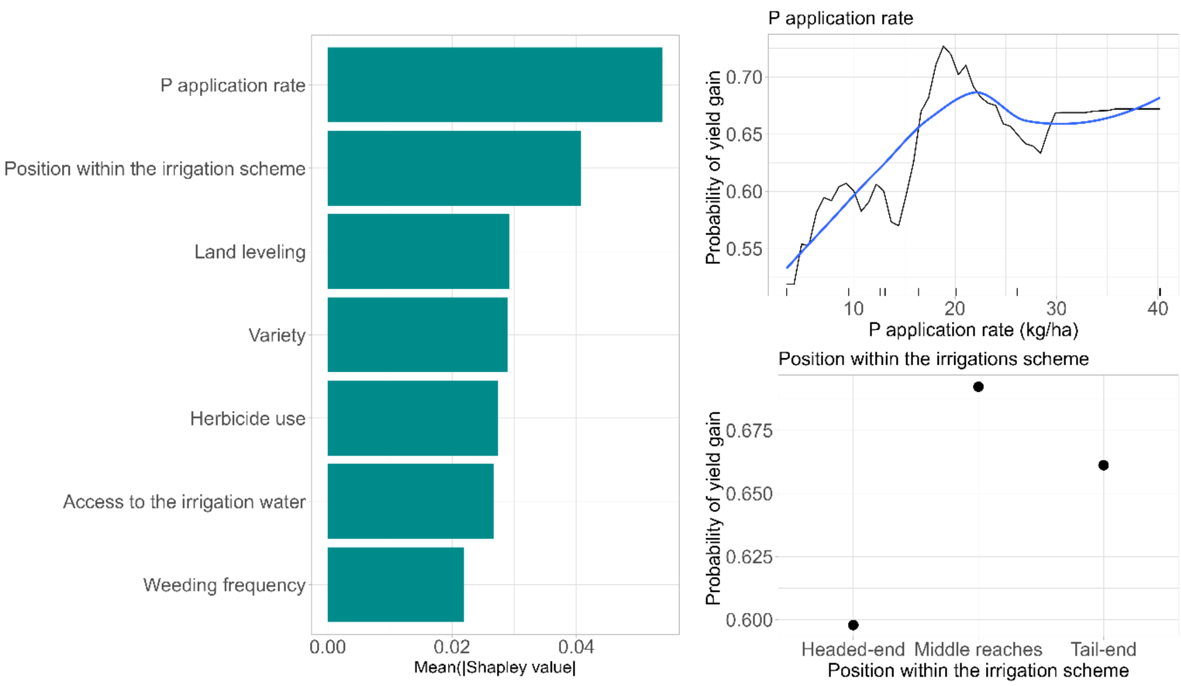
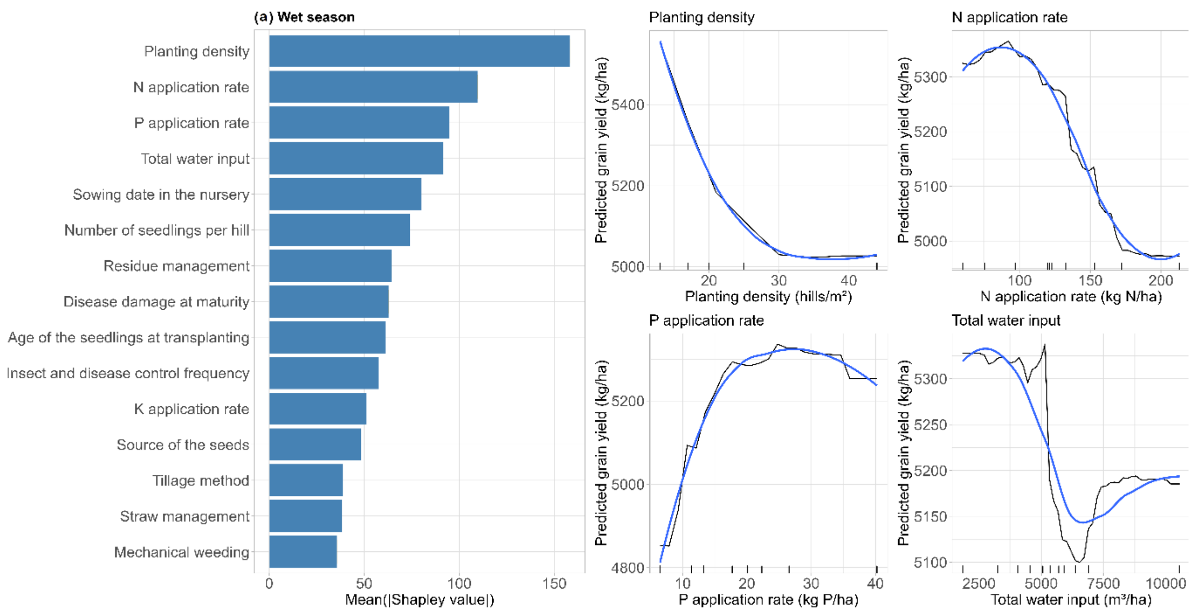


Figure 4.4. *Factors determining the yield gain of alternate wetting and drying (AWD) over farmers' practices irrigation in both wet and dry seasons in Burkina Faso in 2018-2019.*

Results are from the random forest classification model. The model predicts the out-of-bag samples with an accuracy of 75%. The variable importance is expressed as the mean of the absolute Shapley values. Only partial dependence plots (PDPs) of the two top-ranked predictor variables of yield gain are displayed. Each PDP (black line) is overlaid by a Locally Estimated Scatterplot Smoothing (LOESS) curve (blue line). The Y-axis of each plot indicates the probability of yield gain of different values or categories of the X predictor.

4.3.5. Determinants of grain yield variability and their impact

Irrespective of the irrigation management, the main determinants of the observed yield variability were season-specific. Thus, the planting density, N and P fertilizer application rates, and the total water input explained most of the yield variability during the wet season (**Figure 4.5a**). On the other hand, the frequency of mineral N split application, soil dryness index, sowing date, and bird control were prominent factors during the dry season (**Figure 4.5b**). In the wet season, a planting density ≥ 25 hills m^{-2} resulted in lower grain yields. Highest grain yields were obtained by applying 100 kg N ha^{-1} and 25 kg P ha^{-1}. Grain yields decreased when total water input exceeded 5000 m^3 ha^{-1} (**Figure 4.5a**). In the dry season, mineral N fertilizers splitting increased grain yields by 500 kg (~11%) when increasing the frequency from 1 to 4 split applications. Grain yields increased by 500 kg in the absence of water stress (soil dryness index = 0%) compared to fields with a soil dryness index of 20% (**Figure 4.5b**).



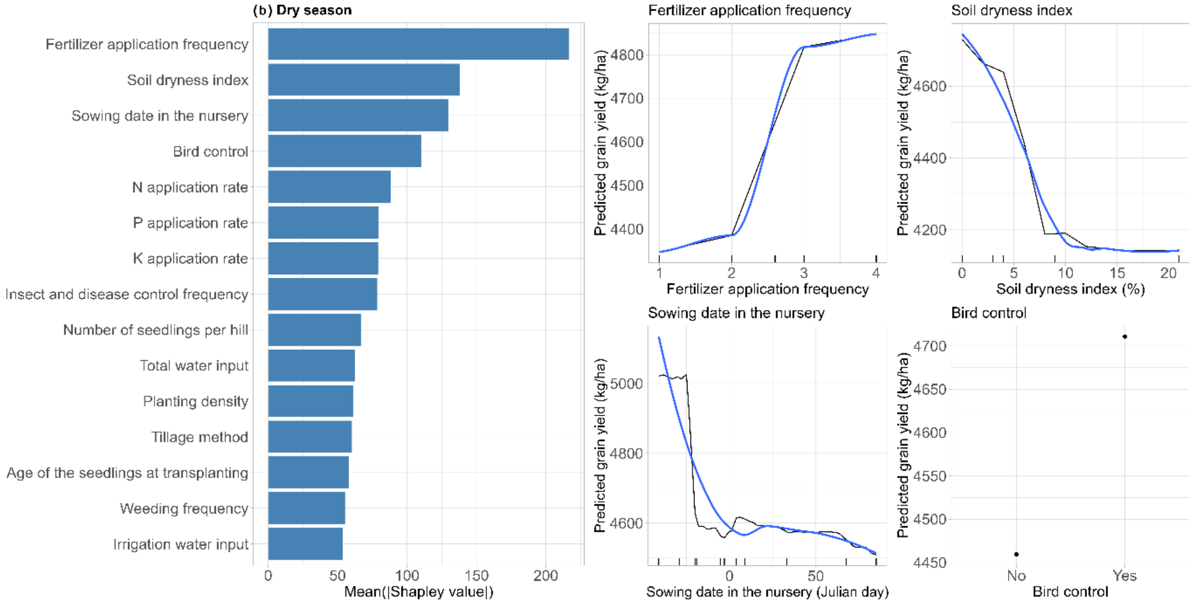


Figure 4.5. *Key crop management factors explaining yield variability in plots under farmers' practices and alternate wetting and drying (AWD) irrigation and their effect on the variation of yield in **(a)** wet season (out-of-bag R^2 = 0.58), and **(b)** dry season (out-of-bag R^2 = 0.62) in irrigated lowland systems in Burkina Faso in 2018-2019.*

Results are from random forest regression models. Only the top 15 most important factors are displayed. The variable importance is expressed as the mean of the absolute Shapley values. Only partial dependence plots (PDPs) of the four top-ranked predictor variables of yield variability are displayed. Each PDP (black line) is overlaid by a Locally Estimated Scatterplot Smoothing (LOESS) curve (blue line). The Y-axis of each plot indicates the average effect of different values or categories of the X predictor on the predicted yield (kg ha^{-1}).

4.4. Discussion

Compared to current farmers' irrigation practices (FP), AWD at a threshold level of -15 cm can save water while increasing yield, farmers' income, and nutrient use efficiency in the dry climatic zones of West Africa. Such benefits were highly variable across fields and irrigation schemes. This finding, however, may apply only when comparing AWD with the local irrigation management as in the present study, and not in comparison to continuous soil flooding, which may anyway not be applicable in most water-scarce zones of West Africa (Johnson *et al.*, 2023a). Keeping this in mind, the synopsis of this study discusses the following three aspects: (i) the water-saving capability of AWD technology and its effects on productivity and income, (ii) the conditions influencing the effect of AWD on grain yield, (iii) and recommendations for improving yield and reducing yield variability, regardless of the irrigation management regime.

4.4.1. Effect of AWD on water input and productivity and farmers' income

Compared to farmers' irrigation practices (FP), AWD reduced irrigation water input while increasing grain yield, resulting in significant increases in irrigation water productivity. Farmers' irrigation practices (FP) in the present study differ from permanent submergence conditions that served as the reference treatment in most studies reported from Asia. Due to only intermittent water availability in the irrigation canals at the study sites in Burkina Faso, field plots under FP were not permanently submerged, with soil flooding indices reaching 71% in the wet and only 62% in the dry seasons. To mitigate the perceived risks of field water shortage, farmers apply excessive amounts (water layers of 10-25 cm), whenever water is available, as reported before from the Senegal River Valley (de Vries *et al.*, 2010). Conversely, with AWD, farmers irrigated their plots only up to a 5 cm layer of ponded water and re-irrigated when the water level reached 15 cm below the soil surface. This entailed a significant reduction in the frequency of irrigation events, and savings of irrigation water input compared to farmers' irrigation practices of > 20% in the wet and > 30% in the dry seasons. Such substantial water savings with AWD may be attributed to less unproductive water outflows, including evaporation, percolation, and seepage as reported in previous studies (Bouman & Tuong, 2001; Dunn & Gaydon, 2011). Thus, water outflows through seepage and percolation can constitute 25–50% of the total water inputs in heavy soils with shallow water tables (Dong *et al.*, 2004), and 50–85% in coarse-textured soils with deep water tables (Bouman, 2007; Sharma *et al.*, 2002). Adopting AWD can avoid such losses, amounting to water savings comparable to those reported from Côte d'Ivoire (Dossou-Yovo & Saito, 2021), and slightly less than those reported from the Senegal River Valley (de Vries *et al.*, 2010), where permanent soil flooding served as the reference treatment. The observed water savings also fall within the range reported in global meta-analyses comparing AWD to continuous soil flooding (Carrijo *et al.*, 2017; Zhang *et al.*, 2023). These meta-analyses reported a 5-6% AWD-related yield penalty compared to continuous soil flooding. This stands in contrast to the AWD-related yield increases over farmers' irrigation practices reported in the present study and similarly reported by Dossou-Yovo and Saito (2021) in Côte d'Ivoire. The current study demonstrated that AWD irrigation increases tiller and panicle numbers, suggesting that these traits were associated with the observed yield gains (Howell *et al.*, 2015). These gains are likely related to the judicious monitoring of field water levels and the timely re-supply of water according to the plant's needs. Even in the absence of ponded water in the paddy fields, soils were still partially saturated, and rice roots could still obtain sufficient water. Thus, as demonstrated in previous studies in West Africa (Dossou-Yovo & Saito, 2021), AWD irrigation has proven to be an efficient water-saving technology, enabling an improvement in water productivity compared to traditional farmers' practices. However, the increase in water productivity under AWD compared to FP is attributed primarily to water savings rather than yield gains.

The adoption of any agricultural technology by farmers mainly depends on its economic viability and ease of use. Field-based studies conducted in Bangladesh, Vietnam, and the Philippines have demonstrated that AWD enhances the economic viability of the system by increasing profits by 9%-38% (Lampayan *et al.*, 2015a). The rather modest increase in profitability by 5% in the present study may be related to fixed water prices being applied per unit of irrigated area per season, and that no additional expenses are incurred for fuel used in supplemental irrigation. Considering the substantial savings in irrigation water, ranging from 12% to 54%, AWD may well turn out to be an economically viable irrigation technology in the dry climatic zones of West Africa.

4.4.2. Conditions influencing the AWD-associated yield gains

The effects of AWD on yield were highly variable (CV > 100%) but overall positive. Carrijo et al. (2017) and Zhang et al. (2023) showed that edaphic attributes such as pH, total organic C, and texture were key drivers underlying the effects of AWD on yield. In the present study, these reported trends could not be confirmed, possibly because the soil hydrological effects between the irrigation regimes were not sufficiently different. However, we found that the water supply and its in-field distribution, crop management practices, and variety were key factors in explaining the effects of AWD on grain yield. Thus, AWD-associated yield gains were higher in fields with poor access to irrigation water than in fields with good access. This finding was unexpected, given that timely access to irrigation was mentioned in previous studies as a pre-condition to adopting AWD (Yamaguchi *et al.*, 2019). These higher yield gains in AWD over FP in fields with poor access to irrigation may well be the result of more rigorous field observations in AWD plots, involving regular monitoring of the field water status and timely water re-supply, especially during critical phenological stages. In addition, even at water levels of -15 cm, soils in most field plots were still partially saturated, thus supplying sufficient water to rice, avoiding drought-related spikelet sterility and preventing yield losses (Bouman *et al.*, 2007). This active and conscious irrigation water management of field plots was much less in FP plots. Furthermore, excessive irrigation, especially during the wet season, could also account for the yield reduction. Hence, we recommend reshaping rice irrigation methods in the dry zones of West Africa by implementing systematic water level monitoring in the fields. Marked field water tubes at 5 cm and -15 cm can be made with cheap materials by using bamboo, tin cans, or even plastic bottles.

We also observed that yield gains associated with AWD were higher with *indica* than with tropical *japonica*, suggesting *indica* types to be better suited for AWD. This finding is consistent with Gealy et al. (2019), who reported that the yield of *indica* genotypes was less affected by AWD-induced water stress than tropical *japonica* genotypes. Similarly, Kato et al., (2009) reported that a high-yielding *indica* cultivar produced higher yields than tropical *japonica* cultivars under aerobic conditions. The AWD-associated yield gains may be due to the higher tillering capacity of *indica* compared to tropical *japonica* genotypes (Barnaby *et al.*, 2022). Further studies are needed to confirm these initial findings and to identify the varietal characteristics for adaptation to variable soil water conditions and aeration status as encountered with AWD in the dry climatic zones of West Africa.

Applying a high rate of P (> 20 kg P ha^{-1}) increased the probability of yield gains in AWD over FP (**Figure 4.4**). This finding is supported by the fact that the application of P fertilizers increases root density, rooting depth, and the available water supply to plants, thereby facilitating optimal crop performance under conditions of limited moisture (Sharma *et al.*, 2015). Moreover, the drying phases of AWD can stimulate the P adsorption capacity of acidic soils, thereby reducing P availability (Haynes & Swift, 1985; Ishfaq *et al.*, 2020). This could explain the higher demand for P fertilizer application under AWD, which may serve to compensate for temporary native P deficiency.

Surprisingly, we observed that AWD-associated yield gains were lower when the weeding frequency was higher, suggesting that weed competition had a more pronounced negative impact on yields in FP than in AWD plots. The underlying reasons for this trend remain unclear, given that the visual weed infestation values did not significantly differ between irrigation regimes. These limitations could be addressed in future studies by implementing a quantitative estimation of weed biomass.

4.4.3. General recommendations for improving grain yield and reducing yield variability

This study suggests that specific key agronomic practices must be optimized, irrespective of the irrigation management to increase yield, reduce yield variability and subsequently improve water productivity. Farmers should focus on different aspects of crop management depending on the growing seasons. During the wet season, we suggest keeping the planting density around 15-20 hills m^{-2} (**Figure 4.5a**). This finding and the associated suggestion are in harmony with previous studies underlining that planting density had a great impact on the rice yield (Yang *et al.*, 2021) and that an increase of density from 15 to 40 plants m^{-2} resulted in low yield (Clerget *et al.*, 2016). Concerning fertilizer application, a rate of 100 kg N ha^{-1} and 25 kg P ha^{-1} resulted in the highest yields. These rates were slightly higher than the average N and P rates (84 kg N ha^{-1}, 17 kg P ha^{-1}) applied by farmers in irrigated lowlands in sub-Saharan Africa (Johnson *et al.*, 2023b). Earlier studies (Dossou-Yovo *et al.*, 2020; Ibrahim *et al.*, 2022) highlighted the importance of N and P fertilizer application rates to increase yields and narrow yield gaps in irrigated lowlands in sub-Saharan Africa. Although water is one of the key production inputs in irrigated rice, increasing inputs of water do not consistently enhance grain yields and additional input beyond threshold values can result in a productivity reduction (Shao *et al.*, 2015). Thus, although we did not strictly monitor the water level in all plots, we could recommend avoiding excessive standing water and drainage if needed after heavy rains. On the other hand, during the dry season, we found that splitting the N fertilizer application into three doses, maintaining the soil dryness index at 0%, sowing early, and implementing bird control measures resulted in higher yields. We could, therefore, recommend these cropping management practices in the dry seasons. Furthermore, early sowing and transplanting offer a distinct advantage by preventing heading and flowering from coinciding with March and April, which are often characterized by water shortages (Johnson *et al.*, 2023a).

4.5. Conclusion

In the context of water scarcity severely affecting irrigated rice production in dry climatic zones of West Africa, we investigated the feasibility and benefits of alternate wetting and drying irrigation (AWD), a promising water-saving technology recently introduced to the region. This study reports for the first time results from on-farm trials under farmers' management comparing AWD with local farmers' irrigation practices across a wide range of biophysical environments in dry climatic zones of West Africa. Three main findings emerged: (i) AWD technology has proven to be an efficient water-saving technology, allowing to reduce irrigation water inputs by 30% compared to the farmer's irrigation practice while increasing yield and profitability by 5%. Consequently, AWD can enhance irrigation water productivity by > 60%. (ii) The yield gains of applying AWD were highly variable depending on the water supply and its in-field distribution, genotypes, and crop management practices. Thus, AWD-associated yield gains were highest under conditions of poor irrigation management and when using *indica* genotypes. And (iii) during the more water-strapped dry season achieving high grain yields and reducing yield variability generally requires reducing the soil dryness index. The findings suggest a need for reshaping rice irrigation practices in the dry climatic zones of West Africa, involving a systematic monitoring of field water levels.

Chapter 5: Alternate wetting and drying: A water-saving technology for sustainable rice production in Burkina Faso? [δ€#]

Word cloud visualization of the 50 most frequent words in this chapter

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Abstract

With emerging water scarcity and rising fertilizer prices, optimising future water use, while maintaining yield and nutrient efficiency in irrigated rice is crucial. Alternate wetting and moderate soil drying irrigation (i.e., re-irrigation when the water level reaches 15 cm below the soil surface) has proven to be an efficient water-saving technology in semi-arid zones of West Africa, reducing water inputs without yield penalty. Alternate wetting and severe soil drying (AWD30), by re-irrigating fields only when the water table reaches 30 cm below the soil surface, may further reduce water inputs compared to farmers' irrigation practices (FP). However, acute soil drying may impair fertilizer use efficiency and reduce the bio-availability of some key nutrients. This study assessed the potentials and risks associated with AWD30 for smallholder rice farmers in the semi-arid zones of West Africa. We conducted 30 on-farm field trials over three seasons (wet and dry seasons of 2019, and dry season of 2020), in Kou Valley, Burkina Faso. We assessed yield, water productivity, nutrient uptake, and use efficiency under AWD30 and FP. In FP, farmers maintained their fields submerged as frequently as possible according to the scheme-dependent water provision schedule. With AWD30, irrigation frequency was reduced by 30%, however, soils were seldom completely dried due to a shallow groundwater table. Compared to FP, AWD30 reduced irrigation water input by 37% with no significant effects on grain yields (average of 4.5 Mg ha^{-1}), thus increasing average water productivity by 39%. Both irrigation management practices provided comparable crop uptake of N, P, and K, and use efficiencies of applied N and P. However, the N content in straw and the P concentration in grain generally increased with total water input (rain + irrigation). We conclude that at locations with a shallow groundwater table, AWD30 can effectively save irrigation water without significantly reducing the grain yield and the use efficiency of applied mineral nutrients.

Keywords: Nutrient use efficiency, nutrient uptake, *Oryza* spp., water scarcity, West Africa

5.1. Introduction

Water is a key input for producing rice, the most important food crop in many developing countries and the staple food consumed by more than half of the world's population (Mishra *et al.*, 2022). Irrigated lowland rice farming plays a crucial role in global food security, providing 75% of the world's rice supply (Global Rice Science Partnership, 2013). However, irrigated rice also requires more water (40% of the global irrigation water) than any other staple crops (Surendran *et al.*, 2021). In addition to water, nitrogen (N) is another essential input limiting rice production (Johnson *et al.*, 2019; Saito *et al.*, 2019). Most cultivable soils contain insufficient amounts of N, and therefore, N accounts for the largest share of fertilizer consumption (Aulakh & Malhi, 2005; Johnson *et al.*, 2023b).

With increasing competition for water resources between domestic, industrial, and agricultural sectors, water scarcity has become one of the main issues faced by poorer communities, particularly in arid areas. Over 2.3 billion people live in water-scarce areas and their number will increase (UN-Water, 2021) due to rapid demographic growth. In West Africa, and mainly in semi-arid and arid zones, water scarcity threatens the sustainability of irrigated rice production (Johnson *et al.*, 2023a).

The rice crop takes up only ~40% of applied N fertilizers, indicating that about 60% of N applied is not assimilated and may be lost from the soil-plant system (Wopereis *et al.*, 1999; Yu *et al.*, 2022), making it a potential source of environmental (water and air) pollution (Tilman *et al.*, 2002). In addition, N fertilizer represents the second-highest input cost in rice production for smallholder farmers in sub-Saharan Africa, and its inefficient use thus contributes significantly to economic losses (Chidiebere-Mark *et al.*, 2019; Saito *et al.*, 2023b). The sharp rise in fertilizer prices following the COVID-19 pandemic and the Russia-Ukraine war further increased concerns in the Global South and emphasized the relevance of improved nutrient management (Arndt *et al.*, 2023). Furthermore, water scarcity may also affect nutrient use efficiency (Datta *et al.*, 2017) and reduce crop N uptake (Lassaletta *et al.*, 2023).

In this context, reducing water input while maintaining grain yield and nutrient use efficiency is of critical importance for sustaining the production of irrigated rice. To tackle this challenge, several water-saving technologies have been advocated. Among these, alternate wetting and drying irrigation (AWD) has become one of the most prominent and widely recommended water-saving technologies in Asia (Cheng *et al.*, 2022; Chu *et al.*, 2018). However, in the semi-arid zones of West Africa, AWD is largely unknown to smallholder farmers (Johnson *et al.*, 2023a). This water-saving irrigation technology involves intentionally allowing the paddy fields to dry out until the field water level reaches a threshold, before re-irrigation, rather than keeping them continuously submerged (Lampayan *et al.*, 2015b). In practice, AWD irrigation is categorized into two groups according to either the soil water potential or the soil water table threshold: (1) Alternate wetting and moderate soil drying (AWD15), which involves re-irrigation when the water level reaches 15 cm below the soil surface (or soil water potential ≥ -20 kPa); and (2) alternate wetting and severe soil drying (AWD30), where re-irrigation occurs when the field water level drops below 15 cm and up to 30 cm below the soil surface (or soil water potential < -20 kPa) (Carrijo *et al.*, 2017). Globally, alternate wetting and moderate soil drying irrigation, considered as “safe” AWD procedure, reduced the water input by 23% without yield penalty compared to continuous submerged field practices (Carrijo *et al.*, 2017). A recent study, comparing it to farmers’ irrigation practices, demonstrated its effectiveness as a water-saving technology in semi-arid areas of sub-Saharan Africa (SSA) (Johnson *et al.*, 2020). Compared to farmers’ irrigation practices, it reduced water input by up to 30% without compromising yield (Johnson *et al.*, 2020). Alternate wetting and severe soil drying has the potential to further reduce water inputs (Carrijo *et al.*, 2017). However, extended periods of aerobic soil conditions may stimulate the germination and growth of terrestrial weeds, thereby increasing the demands for weed control management (Rodenburg *et al.*, 2011). The extended dry periods during AWD implementation may lead to NO_3^--N losses due to nitrification and denitrification, further affecting the nitrogen use efficiency (De Datta *et al.*, 1990). In addition, ammonia (NH_3) volatilization in alkaline soils may enhance the N losses during drying events (Ishfaq *et al.*, 2020; Moormann & van Breemen, 1978). On the other hand, some studies reported no increase in N losses under AWD or even an enhanced N use efficiency due to reduced N leaching, being one of the primary routes of N losses in paddy fields (Ghosh & Bhat, 1998; Peng *et al.*, 2011). Furthermore, AWD irrigation may also potentially reduce the bioavailability of macronutrients such as P and K and some micronutrients (mainly Fe and Mn) (Ishfaq *et al.*, 2020). To date, it is still unclear how AWD affects nutrient uptake and use efficiency.

Most previous studies assessing the effect of AWD on nutrient uptake and use efficiency were conducted in Asia and were obtained from on-station trials (Cheng *et al.*, 2022). Among the limited number of studies providing insights from the Sahelian region in West Africa (de Vries *et al.*, 2010; Djaman *et al.*, 2018), the focus has primarily been on N use efficiency, comparing AWD to continuous submergence. However, continuous submergence is not the predominant water management practice implemented in irrigated rice schemes in West Africa where water is made available on a scheme-depended irrigation schedule (Johnson *et al.*, 2023a). Comparisons between AWD and actual farmers' irrigation practices are limited (Krupnik *et al.*, 2012c). Furthermore, no previous study in the region assessed the effect of AWD on

P use efficiency and the concentration of macro and micronutrients in straw and grain. There is a need to evaluate the impact of AWD in dry climatic zones in West Africa under farmers' field conditions to assess its feasibility and sustainability. To address this knowledge gap, we quantified and compared water input, growth parameters, grain yield, water productivity, N and P use efficiency, and nutrient uptake (N, P, K, Mn, Fe, and Zn) under the farmers' irrigation practices (FP) and alternate wetting and severe drying (AWD30). We hypothesized that due to increased N losses during the drying phases and reduced availability of P under aerobic soil conditions, AWD30 irrigation may reduce the N and P use efficiency compared to FP irrigation. To test this hypothesis, two-year on-farm trials were conducted in Burkina Faso, with the following objectives: (i) to compare the effects of alternate wetting and severe soil drying (AWD30) and farmers' irrigation practices (FP) on growth parameters, weed infestation, grain yield, water productivity, nutrient uptake and use efficiency; (ii) to assess the effect of water input and anaerobic conditions on N, P and K uptake; and (iii) to evaluate the synergies and trade-offs between water productivity and N and P use efficiency.

5.2. Material and Methods

5.2.1. Study area

Burkina Faso, a Sahelian country in West Africa, facing recurrent drought events and water scarcity in the last decades, was chosen as the focus of this present study. In this country, the availability of water for rice field irrigation is dwindling, especially during the dry season (Johnson *et al.*, 2023a). The study was conducted in the Kou Valley irrigation scheme (11°23'7''N, 4°24'20''W, 320 m a.s.l), located in the southwest of Burkina Faso and approximately 30 km north of the town of Bobo-Dioulasso (Fig. S1). Commissioned in 1970, Kou Valley is one of the largest rice irrigation schemes in the country (Dembelé *et al.*, 2005; Johnson *et al.*, 2023a). Covering 1,260 ha within the Kou River watershed, this scheme relies on a run-of-river diversion intake from an upstream headwork (Wellens *et al.*, 2013). Irrigation water is conveyed by gravity through either earthen or concrete-lined canals and then distributed to individual plots using bund breaks. Kou Valley irrigation scheme is a suitable case study, as it directly experiences water scarcity due to the reduced exploitable flow rates in the Kou River, resulting from a decrease in rainfall over the last two decades (Johnson *et al.*, 2023a) and increasing water withdrawals for the city of Bobo-Dioulasso for industrial and households needs (Dembelé *et al.*, 2005).

The region's climate is classified as Sudanian with a unimodal rainfall pattern and an annual rainfall varying between 800 and 1,200 mm, primarily concentrated between June and September. The average annual minimum and maximum temperatures are 21.2 °C and 33.8 °C, respectively (Johnson *et al.*, 2023a). The dominant soil types are Luvisols and Regosols (Johnson *et al.*, 2023a) with generally sandy-clay-loam textured topsoils, progressively turning into clay in subsurface horizons (FAO & IIASA, 2023). Farmers typically engage in two rice-growing seasons each year: the dry season (from January to May) and the wet season (from June to November). More information on the scheme is presented in Johnson *et al.* (2023a).

5.2.2. Description of the on-farm trials and settings

A series of on-farm trials were conducted during the wet and dry seasons of 2019 and the dry season of 2020, comparing alternate wetting and severe drying (AWD30) irrigation to farmers' irrigation practices (FP). The purpose of the experiment was explained during cooperative group meetings, and farmers were chosen based on their willingness to participate. Initially, our goal was to involve 15 participating farmers per cropping season. However, logistic challenges and setbacks in on-farm trials (non-cooperative farmers, farmers' non-compliance with harvesting data collection instructions, cattle grazing fields), led to a total sample size of 30 farmers' fields (12 in the wet season of 2019, 12 in the dry season of 2019 and 6 in the dry season of 2020). No experiment was conducted twice in the same farmer's field.

In each field, two plots of about 500 m^2 each with the same cropping histories were delimited by 30 cm high consolidated bunds of 50 cm width to prevent seepage. In these plots, two water irrigation regimes were applied, namely, i) farmer's practice of irrigation (FP) and ii) AWD30 irrigation practice. The plots were irrigated using the scheme irrigation system. Farmer's practice of irrigation differed from conventional continuous flooding irrigation due to the non-permanent availability of water in the canals. Irrigation frequency was further determined by both individual farmers' water management decisions and the scheme-dependent water supply schedule, with water provision varying from every 4 to 5 days. Generally, in the absence of recent rainfall, whenever water is available, farmers irrigate their fields to reach a standing water level of 10 – 15 cm depth. In AWD30 plots, farmers were instructed to maintain a ponded water level of 2-5 cm during the initial 21 days after transplanting (DAT) to assist seedling recovery and ensure weed suppression. Thereafter, the AWD30 irrigation treatment was imposed. Following the installation of the perforated PVC tubes in every AWD plot to monitor the field water level (Lampayan *et al.*, 2015b), farmers received training in applying AWD to a threshold water level of 30 cm below the surface. As water deficit during the flowering stage of rice can increase spikelet sterility, farmers were instructed to halt the drying phase in AWD30 plots and to maintain ponded water levels of 2 to 5 cm during this critical stage (Bouman *et al.*, 2007). We provided farmers with specific window dates corresponding to this period based on the phenological characteristics of the variety they planted. Thereafter, farmers applied again AWD30 until about 2 weeks before rice harvest. Except for irrigation management, plots in the same fields had identical cropping and land-use histories and were managed according to farmers' cropping practices. Farmers selected their preferred rice variety and decided on the type, quantity, and timing of input (herbicides, pesticides, and fertilizer) use. For further analysis, which includes assessing nutrient concentration in plants and specific indices of N and P use efficiency, we selected a representative subset of farmers' fields (5 in the wet season and 6 in the dry season). Within each irrigation treatment plot in these fields, we marked out and isolated a subplot of 10 m × 12.5 m with no application of mineral NPK, where we assessed rice biomass and grain yield to calculate agronomic nutrient use efficiencies. We used consolidated bunds that were 30 cm high and 50 cm wide for delimitation.

5.2.3. Soil and plant sampling and analysis

Before the onset of the trials, we collected approximately nine soil cores (at a depth of 0 – 20 cm) along the diagonals in each field and combined them to create composite samples. These samples were air-dried, sieved, and analyzed for soil texture (clay, silt, and sand contents), and chemical attributes such as pH (1:2.5 dry soil: water ratio), total organic C, total N, and available P (Bray-2) following the analytical methods described by Johnson et al. (2019).

Six randomly selected rice hills were sampled at maturity from each plot as well as from the nutrient omission subplot to determine yield components (tillers and panicles number), total shoot biomass, and nutrient uptake. Plant samples were separated into straw and grain and oven-dried at 60 ºC for 72 hours to calculate the harvest index.

Dried grain and straw samples were fine ground using a vibrating disc mill (Siebtechnik TS 250, Siebtechnik GmbH, Mülheim an der Ruhr, Germany) and stored in plastic containers for subsequent concentration analysis of N, P, K, Mn, Fe, and Zn. The total N in plant materials was determined using an elemental analyzer (EURO EA Elemental Analyzer series 3000, EuroVector, Pavia, Italy). Plant P, K, Mn, Fe, and Zn were determined after microwave digestion with concentrated nitric acid (HNO_3) using an Inductively Coupled Plasma - Optical Emission Spectrometer (Thermo Fischer ICP-OES iCAP PRO, Thermo Fisher Scientific GmbH, Dreieich, Germany). N, P, K, Mn, Fe, and Zn concentrations in straw and grain were expressed on a dry weight basis. N, P, and K uptake were calculated as the sum of straw and grain dry matter weights, multiplied by their respective nutrient concentrations.

5.2.4. Field survey, observations, and data collection

Weather data (solar radiation, maximum and minimum air temperature, relative air humidity, and rainfall at daily time steps) were retrieved from “aWhere”, a cloud-based real-time data platform (aWhere, Inc., Broomfield, Colorado, United States).

We collected data on (i) farm management practices (source of seeds, straw and residue management, tillage method, land levelling, sowing date, planting density, number of seedlings per hill, weed management, fertilizer management, pests control, irrigation frequency), (ii) weed infestation at flowering, both below and above rice canopy (visually assessed, categorized and scored into four levels: 0 = No weed, 1 = weed cover ≤10%, 2= weed cover >10% and ≤30%, and 3 = weed cover >30% and ≤60%) (Gongotchame *et al.*, 2014), and (iii) farmers’ yield using a standardized protocol [see Niang et al. (2017) and Tanaka et al. (2017)] (Table S1). Three harvest areas of 12 m^2 (~ 360 hills) each were demarcated within both FP and AWD30 plots for assessing farmers’ land and crop management practices and determining grain yield. The harvest areas were positioned along a diagonal to capture the variability of productivity within the fields. At maturity, grain yield was measured within each harvest area and expressed at a standardized moisture content of 14%.

Every three days, the field water status in each plot was visually assessed and scored using a three-point scale [1: ponded water (i.e., standing water table with a depth of more than 1 cm), 2: wet soil surface (i.e., fully saturated or partially saturated soil without standing water table), 3: dry soil surface (i.e., soil surface does not exhibit any visible signs of moisture)] (Haefele *et al.*, 2006). Additionally, the frequency of irrigation (the number of irrigations during the growing cycle) for each irrigation management treatment was recorded. We estimated the water flow rates using the bucket method. The bucket method is a straightforward and efficient technique for measuring low to medium flow rates in channels or small streams. It entails placing a bucket of known capacity at the plot's inlet to capture all the flowing water through bund breaks while timing how long it takes for the container to fill using a stopwatch. The flow rate is then calculated by dividing the volume of the container by the filling time (Saito *et al.*, 2023a; Trimmer, 1994). To ensure accuracy, we repeated these steps at least three times and calculated the average flow rate. In each plot, the quantity of water applied per irrigation was estimated three to four times during the growing season. Total irrigation water input was calculated by multiplying the number of irrigation events by the average water quantity per individual irrigation event.

5.2.5. Soil water status, nutrient use efficiency indices, and performance indicators

Soil water status, nutrient use efficiency indices, and other performance indicators were computed for each plot. The soil flooding index (%) was calculated as the ratio between the number of days with ponded water and the total number of recorded days during the growing season (from three weeks after transplanting to maturity) (Equation 1).

$$Soil\ flooding\ index = \frac{Number\ of\ days\ with\ a\ ponded\ water}{Total\ number\ of\ recorded\ days\ during\ the\ growing\ season} \times 100 \quad (1)$$

Similarly, the soil dryness index was calculated using the number of days with a dry soil surface (Niang *et al.*, 2018).

$$Soil\ dryness\ index = \frac{Number\ of\ days\ with\ a\ dry\ soil\ surface}{Total\ number\ of\ recorded\ days\ during\ the\ growing\ season} \times 100 \quad (2)$$

A soil flooding index of 0 indicates a permanently dry soil surface or wet soil conditions, while a flooding index of 100 indicates a permanent presence of ponded water.

We computed water productivity (WP, in kg grain m^{-3} water), irrigation water productivity (IWP, in kg grain m^{-3} water), and partial factor productivity of applied mineral N (PFPN, in kg grain kg^{-1} N), P (PFPP, in kg grain kg^{-1} P), K (PFPK, in kg grain kg^{-1} K) (Fixen *et al.*, 2015; Sharma *et al.*, 2015) as follows:

$$WP = \frac{Yield}{Total\ volume\ of\ water\ input} \quad (3)$$

$$IWP = \frac{Yield}{Volume\ of\ irrigation\ water\ input} \quad (4)$$

$$PFP_x = \frac{Yield}{Rate\ of\ nutrient_x\ applied} \quad (5)$$

whereby Yield represents grain yield expressed in kg ha^{-1}. The total volume of water input comprises both irrigation and rainfall and is expressed in m^3 ha^{-1} during the rice-growing period, and the rates of N, P, and K applied are expressed on an elemental basis (i.e., kg N, P, or K ha^{-1}).

In addition, specific indices of N use efficiency such as agronomic efficiency (kg grain kg^{-1} N), recovery efficiency (%), physiological efficiency (kg grain kg^{-1} N), soil N dependent (%) rate were calculated according to Ladha *et al.* (2005) and Ye *et al.* (2007) and using the following equations:

$$Agronomic\ efficiency\ of\ N = \frac{Yield_T - Yield_0}{Rate\ of\ N\ applied} \qquad (6)$$

$$Recovery\ efficiency\ of\ N = \frac{Uptake_T - Uptake_0}{Rate\ of\ N\ applied} \times 100 \qquad (7)$$

$$Physiological\ efficiency\ of\ N = \frac{Yield_T - Yield_0}{Uptake_T - Uptake_0} \qquad (8)$$

$$Soil\ N\ dependent\ rate = \frac{Uptake_0}{Uptake_T} \times 100 \qquad (9)$$

where $Yield_T$ represents the grain yield (kg ha^{-1}) in the plot with total N supply (from both the soil and fertilizer); $Yield_0$ is the grain yield (kg ha^{-1}) in the plot without N fertilizer or with only the soil N supply, $Uptake_T$ (kg ha^{-1}) is the plant N uptake measured in aboveground biomass in the plot that received N fertilizer, and $Uptake_0$ (kg ha^{-1}) indicates the plant nutrient uptake in the plot without N fertilizer application.

In addition, for P, we calculated the partial P balance (%) (Syers *et al.*, 2008), expressing the total P uptake as a percentage of the P applied (Equation 10).

$$Partial\ P\ balance = \frac{P\ Uptake}{Rate\ of\ P\ applied} \times 100 \qquad (10)$$

5.2.6. Statistical analyses and visualization

Field survey data were collected using Android mobile devices, and submitted on a server, where they were downloaded, cleaned, gathered into an Excel spreadsheet, and analyzed using R. 4.3.2 (R Core Team, 2023).

Descriptive statistics and Student's t-test

Weather and soil fertility attributes, and farm management practices presented as continuous variables were analyzed using descriptive statistics (mean and standard deviation) while percentage shares were calculated on categorical variables. We computed Chi-squared (χ2) tests of homogeneity to determine whether the proportions of categorical variables were the same across wet and dry seasons (Franke *et al.*, 2012). Continuous variables related to farm management practices were compared between seasons using either the Student's t-test when the normality of residuals and homogeneity of variance were met or the Mann-Whitney-Wilcoxon test as the non-parametric alternative.

Mixed-effects models

We visualized 30 pairwise comparisons of AWD and FP for yield, water productivity, and irrigation water productivity using scatterplots. We subsequently determined the proportion of fields where AWD30 outperformed FP.

Linear mixed-effects models [LMMs, *lme4* package; Bates et al. (2015)] were applied with irrigation management as fixed factors and field as a random factor (1| Field), to compare the overall performance of AWD30 and FP on different response variables (weed infestation, grain yield, yield components, water productivity, partial factor productivity of applied nutrients, water input, N and P use efficiency indices, nutrient concentration in straw and grain, total N, P and K uptake) for both wet and dry seasons. “Field” was considered as a random effect to account for repeated measurements, with two plots within each farmer’s field. We combined the data from the two dry seasons due to the absence of significant differences in terms of yield and water productivity. This approach was also adopted to prevent a reduction in the statistical power of the tests. P-values for the fixed effect (irrigation management) were estimated using type-III analysis of variance with Satterthwaite's method, implemented using the *lmerTest* package (Kuznetsova *et al.*, 2017). When assumptions for the application of LMMs were violated (i.e., heteroscedasticity and deviance of residuals from normality), robust linear mixed-effects models [with *Robustlmm* package; Koller (2016)] were alternatively run and p-values of the fixed effect were obtained using the *emmeans* package (Lenth, 2022). To model count variables (e.g., tiller or panicle number and frequency of irrigation), we employed Poisson generalized linear mixed-effects models (GLMMs) with the log-link function, using the package *lme4* (Bates *et al.*, 2015). After checking overdispersion concerns in the Poisson model, we estimated the p-values of the fixed effect according to the Wald test.

Correlation analysis

Correlation analyses were conducted to explore the relationships between inputs (water, N, P, and K application rates), and outputs (N, P, and K uptakes, and grain yield), regardless of irrigation treatments (FP and AWD30) and season. Furthermore, correlations between grain yield, water productivity, and N and P use efficiency indices were computed to assess potential trade-offs among these performance indicators. The pairwise associations between variables were visualized using a correlogram plotted with the package *corrplot* (Wei & Simko, 2021). As the standard Pearson's correlation estimate is parametric, relying on assumptions of normality and homoscedasticity, it can be sensitive to extreme values. To address these concerns, we opted to compute Spearman's rank correlation coefficient (ρ) (Wilcox, 2016). The effect size ρ was interpreted following Cohen's (1992) guidelines.

5.3. Results

5.3.1. Weather conditions, soil attributes, and farmers' management practices

The weather conditions during the rice-growing period differed between seasons. The relative air humidity varied between 64% and 39%, and the cumulative rainfall amounted to 258 and 60 mm in the wet and dry seasons, respectively. Cumulative solar radiation and maximum air temperature during the growing period were higher in the dry season (639 kWh m^{-2} and 37 °C) than in the wet season (556 kWh m^{-2} and 34 °C) (Table S2).

The soil clay content varied between 4 and 45% and the sand content between 40 and 68%. Soil pH (H_2O) ranged from 5.2 to 6.2 with an average pH of 5.7. Total N ranged from 0.06% to 0.21% and total organic C from 0.70% to 2.0% with an average of 1.19%. Available P (Bray-2) exhibited high variability (CV = 101%) among farmers' fields, with an average of 20 mg kg^{-1} (Table S3).

The mean sowing date in the nursery was August 14th (± 16 days) in the wet, and January 13th (± 20) in the dry season. On average, farmers transplanted 25-day-old seedlings. Rice straw from previous seasons was removed for multiple uses (animal feeding or building of rammed earth houses with straw bales) in a quarter of the studied fields, burned in about half of the fields, and incorporated, mulched, or used for animal feeding in the field in another quarter of the fields. These proportions were similar in both seasons (Table S4). More than 80% of the farmers used animal traction for land preparation and nearly all the fields were well-leveled. Besides, non-certified seeds were used in almost 90% of the surveyed fields. The average growth duration of varieties was 109 ± 11 days and was similar in both seasons. Transplanting was the main crop establishment method. During the rice-growing period, farmers weeded their rice fields between one and five times with an average of three weeding operations. In 95% of the cases, farmers applied herbicides at least once (Table S4). While organic manure was applied in approximately 20% of fields, mineral fertilizers were utilized by all farmers. N, P, and K were applied at average rates of 125, 14, and 27 kg ha^{-1}, respectively (Table S4).

5.3.2. Water input

Irrigation frequency and applied amount of water differed between irrigation treatments. In the wet season, the irrigation frequency in FP (7 ± 2) was higher than in AWD30 (4 ± 2). Similarly, in the dry season, the irrigation frequency in FP (16 ± 4) exceeded that in AWD30 (11 ± 3) ($p < 0.001$). AWD30 reduced irrigation water inputs by 44% in the wet season and by 35% in the dry season. On average, irrigation water contributed to 27% and 79% of the total water input in the wet and dry seasons, respectively. Frequent rainfall events resulted in a higher soil flooding index in the wet season compared to the dry season. As a result, the soil flooding index did not differ between AWD30 and FP irrigation in the wet season (50 ± 28% vs. 60 ± 20%). However, in the dry season, the soil flooding index was lower in AWD30 than in FP (35 ± 19% vs. 51 ± 19%). Regardless of the season, fields rarely fell completely dry, as indicated by the soil dryness index remaining at 0% in the wet season and 2 ± 7% in the dry season (**Table 5.1**).

5.3.3. Crop growth, weed infestation, grain yield, and water productivity

Across water management practices, grain yields ranged from 1.6 to 8.2 Mg ha^{-1}, with a mean of 4.5 Mg ha^{-1}, and did not differ between seasons. Total water productivity ranged from 0.28 to 4.1 kg grain m^{-3} of water, with a mean of 1.6 ± 0.7 kg grain m^{-3} of water, and was higher in the dry season (1.8 ± 0.9 kg grain m^{-3} of water) than in the wet season (1.4 ± 0.3 kg grain m^{-3} of water). Conversely, irrigation water productivity was lower in the dry season (2.6 ± 1.7 kg grain m^{-3} of water) than in the wet season (6.4 ± 3.5 kg grain m^{-3} of water) (Table S5).

AWD30 performed better than FP irrigation in 63%, 97%, and 97% of the pairwise observations for grain yield, total water productivity, and irrigation water productivity, respectively (**Figure 5.1*a***, ***b***, and ***c***). Grain yields did not differ between AWD30 and FP irrigation in both wet and dry seasons (**Table 5.2**). The same trend was apparent for the number of tillers and panicles (**Table 5.3**). Water irrigation management did not affect weed infestation in the fields (**Table 5.3**). On the other hand, AWD30 improved total water productivity by 20% and 50% compared to FP in

Table 5.1 *Water input and soil water status indices under two water management practices: farmers' practices (FP) and alternate wetting and severe soil drying (AWD30) irrigation in Kou Valley, Burkina Faso in 2019-2020*

	Wet season (n = 12)			Dry season (n = 18)		
	FP	AWD30	Test statistic	FP	AWD30	Test statistic
Irrigation frequency			GLMM			GLMM
Mean (SD)	7 (2)	4 (2)	**0.004**	16 (4)	11 (3)	**< 0.001**
Irrigation water input (m^{-3} ha^{-1})			LMM			LMM
Mean (SD)	1,231 (449)	685 (339)	**< 0.001**	2,674 (995)	1,743 (972)	**< 0.001**
Total water input (m^{-3} ha^{-1})			LMM			LMM
Mean (SD)	3,806 (1000)	3,261 (942)	**< 0.001**	3,269 (997)	2,338 (1014)	**< 0.001**
Soil flooding index (%)			LMM			LMM
Mean (SD)	60 (20)	50 (28)	0.190	51 (19)	35 (19)	**0.002**
Soil dryness index (%)						LMM
Mean (SD)	0 (0)	0 (0)		2 (7)	2 (8)	0.168

SD: Standard deviation

LMM: Linear mixed effect model

GLMM: Generalized linear mixed effect model

Significant effects (p < 0.05) are indicated in bold

Table 5.2 *Grain yield, water productivity, and partial factor productivity of applied nutrients under two water management practices: farmers' practices (FP) and alternate wetting and severe soil drying (AWD30) irrigation in Kou Valley, Burkina Faso in 2019-2020*

Key performance indicators	Wet season (n = 12)			Dry season (n = 18)		
	FP	AWD30	Test statistic	FP	AWD30	Test statistic
Grain yield (Mg ha^{-1})			LMM			LMM
Mean (SD)	4.76 (1.36)	4.90 (1.65)	0.470	4.23 (1.36)	4.43 (1.29)	0.223
Total water productivity (kg grain m^{-3})			LMM			LMM
Mean (SD)	1.27 (0.26)	1.52 (0.27)	**0.003**	1.44 (0.66)	2.18 (0.89)	**< 0.001**
Irrigation water productivity (kg grain m^{-3})			LMM			LMM
Mean (SD)	4.46 (2.30)	8.31 (3.58)	**0.002**	1.86 (1.07)	3.27 (1.96)	**< 0.001**
Partial factor productivity of applied N (kg grain kg^{-1} N)			LMM			LMM
Mean (SD)	41 (15)	43 (18)	0.493	33 (10)	35 (9)	0.297
Partial factor productivity of applied P (kg grain kg^{-1} P)			LMM			LMM
Mean (SD)	312 (101)	325 (133)	0.374	331 (124)	346 (123)	0.190
Partial factor productivity of applied K (kg grain kg^{-1} K)			LMM			LMM
Mean (SD)	173 (58)	178 (69)	0.517	174 (65)	182 (65)	0.191

SD: Standard deviation

LMM: Linear mixed effect model

Significant effects ($p < 0.05$) are indicated in bold.

Table 5.3 Weed infestation and plant growth parameters under two water management practices: farmers' practices (FP) and alternate wetting and severe soil drying (AWD30) irrigation in Kou Valley, Burkina Faso in 2019-2020

	Wet season (n = 12)			Dry season (n = 18)		
	FP	AWD30	Test statistic	FP	AWD30	Test statistic
Weed infestation above the canopy#			GLMM			GLMM
Mean (SD)	0 (1)	0 (0)	1.000	1 (1)	1 (1)	1.000
Weed infestation below the canopy#			GLMM			GLMM
Mean (SD)	2 (1)	2 (1)	1.000	1 (1)	1 (1)	1.000
Tiller number $ from 6 hills at harvest			LMM			LMM
Mean (SD)	81 (13)	82 (13)	0.769	87 (15)	92 (18)	0.105
Panicle number from 6 hills at harvest			LMM			LMM
Mean (SD)	75 (12)	76 (13)	0.796	85 (14)	91 (18)	**0.043**

0 = No weed; 1 = Weed cover ≤ 10% of ground cover; 2 = Weed cover > 10% and ≤ 30% of ground cover; 3 = Weed cover > 30% and ≤ 60% of ground cover.

$ This count includes both stems and tillers.

SD: Standard deviation

LMM stands for linear mixed effect model

GLMM: Generalized linear mixed effect model

Significant effects (p < 0.05) are indicated in bold.

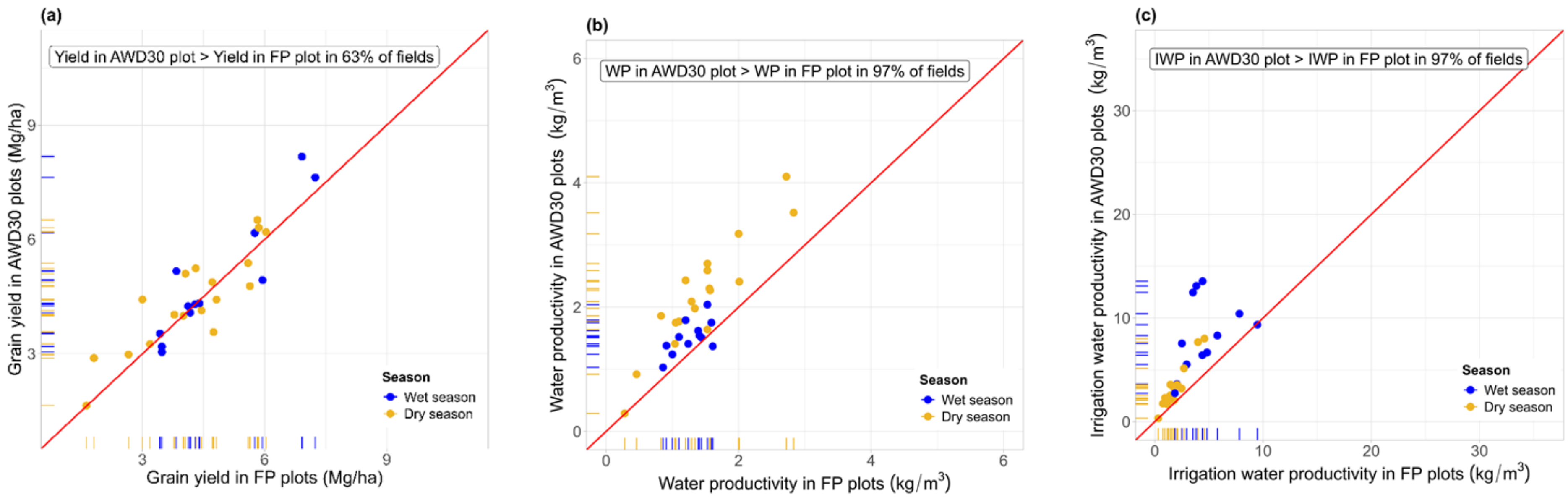


Figure 5.1. *Scatter plots of **(a)** grain yield, **(b)** total water productivity, and **(c)** irrigation water productivity of plots under farmers' irrigation practices (FP) and alternate wetting and severe soil drying (AWD30) irrigation in Kou Valley, Burkina Faso, in 2019-2020.*

The rug lines (i.e., short lines along the axes) indicate the range of the data points plotted and provide insights into the data distribution along each axis. The red solid line is the identity line or line of equality.

wet and dry seasons, respectively (**Table 5.2**).

In non-fertilized plots, grain yields ranged from 1.3 to 4.4 Mg ha^{-1} with a mean of 2.1 Mg ha^{-1} in the wet season and from 1.6 to 4.6 Mg ha^{-1} with a mean of 3.1 Mg ha^{-1} in the dry season. In these plots, grain yields, total water productivity, and irrigation water productivity did not differ between AWD30 and FP in both wet and dry seasons (Table S6).

5.3.4. Nutrient use efficiencies

Across seasons and irrigation management practices, the partial factor productivity of applied N (PFPN) ranged from 15 to 82 with a mean of 37 kg grain kg^{-1} N. The PFP of applied P ranged from 138 to 624 with a mean of 331 kg grain kg^{-1} P and was similar in both wet and dry seasons. Similarly, the PFP of applied K varied from 72 to 328 kg grain kg^{-1} K (Table S5). Furthermore, in both wet and dry seasons, PFPN, PFPP, and PFPK did not differ significantly between AWD30 and FP (**Table 5.2**). The agronomic use efficiency (13 ± 5 kg grain kg^{-1} N), the recovery efficiency (23 ± 11%), the physiological efficiency (66 ± 30 kg grain kg^{-1} N) of N, and the soil N dependent rate (54 ± 17%) were comparable between AWD30 and FP in both seasons. Similarly, there were no significant differences in partial P balance between AWD30 and FP in both seasons with a mean value of 131 ± 63% (**Table 5.4**).

5.3.5. Nutrient content and uptake

With coefficients of variation (CV) ranging from 13 to 62 %, straw, and grain samples exhibited a wide range of nutrient concentrations. Across seasons and irrigation management practices, the N concentration in straw (CV of 18%) and the N, P, K, and

Table 5.4 *N and P use efficiency indices under two water management practices: farmers' practices (FP) and alternate wetting and severe soil drying (AWD30) irrigation in Burkina Faso in 2019-2020*

N and P use efficiency indices	Wet season (n = 5)			Dry season (n = 6)		
	FP	AWD30	Test statistic	FP	AWD30	Test statistic
Agronomic use efficiency of N (kg grain kg^{-1} N)			Robust LMM			LMM
Mean (SD)	14 (1)	17 (4)	0.166	10 (7)	12 (4)	0.356
Recovery efficiency of N (%)			LMM			LMM
Mean (SD)	26 (9)	30 (12)	0.545	18 (10)	18 (12)	1.000
Physiological efficiency of N (kg grain kg^{-1} N)			LMM			Robust LMM
Mean (SD)	58 (17)	59 (13)	0.902	54 (11)	91 (47)	0.088
Soil N dependent rate (%)			LMM			LMM
Mean (SD)	53 (18)	40 (9)	0.152	61 (17)	61 (16)	0.972
Partial P balance (%)			LMM			LMM
Mean (SD)	118 (30)	92 (16)	0.065	161 (81)	144 (79)	0.069

SD: Standard deviation

LMM stands for linear mixed effect model

Zn concentration in grain (CV of 13%, 18%, 14, and 14%, respectively) were less variable than the Mn and Fe concentrations in straw (CV of 62% and 58%, respectively). In both seasons, water irrigation practices (AWD30 vs. FP) did not significantly affect nutrient concentrations in both straw and grain, with few exceptions. In the wet season, the N concentration in straw was reduced by 24% with AWD30 compared to FP ($p = 0.01$). Similarly, in the dry season, the P, K, and Zn concentrations in grain were reduced by about 10-20% compared to FP (**Table 5.5**).

In the wet season, N, P, and K uptake values were 68 ± 18 kg N ha^{-1}, 18 ± 5 kg P ha^{-1}, and 101 ± 36 kg K ha^{-1} with farmers' irrigation practices and 57 ± 15 kg N ha^{-1}, 14 ± 3 kg P ha^{-1}, and 84 ± 14 kg K ha^{-1} with AWD30. In the dry season, N, P, and K uptake values were 67 ± 21 kg N ha^{-1}, 18 ± 8 kg P ha^{-1}, and 103 ± 41 kg K ha^{-1} with farmers' irrigation practices and 64 ± 25 kg N ha^{-1}, 16 ± 8 kg P ha^{-1}, and 107 ± 31 kg K ha^{-1} with AWD30. Differences between AWD30 and FP were not significant ($p > 0.05$) except for N uptake during the wet season, which was 16% lower in AWD30 compared to FP ($p = 0.045$) (**Table 5.6**).

5.3.6. Productivity trade-offs and synergies

The N application rate had a large positive effect ($0.5 < \rho < 0.7$; $p < 0.05$) on K concentration in straw and K uptake. While total water input had no significant effect on grain yield and N, P, and K uptake, increasing the soil flooding index led to higher N and P uptake by rice (**Figure 5.2*a***). There was a strong positive correlation ($\rho = 0.8$; $p < 0.05$) between P concentration in grain and total water input, suggesting that reducing water input may lead to a decrease in P concentration in grains. Conversely, K concentration in straw showed a negative correlation ($\rho = -0.48$; $p < 0.05$) with total water input.

Table 5.5 *Nutrient concentration in straw and grain under two water management practices: farmers' practices (FP) and alternate wetting and severe soil drying (AWD30) irrigation in Kou Valley, Burkina Faso in 2019-2020*

	Wet season (n = 5)			Dry season (n = 6)		
	FP	AWD30	Test statistic	FP	AWD30	Test statistic
N concentration in straw (%)			LMM			LMM
Mean (SD)	0.67 (0.12)	0.51 (0.09)	**0.010**	0.56 (0.06)	0.53 (0.09)	0.423
P concentration in straw (%)			LMM			LMM
Mean (SD)	0.12 (0.03)	0.09 (0.03)	0.128	0.09 (0.04)	0.10 (0.05)	0.733
K concentration in straw (%)			LMM			LMM
Mean (SD)	1.94 (0.46)	1.88 (0.50)	0.830	2.17 (0.39)	2.24 (0.42)	0.760
Mn concentration in straw (mg kg^{-1})			LMM			LMM
Mean (SD)	399 (152)	578 (112)	**0.020**	1,311 (417)	1,310 (681)	0.996
Fe concentration in straw (mg kg^{-1})			Robust LMM			LMM
Mean (SD)	451 (222)	455 (350)	0.667	670 (370)	600 (345)	0.625
Zn concentration in straw (mg kg^{-1})			LMM			LMM
Mean (SD)	33 (10)	33 (6)	1.000	37 (8)	34 (6)	0.358
N concentration in grain (%)			LMM			LMM
Mean (SD)	1.11 (0.16)	1.15 (0.13)	0.160	1.14 (0.14)	1.00 (0.13)	0.094
P concentration in grain (%)			LMM			LMM
Mean (SD)	0.37 (0.05)	0.33 (0.02)	0.167	0.34 (0.06)	0.27 (0.04)	**0.003**
K concentration in grain (%)			LMM			LMM
Mean (SD)	0.42 (0.05)	0.39 (0.03)	0.355	0.47 (0.07)	0.39 (0.03)	**0.015**
Mn concentration in grain (mg kg^{-1})			LMM			LMM
Mean (SD)	80 (18)	95 (5)	0.103	146 (35)	112 (46)	0.056
Fe concentration in grain (mg kg^{-1})			LMM			LMM
Mean (SD)	242 (77)	242 (84)	1.000	157 (40)	178 (71)	0.513
Zn concentration in grain (mg kg^{-1})			LMM			LMM
Mean (SD)	22 (3)	22 (4)	1.000	22 (3)	20 (2)	**0.027**

Significant positive correlations were observed between grain yield and the agronomic use and recovery efficiencies of N, and the partial P balance. Agronomic use and recovery efficiencies of N were not negatively correlated with the total water productivity ($p > 0.05$) (**Figure 5.2*b***).

Table 5.6 *N, P, and K uptake under two water management practices: farmers' practices (FP) and alternate wetting and severe soil drying (AWD30) irrigation in Kou Valley, Burkina Faso in 2019-2020*

	Wet season (n = 5)			Dry season (n = 6)		
	FP	AWD30	Test statistic	FP	AWD30	Test statistic
N uptake (kg N ha^{-1})			LMM			LMM
Mean (SD)	68 (18)	57 (15)	**0.045**	67 (21)	64 (25)	0.569
P uptake (kg P ha^{-1})			LMM			LMM
Mean (SD)	18 (5)	14 (3)	0.060	18 (8)	16 (8)	0.078
K uptake (kg K ha^{-1})			LMM			LMM
Mean (SD)	101 (36)	84 (15)	0.190	103 (41)	107 (31)	0.751

SD: Standard deviation

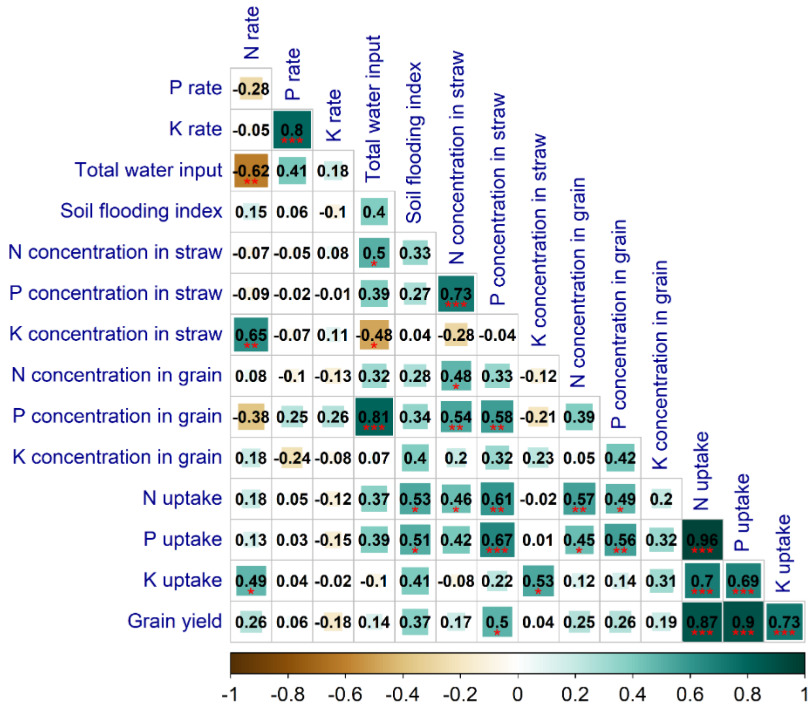
LMM stands for linear mixed effect model

Significant effects ($p < 0.05$) are indicated in bold.

5.4. Discussion

To the best of our knowledge, this is the first on-farm study conducted in the semi-arid zone of West Africa, investigating the effect of AWD irrigation on nutrient uptake in irrigated rice. It showed in locations with a shallow groundwater table, compared to the farmers' irrigation practices (FP), alternate wetting and severe drying can reduce water input without compromising grain yield and the use efficiencies of applied N and P. However, the observed positive correlation between soil flooding index and N and P uptake raises concerns about possible trade-offs between water-savings and nutrient uptake in case of acute soil dryness. The following discussion of key findings is organized into three parts: (i) the water-saving potential of AWD irrigation and its impacts on productivity; (ii) the impact of AWD irrigation and anaerobic conditions on nutrient use; and (iii) the study's limitations and outlook.

(a)



(b)

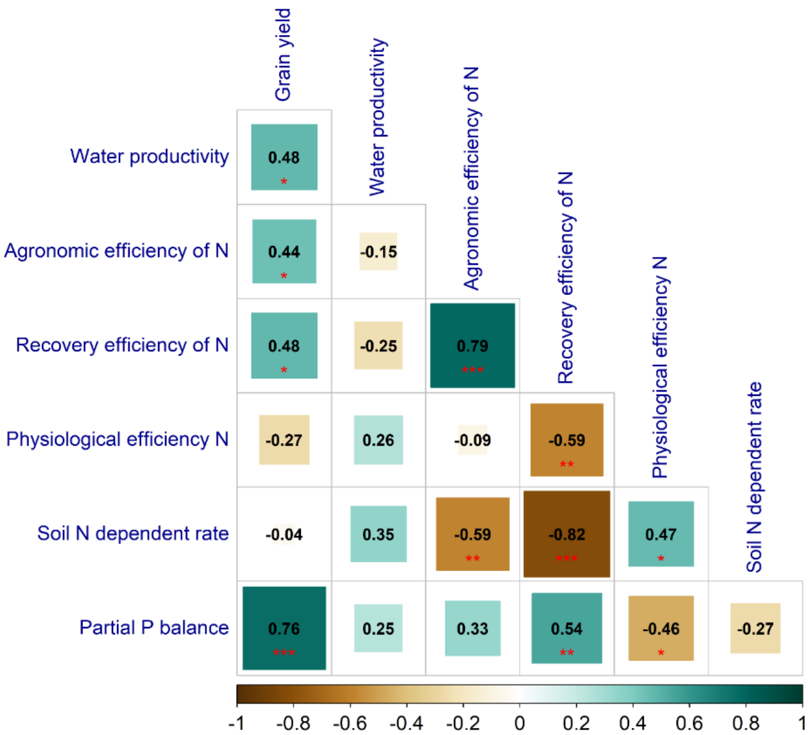


Figure 5.2. *Relationships **(a)** between inputs (water, N, P, and K application rates), and outputs (N, P, and K uptakes, and grain yield) and **(b)** between grain yield, water productivity, and N- and P- use efficiencies (n = 22) in Kou Valley, Burkina Faso, in 2019-2020.*

The values displayed are Spearman's rank correlation coefficients (ρ). Positive correlations are displayed in green and negative correlations in golden brown. The colour intensity (see colour bar) and the square size are proportional to the correlation coefficients. Significant correlation coefficients are indicated by asterisks (p < 0.05, ** p < 0.01, and *** p < 0.001), coefficients without asterisks are not significant (p > 0.05).*

5.4.1. AWD reduced water input without grain yield penalty

Alternate wetting and severe soil drying irrigation (AWD30) reduced total water input by 14% and 28% in the wet and dry seasons, respectively, without compromising the grain yield. This led to a 20% increase in water productivity during the wet season and a 50% increase during the dry season. This water-saving is attributed to the reduction in unproductive water outflows, including percolation, evaporation, and seepage. The water savings recorded in this study are lower than those reported in previous studies (30% - 36%), comparing alternate wetting and severe drying regime to continuous submerged field conditions (Carrijo *et al.*, 2017). This could be explained by the reference for the comparison, which differs from the continuous submerged field conditions. Indeed, in the present study, farmers' irrigation practices provided a water layer only on ~60% of the days during the growing season. Compared to alternate wetting and moderate drying regime (AWD15) in the same scheme in the dry season (Johnson *et al.*, 2024), AWD30 did not increase water savings. Thus, despite a reduced irrigating frequency, irrigation water inputs tended to be higher for individual irrigation events to compensate for the more extensive water losses from the soil water storage reservoir in AWD30 compared to AWD15. This raises questions about the relevance of severe drying in the dry season. Moreover, alternate wetting and severe soil drying irrigation presents higher risks and can entail a yield penalty of about 22% (Carrijo *et al.*, 2017). In our study, AWD30 did not compromise grain yield likely because the soil did not completely dry out due to the capillary rise of water from the shallow groundwater table (**Table 5.1**). Additionally, partial soil drying also occurred in farmers' irrigation practices (FP). The assessment of the field water status was exclusively done through visual observation, limiting a comprehensive comparison of the effect of the two water management irrigation regimes (FP and AWD) on soil dryness levels. Using appropriate instruments, such as tensiometers, could have improved the precision of measurements, resulting in more accurate and reliable insight into the soil moisture content.

5.4.2. AWD did not impair nitrogen and phosphorus use efficiencies

Regardless of the seasons, the partial factor productivity and the agronomic use and recovery efficiencies of applied mineral N were comparable for both irrigation management practices. However, the mean agronomic use efficiency of 13 kg grain kg^{-1} N and the N recovery of 23% were lower than the global average values of 22 kg grain kg^{-1} N, and 46%, respectively (Ladha *et al.*, 2005). Such low N use efficiency values may well reflect poor N fertilizer management in farmers' fields, a common issue in rice production in sub-Saharan Africa (Chivenge *et al.*, 2021b). Thus, site-specific nutrient management has been advocated for optimizing fertilizer use, enhancing the synchrony of N supply and demand, and improving N use efficiency (Saito *et al.*, 2023b). Synergistic interaction effects between site-specific N management and AWD could well enhance grain yields while also increasing N-use efficiency (Liu *et al.*, 2013b).

There is no consensus in the scientific debate on whether AWD improves N-use efficiency or not. Thus, some studies indicated low N use efficiency under AWD irrigation due to increased NO_3^--N losses (Dunn & Gaydon, 2011). Other studies demonstrated improved N-use efficiency with AWD (Djaman *et al.*, 2018; Liu *et al.*, 2013b), while yet others showed no significant difference in N-use efficiency between continuous submergence and AWD irrigation (Cabangon *et al.*, 2004; Islam *et al.*, 2022; Pan *et al.*, 2017). These studies explained that AWD irrigation may decrease N losses due to the decrease in N leaching (Wang *et al.*, 2011), and NH_3 volatilization (Xu *et al.*, 2012). On the other hand, AWD may potentially enhance nitrate-N losses through denitrification during severe soil drying and subsequent soil flooding (Yang *et al.*, 2017), which may, in turn, negatively affect N use efficiency (Zhang *et al.*, 2009). However, in the present study, agronomic use, recovery, and physiological efficiencies of N were not impaired by alternate wetting and severe drying. The shallow groundwater table may have mitigated the effects of severe drying, reducing the NO_3-N formation and the subsequent N losses (Wang *et al.*, 2016). This aligns with suggestions from studies in China and the Philippines conducted in environments with shallow groundwater tables (Belder *et al.*, 2005; Cabangon *et al.*, 2004). On the other hand, we found a positive correlation ($\rho = 0.53$; $p < 0.05$) between the soil flooding index and N uptake supporting that soil submergence fosters N uptake. This result is somewhat consistent with Atwill II *et al.* (2018) who demonstrated that N uptake were reduced for aerobic irrigated rice compared to other irrigation treatments having higher soil flooding index. Soil submergence can buffer pH extremes. Thus, Narteh & Sahrawat (1999) surmised that the convergence of soil pH in the neutral range following soil submergences benefits the lowland rice crop through an improved plant availability of NH_4^+.

It is still unclear whether AWD irrigation improves P-use efficiency (Ishfaq *et al.*, 2020). Contrary to the results of pot experiments conducted by Deng *et al.* (2021) and Acosta-Motos *et al.* (2020), we found no evidence of altered P-use efficiency with AWD30 compared to farmers' irrigation practices. In the dry season, AWD30 even decreased grain P concentrations compared to farmers' irrigation practices as reported before (Norton *et al.*, 2017a; Song *et al.*, 2018). Overall, sustaining a perched water table fosters rice P uptake (**Figure 5.2*a***). This is primarily because anaerobic reducing conditions in submerged soils may increase the concentration of plant availability P in the soil solution (Young & Ross, 2001) due to the supplementary release of organic P via redox-sensitive dissociation from iron/manganese oxides. In contrast, aerobic conditions may reduce the amount of available P because of P precipitation with oxidized Fe and Mn, or by P immobilization in the soil microbial biomass (Adhikary *et al.*, 2023). Therefore, increased P fertilizer application rates may be required under AWD, especially in acid soils (Johnson *et al.*, 2024).

Although inconsistent across seasons, alternate wetting and severe drying negatively affected nutrient concentrations in rice grains. Thus, in the dry season, P and K concentrations in rice grain decreased under AWD30 as reported before by Norton *et al.* (2017b). In contrast to P, Zn is usually less available in anaerobic (low redox potential) than in aerobic (high redox potential) soils (Johnson-Beebout *et al.*, 2009). Yet, we observed lower Zn concentration in rice grains under AWD30 in the present study (**Table 5.5**). This contrasts also with previous studies that showed AWD significantly increased available soil Zn but did not affect grain Zn concentration (Rubianes *et al.*, 2018). Further investigations are needed to explore the effect of AWD on soil zinc availability and grain zinc concentration.

5.4.3. Limitations of the study and outlook

This on-farm-based study improved our understanding of the impact of AWD on performance indicators of irrigated rice in fields with a shallow groundwater table (Cabangon *et al.*, 2004). We were able to demonstrate the feasibility of the AWD30 technology and its implementation in the local context of Burkina Faso. However, uncertainties persist due to the relatively small sample size, variabilities in farmers' implementation of the AWD technology, and site-specific conditions of water availability. Additionally, obtaining farmers' approval to make significant changes to the setting or layout of their fields was challenging, especially for this series of on-farm farmer-managed trials, where participation was voluntary, and farmers did not receive any incentives. Consequently, we were unable to implement additional measures, such as those carried out in on-station trials (Krupnik *et al.*, 2012a), to reduce underground seepage, apart from using large consolidated bunds. Therefore, the water savings and water productivity gains attributed to AWD30 may have been overestimated and should be considered with caution.

A larger study is needed to confirm the effect sizes on performance indicators (Hackshaw, 2008) and to further investigate the interaction between water management and fertilizer application rates. Subsequent investigations using locally calibrated and validated models (Grotelüschen *et al.*, 2021, 2022) can help draw insights into a wide range of climatic and hydro-edaphic conditions, as well as their interactions. In future on-farm trials, we recommend monitoring the field water level and soil water potential to assess their impact on grain yield, nutrient uptake, and use efficiency (Tuong & Bouman, 2003). Furthermore, expanding the study to contrasting environments will be crucial in determining suitable niches for scaling the AWD irrigation technology to other irrigation schemes in the semi-arid zone of West Africa.

5.5. Conclusion

Compared to actual farmers' irrigation practices, alternate wetting and severe soil drying reduced irrigation water input by 37% (mean across seasons) without yield penalty while maintaining N- and P-use efficiencies. This improved irrigation water productivity by about 39%. This study did not reveal any evident trade-offs between water productivity and agronomic use and recovery efficiencies of N. We conclude that alternate wetting and severe drying can efficiently increase water productivity and serve as a water-saving technology for sustainable rice production in locations with shallow groundwater tables, as observed in the case of the Kou Valley. Therefore, water management institutions and policymakers should incentivize smallholder rice farmers to adopt this water-saving technology in these locations in Burkina Faso and beyond. Furthermore, this study underscores the importance of the hydrological characterization of irrigation schemes in West Africa, especially in terms of percolation rate and groundwater table depth. Future investigations in contrasting environments should also explore the influence of alternate wetting and severe soil drying irrigation on greenhouse gas emissions and its long-term effects on soil chemical properties, as well as nitrogen and carbon storage.

Chapter 6: General discussion and conclusion

Word cloud visualization of the 50 most frequent words in this chapter

In the face of increasing water scarcity, driven by factors such as rapid population growth and climate change, producing more rice with less water in irrigated systems poses a tremendous challenge for food, economic, social, and water security in the arid and semi-arid regions of sub-Saharan Africa. Among the wide range of water-saving technologies, alternate wetting and drying (AWD) irrigation is most promising, yet poorly known by rice farmers in those regions. This thesis provides an overview of farmers' perceived water constraints in irrigated rice systems in Burkina Faso, investigates current determinants of yield and water productivity and their variability at the farm scale, and assesses the feasibility and impact of AWD on productivity and resources (water and fertilizer) use efficiency compared to farmers' irrigation practices. The research chapters (chapters 2, 3, 4, and 5) composing this thesis have already presented an in-depth discussion and conclusions of each specific research objective. Therefore, this concluding chapter will (i) summarize the main findings concerning the initial research questions, (ii) highlight the implications in terms of policy recommendations, (iii) underscore the strengths but also acknowledge the limitations of this study to enable improvement of similar studies in other regions, and (iv) suggest future research directions.

6.1. Main findings and conclusions

The key findings of this thesis are summarized in the four following sub-sections corresponding to the main research questions.

6.1.1. What are smallholder farmers' perceptions about water scarcity and what are key adaptive response strategies?

Nearly 80% of the smallholder farmers have experienced water scarcity in their irrigated rice fields during the past 5 years (2014-2019) and perceive access to irrigation water as a key limitation to rice production in dry seasons. Furthermore, increasing dryness trends have been visible since the year 2000 in some regions. To cope with and mitigate the adverse impacts of water scarcity, farmers implemented seven types of adaptation strategies, the three most popular being “Water and soil conservation practices” (consisting mainly of field bunding and levelling), “No rice cultivation”, and “Crop rotation” (mainly by replacing dry season rice by less water-demanding upland crops).

6.1.2. What are actual and attainable rice yields, and which crop management practices improve yields and water productivity while reducing their variability?

Actual and attainable yields were higher in wet (5.3 Mg ha^{-1} and 7.7 Mg ha^{-1}, respectively) than in dry seasons (3.7 Mg ha^{-1} and 5.8 Mg ha^{-1}, respectively), while the variability was higher in the dry (CV = 46%) than in the wet seasons (CV = 29%). Thus, the dry-season rice was less productive and showed higher yield variability than the wet-season rice. This confirms the large and growing impact of water scarcity on rice yields in dry climatic zones of West Africa. The yield gap was slightly higher in the dry (36%) than in the wet seasons (31%). The determinants of yield and yield variability were season-specific. Indeed, while the number of seedlings per hill and the source of seeds were the most important crop management practices for improving yield and reducing the variability in wet-season rice, the split of N fertilizer applications, bird control, and the soil dryness index were most important in dry-season rice. The variability in water productivity was directly linked with the drivers of yield variability.

6.1.3. What are the overall gains on grain yields, water productivity, and profitability associated with AWD over farmers’ irrigation practice and which crop management practices favor the yield gains?

AWD has proven to be an efficient water-saving technology, allowing to reduce irrigation water inputs by 30% compared to the farmer's irrigation practice, while increasing grain yield by 5% ($p < 0.05$). Consequently, AWD increased irrigation water productivity by 62% and profitability by 5% over farmers' irrigation practices. The AWD-associated yield gains were highest under conditions of poor irrigation management, and when using *indica* varieties.

6.1.4. What are the effects of alternate wetting and severe soil drying on grain yield, nutrient uptake and use efficiency and are there synergies or trade-offs between water productivity and N and P use efficiency?

Compared to actual farmers' irrigation practices, alternate wetting and severe drying reduced irrigation water input by 37% (mean across seasons) without yield penalty, while maintaining N- and P-use efficiencies. There were no evident trade-offs between water productivity and agronomic use and recovery efficiencies of N. Thus, alternate wetting and severe drying can efficiently increase water productivity and serve as a water-saving technology for sustainable rice production in locations with shallow groundwater tables.

6.2. Policy recommendations

Some findings in this thesis have practical implications, enabling the formulation of policy recommendations. These recommendations should be considered by agricultural authorities and by development and extension agencies to support smallholder rice farmers in increasing their productivity and resource use efficiency, while adapting to water scarcity in semi-arid regions of West Africa.

6.2.1. Supporting the establishment and strengthening of farmer organizations

Belonging to farming associations increased the probability of implementing several strategies to alleviate water scarcity (Chapter 2). Promoting the organization of smallholders can enhance knowledge sharing and mutual aid, leading to better resilience. We thus advocate for national policy interventions that support the establishment and strengthening of farmer organizations.

6.2.2. Dissemination of scheme- and household-specific technology options

Female-headed households tend to have a lower propensity to adopt and implement concomitantly several adaptation strategies in comparison with their male counterparts (Chapter 2). Consequently, providing training on scheme-specific adaptation to water scarcity and climate change, encouraging specifically the participation of female farmers is needed. Disseminating scheme- and household-specific technology options could contribute to mitigating water scarcity in irrigated rice systems, thereby enhancing rural livelihoods and food security. Additionally, such measures are expected to increase farmers' capacity to adapt to emerging water scarcity, leading to positive impacts on crop productivity in the dry climatic zones of West Africa. Only a small percentage of smallholder farmers (0.3% of the respondents) were aware of modern water-saving technologies in irrigated systems, such as alternate wetting and drying (AWD) or systems of rice intensification (SRI) (Chapter 2). This indicates that one of the major challenges to the large-scale adoption of such technologies is farmers' lack of knowledge about their existence and associated opportunities. Continued support from research and extension agencies is therefore imperative to ensure the diffusion and effective scaling up of water-saving technologies among farmers.

6.2.3. Providing season-specific recommendations to farmers

The primary factors influencing yield and yield variability in irrigated rice in West Africa were found to be season-specific (Chapter 3). As a result, extension agents and farmers should prioritize different aspects of crop management depending on the growing seasons to improve productivity.

6.2.4. Reshaping rice irrigation by implementing systematic monitoring of field water levels

During the more water-strapped dry season, achieving high grain yields and reducing yield variability generally requires reducing the soil dryness index (Chapter 3). In addition, the higher yield gains in AWD over FP in fields with poor access to irrigation may well be the result of more rigorous field observations in AWD plots, involving regular monitoring of the field water status and timely water re-supply, especially during critical phenological stages. Furthermore, excessive irrigation, especially during the wet season, may account for the observed yield reductions (Chapter 4). This suggests a need for reshaping rice irrigation practices in the dry climatic zones of West Africa, involving systematic monitoring of field water levels. Cheap materials like bamboo, tin cans, or even plastic bottles can be used to create marked field water tubes.

6.2.5. Incentivize smallholder rice farmers to adopt AWD technology

Increased resource (water and fertilizer) use efficiencies were associated with narrowing the yield gaps. Achieving both high yields and high resource-use efficiencies are not conflicting goals (Chapter 3). Thus, the diffusion of improved water management practices can contribute to achieving the dual goal of narrowing the yield gap and improving water productivity, while increasing nutrient use efficiency. Furthermore, given the overall positive gain in water productivity associated with alternate wetting and drying (AWD) without significant negative effects on yield and nutrient use efficiencies (Chapters 4 and 5), and in the absence of contradictory results in the region, this thesis recommends the large-scale diffusion of AWD. National governments should promote water-saving incentives in rice cultivation (Zhang & Oki, 2023), for example, by fixing irrigation payment schemes based on the volume of water used, rather than fixed-rate arrangements that have already been decided prior to the start of the season (Chapters 2 and 4). Implementing such specific incentive policies may ensure the widespread adoption of water-saving technologies.

6.3. Methodological strengths and weakness

The present on-farm-based study demonstrates the feasibility of the AWD technology and its implementation by smallholder rice farmers in Burkina Faso. Thus, the study took into account the wide range of management and environmental conditions encountered in farmers' fields and the socio-economic diversity among farming households. This is one of the main strengths of the study, as it allows for a comprehensive understanding of the local context. Additionally, the study was conducted across multiple locations (four irrigation schemes) and over two or three consecutive seasons, in contrast to most studies that are implemented only during the wet seasons (Carrijo *et al.*, 2017; Dossou-Yovo & Saito, 2021). Using diverse and modern analytical methods, such as linear mixed effect models and machine-learning algorithms (random forest, brute force, Shapley additive explanation), allows for extracting valuable information from datasets while considering the complexities of the data structure. This ultimately results in more accurate and precise insights (Cartolano *et al.*, 2024; Schielzeth *et al.*, 2020). Finally, combining household surveys and participatory on-farm trials provided both general and specific socio-economic and agronomic insights.

However, uncertainties persist due to the relatively small sample size and site-specific conditions (shallow groundwater table in the Kou valley irrigation scheme) for the in-depth studies (Chapter 5), and variabilities in farmers' implementation of the AWD technology (Chapters 4 and 5). Obtaining farmers' approval to make significant changes to the setting or layout of their fields was challenging, especially as participation was voluntary and farmers did not receive any incentives. Consequently, we were unable to implement additional measures, such as those carried out in on-station trials (Krupnik *et al.*, 2012a), to reduce underground seepage, apart from using large consolidated bunds. Therefore, the water savings and water productivity gains attributed to AWD may have been overestimated and should be considered with caution (Chapters 4 and 5). Additionally, some agronomic assessments were conducted exclusively through visual observation (e.g., soil water content, weed infestation) (Chapters 4 and 5). Using appropriate instruments can enhance the precision of measurements, resulting in more accurate and reliable insights.

6.4. Outlook and future research directions

This thesis provided answers to key research questions, but also revealed unexpected or intriguing results suggesting new directions for research. For example, contrary to the reports in many parts of the world (e.g., Vietnam, Sri Lanka, Indonesia, and China) (Devkota *et al.*, 2019), this study reported lower irrigated rice yields in the dry season compared to the wet season (Chapter 3). Investigating the climatic yield potential using the ORYZA model (Yu *et al.*, 2023) could confirm or reverse the higher yielding potential in the wet season compared to the dry season in this local context. The decomposition of the yield gaps into efficiency, resource, and technology components, using a combination of frontier analysis and crop modelling (Silva *et al.*, 2017, 2023a), could further improve the season-specific analysis and identify relevant management recommendations and policy interventions for sustainable intensification of rice production in the region. Furthermore, The comparison of the average yields of the present study and those conducted about 20 years ago in the same location (Kou Valley, 1995-1996 - Wopereis et al., 1999) or locations belonging to the same climatic zones (Bagré scheme, 1999-2000 - Segda et al., 2004) seems to indicate that irrigated rice yields have stagnated. National statistics on global rice productivity in Burkina

Faso support this trend of yield stagnation (Ray *et al.*, 2012). Further studies aiming to unravel the causes of rice yield trends in different West African countries are required to provide country-specific guidelines for governments and international agencies for increasing rice productivity and, in turn, reducing dependence on food imports.

This thesis suggests that *indica* cultivars may be better suited for AWD than *japonica* and also emphasizes the importance of P fertilizer rates. Further studies are needed to confirm these initial findings and to identify varietal characteristics for adapting to variable soil water conditions and aeration status encountered with AWD in the dry climatic zones of West Africa.

The shift from continuous flooding to AWD water management may affect soil carbon (C) and nitrogen (N) dynamics, as well as soil fertility. AWD makes soil C and N more unstable than continuous flooding, resulting in higher losses of C and N into the environment (Islam *et al.*, 2018). However, this aspect was not studied, and data on soil C emissions in Africa are scarce (Liu *et al.*, 2024). Therefore, investigating the impact of AWD on greenhouse gas emissions and its long-term effects on soil chemical properties is a relevant research direction in sub-Saharan Africa.

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Appendices

A- Supplementary material for Chapter 2: Farmers' perception and management of water scarcity in irrigated rice-based systems in dry climatic zones of West Africa.
https://static-content.springer.com/esm/art%3A10.1007%2Fs13593-023-00878-9/MediaObjects/13593_2023_878_MOESM1_ESM.pdf

B- Supplementary material for Chapter 3: Improving rice yield and water productivity in dry climatic zones of West Africa: Season-specific strategies
https://ars.els-cdn.com/content/image/1-s2.0-S0378429024002727-mmc1.pdf

C- Supplementary material for Chapter 4: Enhancing rice yields, water productivity, and profitability through alternate wetting and drying technology in dry climatic zones of West Africa
https://ars.els-cdn.com/content/image/1-s2.0-S0378377424004323-mmc1.pdf

D- Supplementary material for Chapter 5: Alternate wetting and drying: A water-saving technology for sustainable rice production in Burkina Faso?
https://static-content.springer.com/esm/art%3A10.1007%2Fs10705-024-10360-x/MediaObjects/10705_2024_10360_MOESM1_ESM.pdf

Appendix A: Supplementary material for Chapter 2

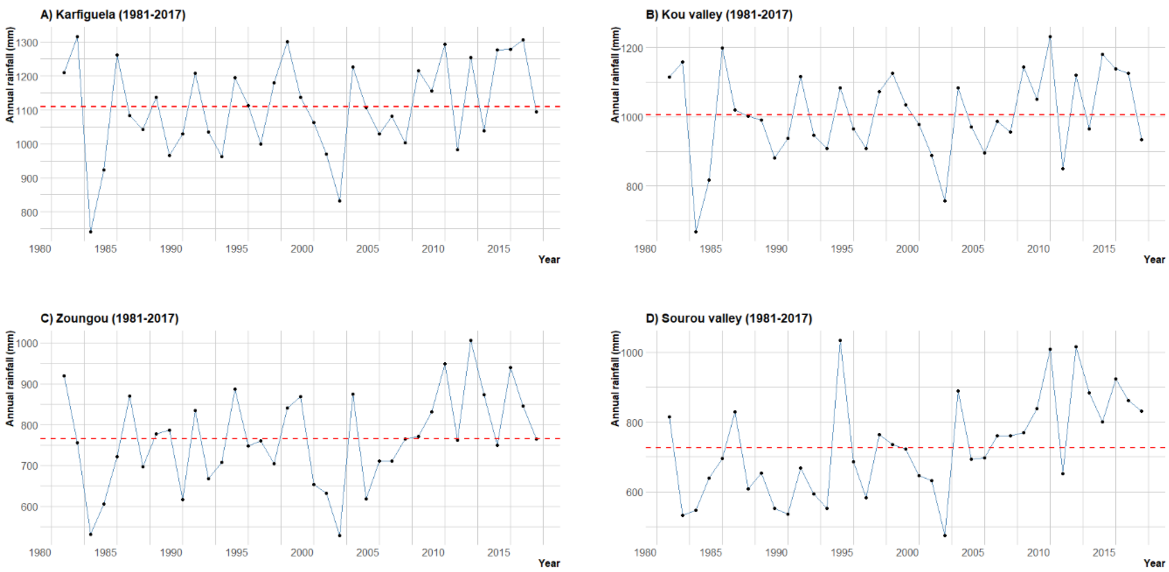

Fig. S1. Total annual precipitation (mm) from 1981–2017 for **(A)** Karfiguela, **(B)** Kou valley, **(C)** Zoungou, and **(D)** Sourou valley. In all cases, connected black dots indicate the total precipitation value in each year; the red dashed lines represent the mean value over the mentioned period.

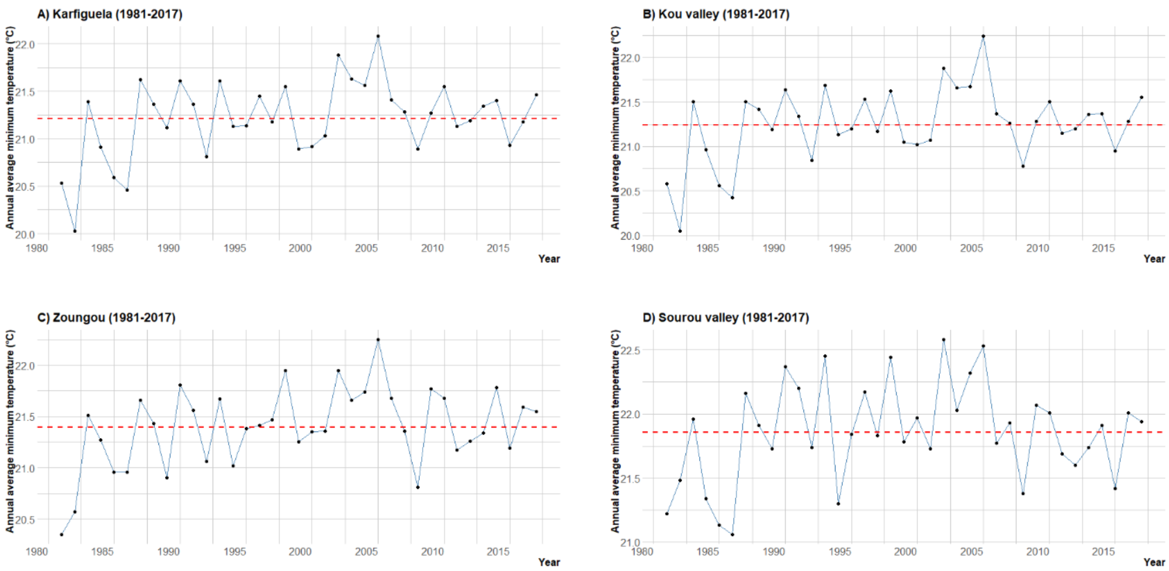

Fig. S2. Annual average minimum temperature (°C) from 1981–2017 for **(A)** Karfiguela, **(B)** Kou valley, **(C)** Zoungou, and **(D)** Sourou valley. In all cases, connected black dots indicate average minimum temperature values in each year; the red dashed lines represent the mean value over the mentioned period.

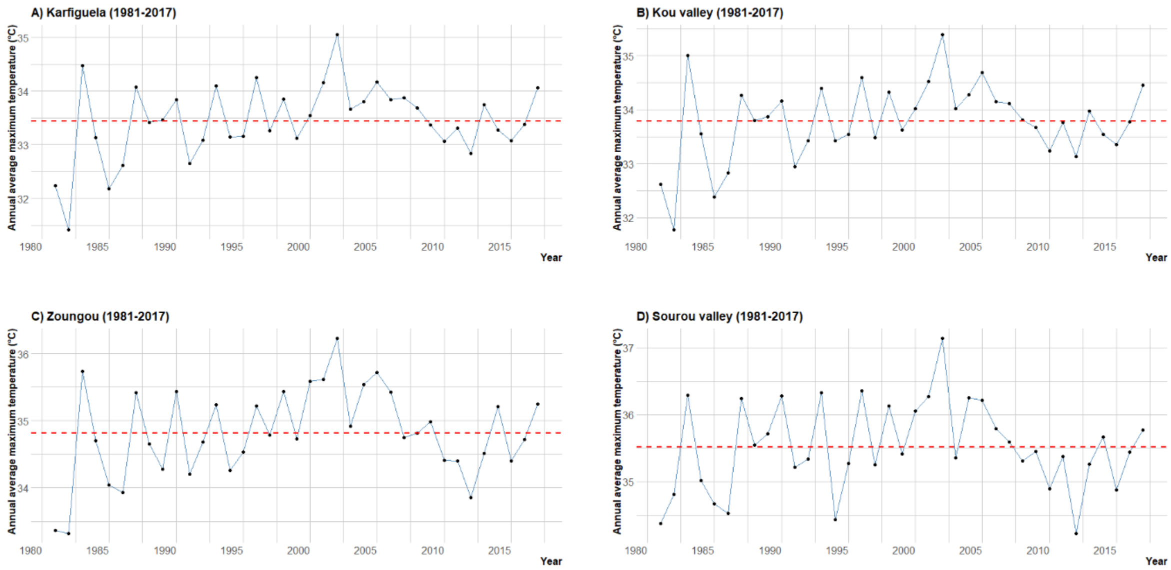

Fig. S3. Annual average maximum temperature (°C) from 1981–2017 for **(A)** Karfiguela, **(B)** Kou valley, **(C)** Zoungou, and **(D)** Sourou valley. In all cases, connected black dots indicate average maximum temperature values in each year; the red dashed lines represent the mean value over the mentioned period.

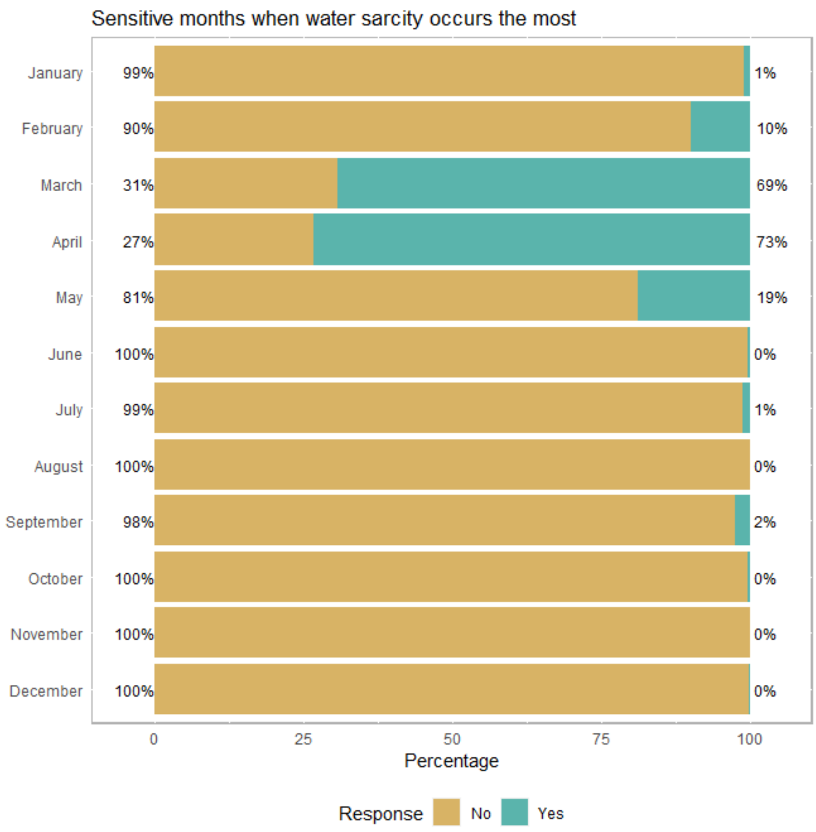

Fig. S4. Farmers' perception of sensitive months when water scarcity occurs the most. The question was: "What are the most critical months when water scarcity occurs in your rice field?" (multiple responses were allowed). The colouring represents the proportion of each response ("No" or "Yes") for each month. The percentage on the left side is for "No" and the one on the right side for "Yes".

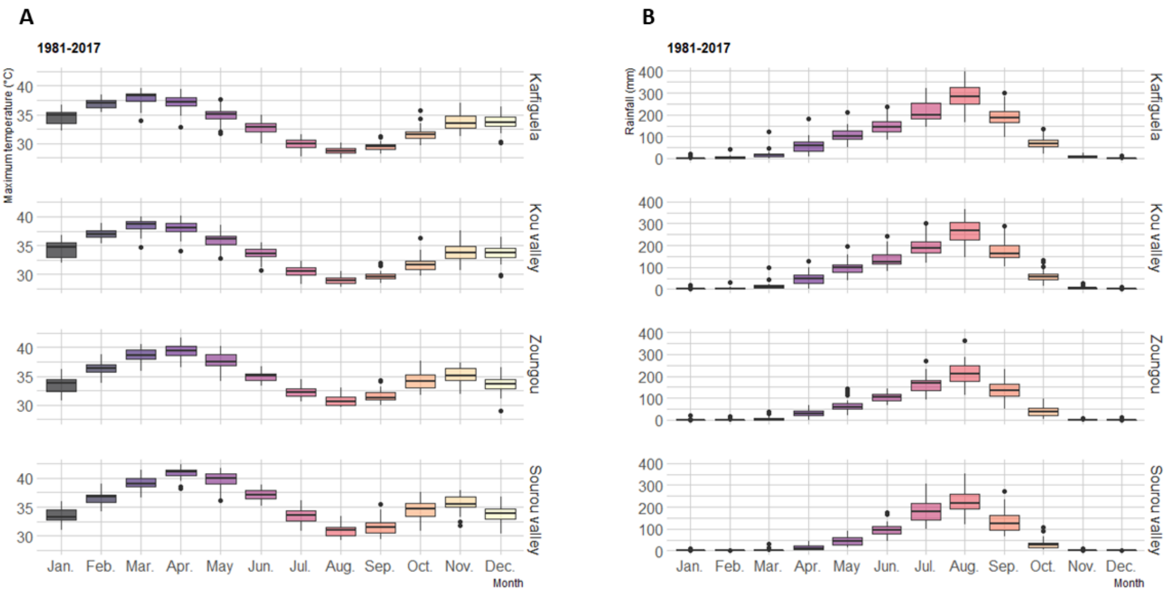

Fig. S5. **A)** Monthly maximum temperature (°C) and **B)** Monthly rainfall (mm) from 1981to 2017 for Karfiguela, Kou Valley, Zoungou, and Sourou Valley. The black dashed line inside a boxplot indicates the median value for each month over the mentioned period. The black dots represent the outliers [i.e. outside 1.5 times the interquartile range above the upper quartile and below the lower quartile (Q1 - 1.5 × IQR or Q3 + 1.5 × IQR)] for each month. IQR is the interquartile.

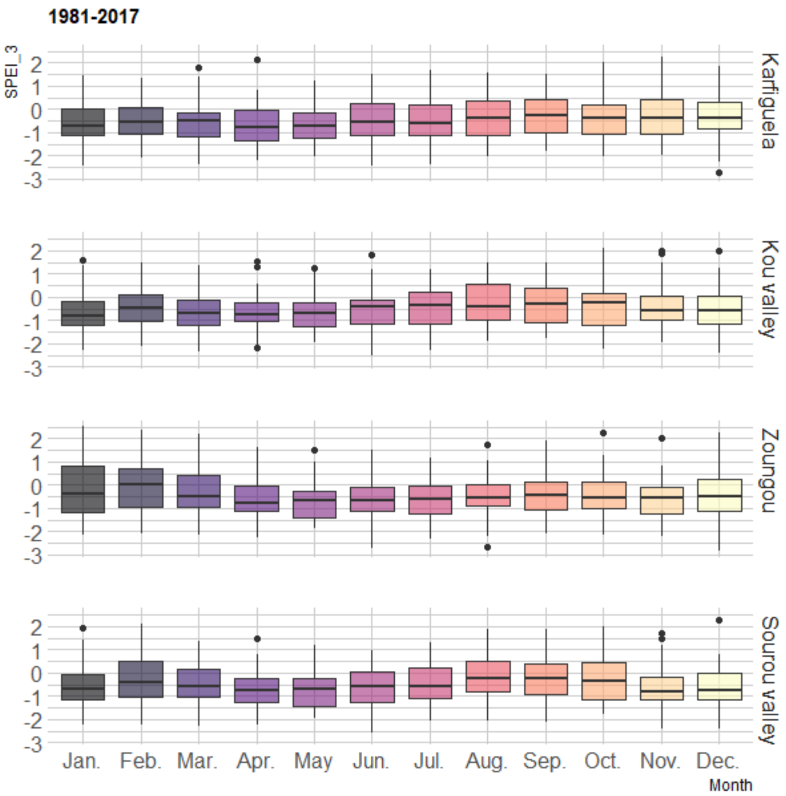

Fig. S6. Standardized Precipitation-Evapotranspiration Index (SPEI) from 1981–2017 for Karfiguela, Kou valley, Zoungou, and Sourou valley. SPEI_3 is computed calculated over a 3-month SPEI accumulation period. The horizontal black line inside a boxplot indicates the median value for each month over the mentioned period. The black dots represent the outliers [i.e. outside 1.5 times the interquartile range above the upper quartile and below the lower quartile (Q1 - 1.5 × IQR or Q3 + 1.5 × IQR)] for each month. IQR is the interquartile.

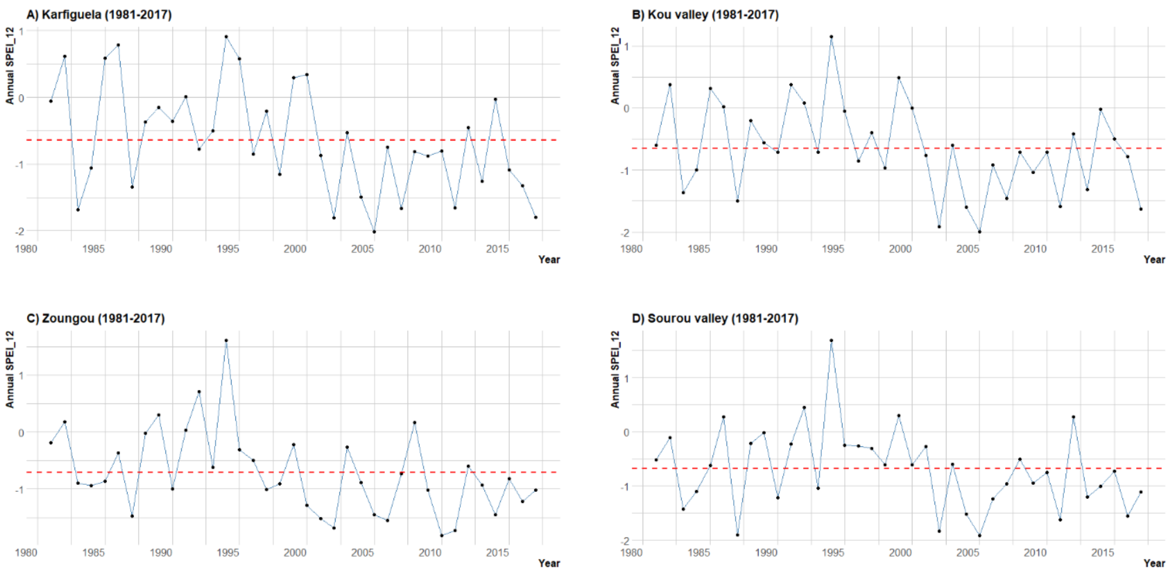

Fig. S7. Evolution of the annual 12-month Standardised Precipitation-Evapotranspiration Index (SPEI_12) values from 1981–2017 for **(A)** Karfiguela, **(B)** Kou valley, **(C)** Zoungou, and **(D)** Sourou valley. In all cases, connected black dots indicate annual SPEI_12 values; the red dashed lines represent the mean value over the mentioned period.

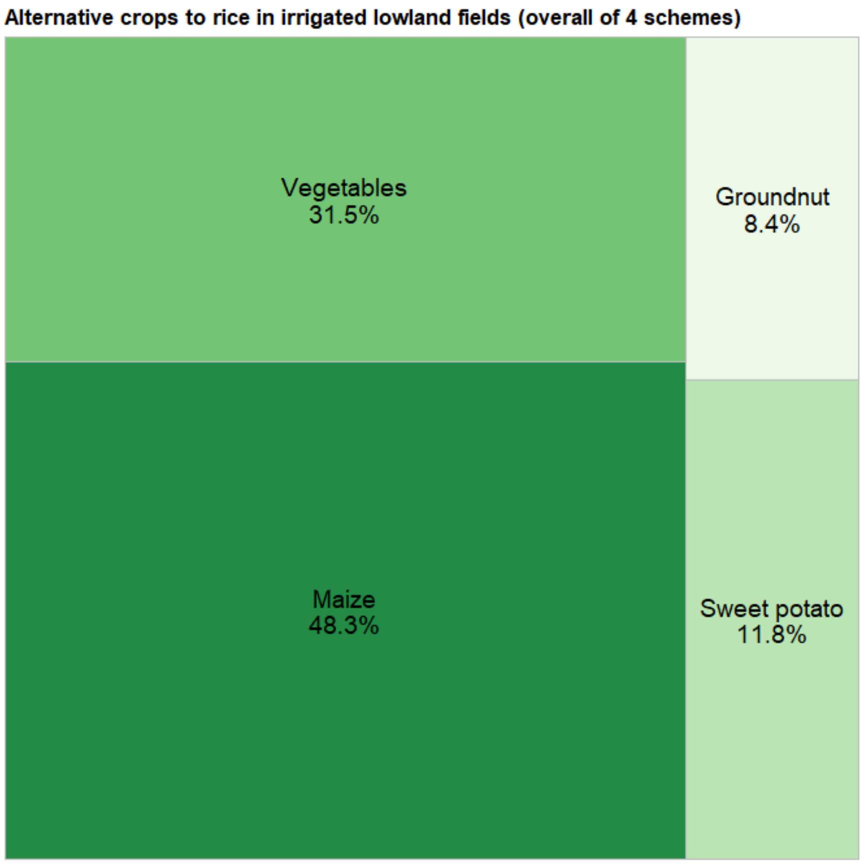

Fig. S8. Treemap showing the alternative crops to rice in irrigated lowland fields in the study sites (Karfiguela, Kou valley, Zoungou, and Sourou valley). The size of each rectangle represents a proportion, while the colouring represents a value number and a category. The larger the rectangle and the darker the colour, the higher is the proportion.

Fig. S9. Treemap showing the alternative crops to rice in irrigated lowland fields in **A)** Karfiguela, **B)** Kou valley, **C)** Zoungou, and **D)** Sourou valley). The size of each rectangle represents a proportion, while the colouring represents a value number and a category. The larger the rectangle and the darker the colour, the higher is the proportion.

Table S1

Characteristics of the rice farm households in the study sites (irrigation schemes) (n = 572)

	Karfiguela (n = 138)	**Kou valley (n = 141)**	**Zoungou (n = 185)**	**Sourou valley (n = 108)**	Overall (n = 572)	Test statistic
(Row %)(Col %)[#]						
Soil texture						<0.001
Clayey	51 (15.45%) (36.96%)	109 (33.03%) (77.30%)	167 (50.61%) (90.27%)	3 (0.91%) (2.78%)	330 (100.00%) (57.69%)	Chi-square
Loamy	43 (21.94%) (31.16%)	30 (15.31%) (21.28%)	18 (9.18%) (9.73%)	105 (53.57%) (97.22%)	196 (100.00%) (34.27%)	
Sandy	44 (95.65%) (31.88%)	2 (4.35%) (1.42%)	0 (0.00%) (0.00%)	0 (0.00%) (0.00%)	46 (100.00%) (8.04%)	
Farming group						<0.001
Yes	138 (32.62%) (100.00%)	141 (33.33%) (100.00%)	81 (19.15%) (43.78%)	63 (14.89%) (58.33%)	423 (100.00%) (73.95%)	Chi-square
No	0 (0.00%) (0.00%)	0 (0.00%) (0.00%)	104 (69.80%) (56.22%)	45 (30.20%) (41.67%)	149 (100.00%) (26.05%)	
Gender of the household head						<0.001
Male	120 (27.84%) (86.96%)	129 (29.93%) (91.49%)	74 (17.17%) (40.00%)	108 (25.06%) (100.00%)	431 (100.00%) (75.35%)	Chi-square
Female	18 (12.77%) (13.04%)	12 (8.51%) (8.51%)	111 (78.72%) (60.00%)	0 (0.00%) (0.00%)	141 (100.00%) (24.65%)	
Age group of the household head						0.025
Young adult	37 (21.02%) (26.81%)	33 (18.75%) (23.40%)	66 (37.50%) (35.68%)	40 (22.73%) (37.04%)	176 (100.00%) (30.77%)	Chi-square
Middle aged adult	79 (24.69%) (57.25%)	94 (29.38%) (66.67%)	90 (28.12%) (48.65%)	57 (17.81%) (52.78%)	320 (100.00%) (55.94%)	
Senior adult	22 (28.95%) (15.94%)	14 (18.42%) (9.93%)	29 (38.16%) (15.68%)	11 (14.47%) (10.19%)	76 (100.00%) (13.29%)	
Education level of the household head						<0.001
Illiterate	102 (26.98%) (73.91%)	65 (17.20%) (46.10%)	147 (38.89%) (79.46%)	64 (16.93%) (59.26%)	378 (100.00%) (66.08%)	Chi-square
Primary school	32 (21.19%) (23.19%)	63 (41.72%) (44.68%)	30 (19.87%) (16.22%)	26 (17.22%) (24.07%)	151 (100.00%) (26.40%)	
Secondary school & University	4 (9.30%) (2.90%)	13 (30.23%) (9.22%)	8 (18.60%) (4.32%)	18 (41.86%) (16.67%)	43 (100.00%) (7.52%)	
Farm type*						<0.001
LRE	107 (33.02%) (77.54%)	81 (25.00%) (57.45%)	99 (30.56%) (53.51%)	37 (11.42%) (34.26%)	324 (100.00%) (56.64%)	Chi-square
MRE	31 (13.30%) (22.46%)	55 (23.61%) (39.01%)	83 (35.62%) (44.86%)	64 (27.47%) (59.26%)	233 (100.00%) (40.73%)	
HRE	0 (0.00%) (0.00%)	5 (33.33%) (3.55%)	3 (20.00%) (1.62%)	7 (46.67%) (6.48%)	15 (100.00%) (2.62%)	
Household size						<0.001
Mean (SD)	10.45 (4.99)	14.41 (8.78)	12.54 (7.46)	17.47 (14.31)	13.43 (9.32)	Kruskal-Wallis
Median (IQR)	9.50 (6.00)	12.00 (8.00)	11.00 (9.00)	13.00 (12.00)	11.00 (8.00)	

Number of farmworkers						<0.001
Mean (SD)	5.62 (2.84)	6.28 (5.14)	7.19 (5.77)	7.68 (4.52)	6.68 (4.85)	Kruskal-Wallis
Median (IQR)	5.00 (3.00)	5.00 (3.00)	6.00 (5.00)	7.00 (4.25)	6.00 (4.00)	
Total farmland size (ha)						<0.001
Mean (SD)	2.50 (2.39)	2.98 (2.55)	2.93 (2.23)	3.55 (2.72)	2.95 (2.46)	Kruskal-Wallis
Median (IQR)	1.50 (2.00)	2.00 (2.50)	2.00 (2.50)	2.62 (2.50)	2.00 (2.60)	
Rice field size (ha)						<0.001
Mean (SD)	0.46 (0.29)	0.82 (0.28)	0.11 (0.08)	1.44 (0.89)	0.62 (0.65)	Kruskal-Wallis
Median (IQR)	0.50 (0.25)	1.00 (0.50)	0.10 (0.15)	1.00 (1.00)	0.50 (0.80)	
Herd size (TLU)						0.007
Mean (SD)	3.61 (6.84)	3.30 (5.63)	3.47 (3.66)	6.83 (20.37)	4.10 (10.14)	Kruskal-Wallis
Median (IQR)	2.10 (3.17)	1.90 (2.90)	2.50 (3.70)	2.85 (3.30)	2.30 (3.53)	
Number of farm machines						<0.001
Mean (SD)	0.00 (0.00)	0.27 (0.58)	0.24 (0.55)	0.79 (1.28)	0.29 (0.74)	Kruskal-Wallis
Median (IQR)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (1.00)	0.00 (0.00)	
Average rice yield (Mg/ha)						<0.001
Mean (SD)	4.46 (1.33)	4.91 (1.19)	4.30 (1.62)	5.51 (1.38)	4.73 (1.47)	Kruskal-Wallis
Median (IQR)	4.40 (1.36)	5.10 (1.15)	4.00 (2.00)	5.20 (1.80)	4.70 (1.70)	
Rice farming experience (Years)						<0.001
Mean (SD)	29.07 (12.95)	29.22 (11.22)	17.75 (10.15)	9.48 (10.41)	21.75 (13.60)	Kruskal-Wallis
Median (IQR)	30.00 (20.75)	30.00 (20.00)	20.00 (15.00)	4.00 (8.25)	20.00 (20.00)	
Main income source						<0.001
Agriculture	136 (25.37%) (98.55%)	138 (25.75%) (97.87%)	159 (29.66%) (85.95%)	103 (19.22%) (95.37%)	536 (100.00%) (93.71%)	Chi-square
Trade	0 (0.00%) (0.00%)	1 (4.17%) (0.71%)	23 (95.83%) (12.43%)	0 (0.00%) (0.00%)	24 (100.00%) (4.20%)	
Other	2 (16.67%) (1.45%)	2 (16.67%) (1.42%)	3 (25.00%) (1.62%)	5 (41.67%) (4.63%)	12 (100.00%) (2.10%)	
Ratio of rice production sold (%)						<0.001
Mean (SD)	25.72 (20.99)	22.41 (37.43)	47.92 (31.99)	67.31 (23.88)	39.94 (34.25)	Kruskal-Wallis
Median (IQR)	30.00 (40.00)	0.00 (70.00)	50.00 (50.00)	75.00 (20.00)	40.00 (70.00)	

[#] For categorical variables, the first presented percentages in brackets are row percentages and the second ones are column percentages.

[*] The three farm types are Low Resource Endowed (LRE), Medium Resource Endowed (MRE), and High Resource Endowed (HRE) farms.

Table S2

Characteristics of the 3 rice farm types* (n = 572)

	LRE [n = 324 (56.64%)]	**MRE** [n = 233 (40.73%)]	**HRE** [n = 15 (2.62%)]	Test statistic
(Row %)(Col %)#				
Soil texture				<0.001
Clayey	206 (62.42%) (63.58%)	118 (35.76%) (50.64%)	6 (1.82%) (40.00%)	Fisher exact
Loamy	84 (42.86%) (25.93%)	103 (52.55%) (44.21%)	9 (4.59%) (60.00%)	
Sandy	34 (73.91%) (10.49%)	12 (26.09%) (5.15%)	0 (0.00%) (0.00%)	
Gender of the household head				<0.001
Male	218 (50.58%) (67.28%)	200 (46.40%) (85.84%)	13 (3.02%) (86.67%)	Fisher exact
Female	106 (75.18%) (32.72%)	33 (23.40%) (14.16%)	2 (1.42%) (13.33%)	
Age group of the household head				0.139
Young adult	109 (61.93%) (33.64%)	66 (37.50%) (28.33%)	1 (0.57%) (6.67%)	Fisher exact
Middle aged adult	173 (54.06%) (53.40%)	136 (42.50%) (58.37%)	11 (3.44%) (73.33%)	
Senior adult	42 (55.26%) (12.96%)	31 (40.79%) (13.30%)	3 (3.95%) (20.00%)	
Education level of the household head				0.141
Illiterate	220 (58.20%) (67.90%)	144 (38.10%) (61.80%)	14 (3.70%) (93.33%)	Fisher exact
Primary school	81 (53.64%) (25.00%)	69 (45.70%) (29.61%)	1 (0.66%) (6.67%)	
Secondary school & University	23 (53.49%) (7.10%)	20 (46.51%) (8.58%)	0 (0.00%) (0.00%)	
Household size				<0.001
Mean (SD)	9.56 (4.13)	16.90 (8.54)	43.07 (21.33)	Kruskal-Wallis
Median (IQR)	9.00 (5.00)	15.00 (11.00)	40.00 (21.00)	
Number of farmworkers				<0.001
Mean (SD)	4.81 (1.95)	8.18 (4.00)	23.80 (13.25)	Kruskal-Wallis
Median (IQR)	5.00 (2.00)	7.00 (5.00)	20.00 (14.50)	
Total farmland size (ha)				<0.001
Mean (SD)	1.72 (0.95)	4.34 (2.52)	8.27 (4.87)	Kruskal-Wallis
Median (IQR)	1.50 (1.00)	4.00 (3.75)	8.00 (6.88)	

Rice field size (ha)				<0.001
Mean (SD)	0.51 (0.48)	0.72 (0.71)	1.56 (1.46)	Kruskal-Wallis
Median (IQR)	0.50 (0.65)	0.50 (0.80)	1.00 (1.00)	
Herd size (TLU)				<0.001
Mean (SD)	2.15 (2.17)	5.25 (7.10)	28.05 (50.25)	Kruskal-Wallis
Median (IQR)	1.60 (2.42)	3.40 (4.00)	10.50 (28.85)	
Number of farm machines				<0.001
Mean (SD)	0.00 (0.06)	0.58 (0.76)	2.00 (2.56)	Kruskal-Wallis
Median (IQR)	0.00 (0.00)	0.00 (1.00)	1.00 (1.50)	
Farming group				0.078
Yes	251 (59.34%) (77.47%)	162 (38.30%) (69.53%)	10 (2.36%) (66.67%)	Fisher exact
No	73 (48.99%) (22.53%)	71 (47.65%) (30.47%)	5 (3.36%) (33.33%)	
Average rice yield (Mg/ha)				0.021
Mean (SD)	4.56 (1.35)	4.92 (1.55)	5.59 (1.80)	Kruskal-Wallis
Median (IQR)	4.50 (1.51)	5.00 (2.07)	5.20 (2.70)	
Rice farming experience (Years)				0.375
Mean (SD)	22.50 (14.20)	20.84 (12.65)	19.73 (14.50)	Kruskal-Wallis
Median (IQR)	21.00 (21.25)	20.00 (20.00)	20.00 (27.00)	
Main income source (%)				0.576
Agriculture	303 (56.53%) (93.52%)	219 (40.86%) (93.99%)	14 (2.61%) (93.33%)	Fisher exact
Other	6 (50.00%) (1.85%)	5 (41.67%) (2.15%)	1 (8.33%) (6.67%)	
Trade	15 (62.50%) (4.63%)	9 (37.50%) (3.86%)	0 (0.00%) (0.00%)	
Ratio of rice production sold (%)				0.004
Mean (SD)	36.05 (34.13)	44.06 (33.98)	60.00 (27.77)	Kruskal-Wallis
Median (IQR)	30.00 (70.00)	50.00 (75.00)	70.00 (30.00)	

[#] For categorical variables, the first presented percentages in brackets are row percentages and the second ones are column percentages.

[*] The three farm types are Low Resource Endowed (LRE), Medium Resource Endowed (MRE), and High Resource Endowed (HRE) farms.

Table S3

Water management practices in the irrigated lowland rice fields

	Karfiguela (n = 138)	Kou valley (n = 141)	Zoungou (n = 185)	Sourou valley (n = 108)	Overall (n = 572)	Test statistic
(Row %)(Col %)						
Payment of consumed irrigation water						<0.001
Yes	138 (24.95%) (100.00%)	129 (23.33%) (91.49%)	178 (32.19%) (96.22%)	108 (19.53%) (100.00%)	553 (100.00%) (96.68%)	Chi-square
No	0 (0.00%) (0.00%)	12 (63.16%) (8.51%)	7 (36.84%) (3.78%)	0 (0.00%) (0.00%)	19 (100.00%) (3.32%)	
Irrigation water paid (€)						<0.001
Mean (SD)	9.00 (0.00)	16.49 (5.05)	22.13 (4.40)	103.88 (6.30)	33.01 (34.86)	Kruskal-Wallis
Median (IQR)	9.00 (0.00)	18.00 (0.00)	23.00 (0.00)	106.00 (8.00)	21.50 (14.00)	
Irrigation frequency in dry season						<0.001
Every 2-3 days	14 (8.92%) (10.14%)	25 (15.92%) (17.73%)	113 (71.97%) (61.08%)	5 (3.18%) (4.63%)	157 (100.00%) (27.45%)	Chi-square
Once a week	118 (35.12%) (85.51%)	67 (19.94%) (47.52%)	50 (14.88%) (27.03%)	101 (30.06%) (93.52%)	336 (100.00%) (58.74%)	
Less than once a week	3 (5.08%) (2.17%)	35 (59.32%) (24.82%)	19 (32.20%) (10.27%)	2 (3.39%) (1.85%)	59 (100.00%) (10.31%)	
Erratic and very scarce (almost no irrigation)	3 (15.00%) (2.17%)	14 (70.00%) (9.93%)	3 (15.00%) (1.62%)	0 (0.00%) (0.00%)	20 (100.00%) (3.50%)	
Factors influencing the irrigation frequency						<0.001
Water turn	40 (12.94%) (28.99%)	139 (44.98%) (98.58%)	52 (16.83%) (28.11%)	78 (25.24%) (72.22%)	309 (100.00%) (54.02%)	Chi-square
Water availability in the canal	83 (73.45%) (60.14%)	2 (1.77%) (1.42%)	14 (12.39%) (7.57%)	14 (12.39%) (12.96%)	113 (100.00%) (19.76%)	
Topography	2 (100.00%) (1.45%)	0 (0.00%) (0.00%)	0 (0.00%) (0.00%)	0 (0.00%) (0.00%)	2 (100.00%) (0.35%)	
Distance from the secondary/tertiary canal	12 (92.31%) (8.70%)	0 (0.00%) (0.00%)	1 (7.69%) (0.54%)	0 (0.00%) (0.00%)	13 (100.00%) (2.27%)	
Soil water status	0 (0.00%) (0.00%)	0 (0.00%) (0.00%)	91 (88.35%) (49.19%)	12 (11.65%) (11.11%)	103 (100.00%) (18.01%)	
Soil type	1 (3.12%) (0.72%)	0 (0.00%) (0.00%)	27 (84.38%) (14.59%)	4 (12.50%) (3.70%)	32 (100.00%) (5.59%)	

Table S4

Rice farmers' perception of the critical phases for irrigation

	Karfiguela (n = 138)	Kou valley (n = 141)	Zoungou (n = 185)	Sourou valley (n = 108)	Overall (n = 572)	Test statistic
(Row %)(Col %) #						
Sensitive stage to drought: Transplanted seedling						<0.001
Yes	1 (5.00%) (0.72%)	2 (10.00%) (1.42%)	16 (80.00%) (8.65%)	1 (5.00%) (0.93%)	20 (100.00%) (3.50%)	Chi-square
No	137 (24.82%) (99.28%)	139 (25.18%) (98.58%)	169 (30.62%) (91.35%)	107 (19.38%) (99.07%)	552 (100.00%) (96.50%)	
Sensitive stage to drought: Tillering						<0.001
Yes	49 (89.09%) (35.51%)	2 (3.64%) (1.42%)	4 (7.27%) (2.16%)	0 (0.00%) (0.00%)	55 (100.00%) (9.62%)	Chi-square
No	89 (17.21%) (64.49%)	139 (26.89%) (98.58%)	181 (35.01%) (97.84%)	108 (20.89%) (100.00%)	517 (100.00%) (90.38%)	
Sensitive stage to drought: Panicle initiation						0.082
Yes	3 (75.00%) (2.17%)	0 (0.00%) (0.00%)	0 (0.00%) (0.00%)	1 (25.00%) (0.93%)	4 (100.00%) (0.70%)	Chi-square
No	135 (23.77%) (97.83%)	141 (24.82%) (100.00%)	185 (32.57%) (100.00%)	107 (18.84%) (99.07%)	568 (100.00%) (99.30%)	
Sensitive stage to drought: Booting						<0.001
Yes	7 (100.00%) (5.07%)	0 (0.00%) (0.00%)	0 (0.00%) (0.00%)	0 (0.00%) (0.00%)	7 (100.00%) (1.22%)	Chi-square
No	131 (23.19%) (94.93%)	141 (24.96%) (100.00%)	185 (32.74%) (100.00%)	108 (19.12%) (100.00%)	565 (100.00%) (98.78%)	
Sensitive stage to drought: Heading						<0.001
Yes	120 (29.20%) (86.96%)	132 (32.12%) (93.62%)	90 (21.90%) (48.65%)	69 (16.79%) (63.89%)	411 (100.00%) (71.85%)	Chi-square
No	18 (11.18%) (13.04%)	9 (5.59%) (6.38%)	95 (59.01%) (51.35%)	39 (24.22%) (36.11%)	161 (100.00%) (28.15%)	
Sensitive stage to drought: Flowering						<0.001
Yes	34 (8.59%) (24.64%)	95 (23.99%) (67.38%)	163 (41.16%) (88.11%)	104 (26.26%) (96.30%)	396 (100.00%) (69.23%)	Chi-square
No	104 (59.09%) (75.36%)	46 (26.14%) (32.62%)	22 (12.50%) (11.89%)	4 (2.27%) (3.70%)	176 (100.00%) (30.77%)	
Sensitive stage to drought: All stages						<0.001
Yes	17 (77.27%) (12.32%)	2 (9.09%) (1.42%)	3 (13.64%) (1.62%)	0 (0.00%) (0.00%)	22 (100.00%) (3.85%)	Chi-square
No	121 (22.00%) (87.68%)	139 (25.27%) (98.58%)	182 (33.09%) (98.38%)	108 (19.64%) (100.00%)	550 (100.00%) (96.15%)	
Sensitive stage to drought: No idea						0.553
Yes	0 (0.00%) (0.00%)	0 (0.00%) (0.00%)	1 (100.00%) (0.54%)	0 (0.00%) (0.00%)	1 (100.00%) (0.17%)	Chi-square
No	138 (24.17%) (100.00%)	141 (24.69%) (100.00%)	184 (32.22%) (99.46%)	108 (18.91%) (100.00%)	571 (100.00%) (99.83%)	

For categorical variables, the first presented percentages in brackets are row percentages and the second ones are column percentages.

Table S5

Rice farmers' perception of the relevance and usefulness of saving water

	Karfiguela (n = 138)	Kou valley (n = 141)	Zoungou (n = 185)	Sourou valley (n = 108)	Overall (n = 572)	Test statistic
(Row %)(Col %)[#]						
Relevance and usefulness of saving water						<0.001
Yes	125 (23.76%) (90.58%)	112 (21.29%) (79.43%)	184 (34.98%) (99.46%)	105 (19.96%) (97.22%)	526 (100.00%) (91.96%)	Chi-square
No	13 (28.26%) (9.42%)	29 (63.04%) (20.57%)	1 (2.17%) (0.54%)	3 (6.52%) (2.78%)	46 (100.00%) (8.04%)	
Possible usability of water saved						<0.001
Expand rice cultivation area	0 (0.00%) (0.00%)	2 (100.00%) (1.79%)	0 (0.00%) (0.00%)	0 (0.00%) (0.00%)	2 (100.00%) (0.38%)	Chi-square
Legumes or other crops	101 (27.37%) (80.80%)	61 (16.53%) (54.46%)	136 (36.86%) (73.91%)	71 (19.24%) (67.62%)	369 (100.00%) (70.15%)	
Reduction of water price	0 (0.00%) (0.00%)	0 (0.00%) (0.00%)	0 (0.00%) (0.00%)	1 (100.00%) (0.95%)	1 (100.00%) (0.19%)	
Fishing or fish farming	1 (4.00%) (0.80%)	12 (48.00%) (10.71%)	0 (0.00%) (0.00%)	12 (48.00%) (11.43%)	25 (100.00%) (4.75%)	
Livestock farming	11 (11.58%) (8.80%)	20 (21.05%) (17.86%)	43 (45.26%) (23.37%)	21 (22.11%) (20.00%)	95 (100.00%) (18.06%)	
No idea	12 (35.29%) (9.60%)	17 (50.00%) (15.18%)	5 (14.71%) (2.72%)	0 (0.00%) (0.00%)	34 (100.00%) (6.46%)	
Missing	13	29	1	3	46	

[#] The first presented percentages in brackets are row percentages and the second ones are column percentages

Table S6 Current situation of the water availability and usage restrictions in the irrigated lowland rice fields

	Karfiguela (n = 138)	Kou Valley (n = 141)	Zoungou (n = 185)	Sourou Valley (n = 108)	Overall (n = 572)	Test statistic
(Row %)(Col %)[#]						
Cropping frequency						<0.001
Once	0 (0%) (0%)	89 (58%) (63%)	56 (37%) (30%)	7 (5%) (6%)	152 (100%) (27%)	Chi-square
Twice	138 (33%) (100%)	52 (12%) (37%)	129 (31%) (70%)	101 (24%) (94%)	420 (100%) (73%)	
Rice cultivation in wet season (WS)						<0.001
Yes	135 (24%) (98%)	141 (25%) (100%)	180 (33%) (97%)	98 (18%) (91%)	554 (100%) (97%)	Chi-square
No	3 (17%) (2%)	0 (0%) (0%)	5 (28%) (3%)	10 (55%) (9%)	18 (100%) (3%)	
Rice cultivation in dry season (DS)						<0.001
Yes	135 (32%) (98%)	51 (12%) (36%)	132 (32%) (71%)	102 (24%) (94%)	420 (100%) (73%)	Chi-square
No	3 (2%) (2 %)	90 (59%) (64%)	53 (35%) (29%)	6 (4%) (6%)	152 (100%) (27%)	
Recent water scarcity						<0.001
Yes	130 (29%) (94%)	115 (26%) (82%)	178 (40%) (96%)	22 (5%) (20%)	445 (100%) (78%)	Chi-square
No	8 (6%) (6%)	26 (20%) (18%)	7 (6%) (4%)	86 (68%) (81%)	127 (100%) (22%)	
Water scarcity frequency (in years/5 years)						<0.001
Mean (SD)	2.6 (1.3)	3.5 (2.1)	2.4 (1.3)	0.5 (1.1)	2.4 (1.8)	Kruskal-Wallis
Median (IQR)	3.0 (1.0)	5.0 (4.0)	2.0 (1.0)	0.0 (0.0)	2.0 (3.0)	
Season of occurrence of water scarcity						<0.001
WS	3 (60%) (2%)	0 (0%) (0%)	1 (20%) (0%)	1 (20%) (1%)	5 (100%) (1%)	Chi-square
DS	127 (29%) (92%)	115 (26%) (82%)	177 (40%) (96%)	21 (5%) (19%)	440 (100%) (77%)	
None	8 (6%) (6%)	26 (20%) (18%)	7 (6%) (4%)	86 (68%) (80%)	127 (100%) (22%)	
Access restriction to irrigation water in DS						<0.001
Yes	126 (27%) (91%)	130 (27%) (92%)	165 (35%) (89%)	51 (11%) (47%)	472 (100%) (83%)	Chi-square
No	12 (12%) (9%)	11 (11%) (8%)	20 (20%) (11%)	57 (57%) (53%)	100 (100%) (17%)	
Water scarcity effect on rice production						<0.001
Yield reduction	125 (32%) (91%)	105 (26%) (81%)	120 (30%) (66%)	47 (12%) (96%)	397 (100%) (80%)	Chi-square
Complete crop failure	12 (12%) (9%)	24 (24%) (19%)	61 (62%) (34%)	2 (2%) (4%)	99 (100%) (20%)	

[#] For categorical variables, the first presented percentages in brackets are row percentages and the second ones are column percentages.

Table S7

Causes explaining no rice cropping in different seasons in irrigated lowland fields (Burkina Faso)

Reasons	Wet season		Dry season	
	n	%	n	%
Busy with other activities	0	0.0	1	0.7
Flooding	6	33.3	0	0.0
High bird pressure	0	0.0	1	0.7
Low level of soil suitability	1	5.6	1	0.7
Low yield	0	0.0	1	0.7
New rice farmer	5	27.8	2	1.3
No available land	5	27.8	2	1.3
No seed	1	5.6	0	0.0
Vegetable cropping	0	0.0	1	0.7
Water shortage	0	0.0	143	94.1

Table S8

Median and mean and monthly SPEI_3* from 1981–2017 for Karfiguela, Kou valley, Zoungou, and Sourou valley.

Months	Karfiguela		Kou valley		Zoungou		Sourou valley	
	Median	Mean	Median	Mean	Median	Mean	Median	Mean
Jan.	-0.74	-0.50	-0.78	-0.60	-0.37	-0.24	-0.67	-0.47
Feb.	-0.53	-0.50	-0.48	-0.50	0.04	-0.06	-0.42	-0.28
Mar.	-0.51	-0.58	-0.67	-0.61	-0.50	-0.36	-0.58	-0.50
Apr.	-0.76	-0.60	-0.72	-0.66	-0.80	-0.63	-0.73	-0.69
May	-0.70	-0.62	-0.72	-0.68	-0.67	-0.63	-0.67	-0.71
Jun.	-0.56	-0.48	-0.43	-0.54	-0.66	-0.60	-0.61	-0.63
Jul.	-0.59	-0.42	-0.37	-0.45	-0.60	-0.58	-0.59	-0.48
Aug.	-0.38	-0.35	-0.38	-0.34	-0.56	-0.46	-0.23	-0.23
Sep.	-0.23	-0.31	-0.32	-0.32	-0.44	-0.41	-0.22	-0.19
Oct.	-0.35	-0.30	-0.22	-0.33	-0.57	-0.44	-0.38	-0.31
Nov.	-0.37	-0.27	-0.57	-0.39	-0.53	-0.57	-0.79	-0.53
Dec.	-0.39	-0.39	-0.58	-0.51	-0.47	-0.48	-0.75	-0.62

* SPEI stands for Standardised Precipitation-Evapotranspiration Index. SPEI_3 is computed calculated over 3-month accumulation period.

Table S9

Trends of annual SPEI_12* from 1981–2017 for Karfiguela, Kou valley, Zoungou, and Sourou valley.

Sites	Annual SPEI_12					
	Z	p-value	Sen's slope	Change-point	Frequency of dry years from 1981 to 1999 (%)	Frequency of dry years from 2000 to 2017 (%)
Karfiguela	-2.73	0.006	-0.04	2000	21	50
Kou valley	-2.03	0.043	-0.02	2000	11	44
Zoungou	-2.66	0.008	-0.03	1999	16	61
Sourou valley	-2.00	0.045	-0.02	2001	26	50

* SPEI stands for Standardised Precipitation-Evapotranspiration Index. SPEI_12 is computed calculated over a 12-month accumulation period

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Table S10 Estimated parameters of binomial logistic models: Determinants of farmers' adaptation strategies to water scarcity in irrigated rice fields (n = 572)

Explanatory variables	Use of more Irrigation water		Use of supplemental irrigation		Water and Soil Conservation practices		Adjustment of agricultural calendar		Crop rotation	
	Coefficient	P-value	Coefficient	P-value	Coefficient	P-value	Coefficient	P-value	Coefficient	P-value
Intercept	-5.673	6.62E-07	-3.249	3.56E-06	2.995	6.88E-04	-1.792	0.007	-1.863	0.002
Climatic zone |Sudano-Sahelian	-1.236	0.123	**1.594**	0.001	**-3.575**	1.85E-08	0.698	0.142	-0.130	0.746
Texture|Loamy	**2.802**	3.00E-11	-0.308	0.492	-0.765	0.078	**0.820**	0.020	0.387	0.167
Texture|Sandy	**2.202**	5.07E-06	0.848	0.116	**-1.371**	0.020	0.233	0.662	**1.205**	0.002
Farming association |Yes	**2.730**	0.001	**0.752**	0.012	-0.277	0.410	0.507	0.099	**0.861**	0.004
Gender| Female	-0.822	0.184	-0.589	0.147	0.168	0.650	0.579	0.106	**-0.998**	0.002
Age |Young adult	**0.945**	0.014	0.005	0.986	-0.152	0.660	**0.686**	0.017	-0.366	0.164
Age|Senior adult	-0.500	0.367	-0.407	0.330	-0.710	0.097	-0.886	0.076	-0.305	0.360
Education |Primary school	0.135	0.692	0.326	0.276	**-0.782**	0.027	-0.144	0.625	**-0.491**	0.044
Education|High school	-0.358	0.520	-0.351	0.499	0.531	0.477	-0.411	0.405	-0.111	0.777
Farm type |MRE	-0.097	0.760	**0.601**	0.024	0.235	0.447	0.146	0.569	0.082	0.715
Farm type |HRE	-0.715	0.536	0.885	0.200	0.824	0.498	-1.226	0.277	0.249	0.700
Rice field size	0.096	0.750	0.061	0.797	0.251	0.675	0.250	0.327	-0.485	0.060
Rice farming experience	0.007	0.682	-0.016	0.257	0.012	0.463	-0.011	0.477	-0.009	0.431
Main income source |Trade	-12.290	0.985	**1.055**	0.037	**-1.165**	0.030	0.651	0.202	0.769	0.168
Main income source|Other	1.212	0.283	0.696	0.359	-1.199	0.188	0.036	0.967	0.583	0.404
Ratio of rice production sold	0.006	0.281	0.004	0.365	-0.006	0.172	0.003	0.395	**0.009**	0.010
Irrigation water paid	-2.03E-07	0.990	-3.24E-06	0.790	**8.69E-05**	2.10E-05	**-2.61E-05**	0.026	3.82E-06	0.702
Irrigation frequency in DS | < once a week	**-1.59**	0.030	0.60	0.155	0.19	0.70	-0.20	0.676	**-1.53**	3.58E-04
Irrigation frequency in DS | Very scarce	-1.32	0.080	-14.78	0.987	15.46	0.98	-15.55	0.985	**-2.14**	0.007
Irrigation water availability in DS | Very bad & Bad	**1.895**	4.51E-06	**-1.452**	4.47E-04	0.423	0.277	**-0.698**	0.047	**0.988**	4.22E-04
Irrigation water availability in DS | Very good & Good	-0.302	0.51	0.184	0.527	-0.362	0.306	-0.124	0.665	0.537	0.063
Frequency of water scarcity	**-0.416**	3.26E-04	**0.210**	0.044	-0.100	0.383	-0.163	0.091	0.126	0.104
χ^2	187.9 ***	< 2.2E-16	87.474 ***	9.19E-10	201.71 ***	< 2.2E-16	75.235 ***	9.68E-08	96.877 ***	2.26E-11
Log likelihood	-246.59		-264.32		-271.89		-242.2		-353.17	
Nagelkerke Pseudo R^2	0.49		0.24		0.49		0.21		0.23	

Bold values indicate the coefficients are statistically significant at a p-value less than 0.05.
The reference or base category of each explanatory variable is presented in Table 2.

Table S11 Average marginal effects (AME) of binomial logistic models: Determinants of farmers' adaptation strategies to water scarcity in irrigated rice fields (n = 572)

Explanatory variables	Use of more Irrigation water		Use of motor pump for supplemental irrigation		Water and soil conservation practices		Adjustment of agricultural calendar		Crop rotation	
	AME	P-value	AME	P-value	AME	P-value	AME	P-value	AME	P-value
Climatic zone |Sudano-Sahelian	-0.100	0.100	**0.186**	4.94E-04	**-0.399**	6.03E-11	0.090	0.134	-0.024	0.746
Texture|Loamy	**0.248**	1.36E-12	-0.036	0.482	-0.071	0.071	**0.111**	0.022	0.071	0.172
Texture|Sandy	**0.171**	2.41E-04	0.123	0.145	**-0.134**	0.017	0.027	0.675	**0.238**	0.003
Farming association |Yes	**0.159**	7.25E-10	**0.087**	0.007	-0.027	0.396	0.063	0.079	**0.147**	0.002
Gender| Female	-0.061	0.126	-0.067	0.115	0.016	0.644	0.081	0.127	**-0.167**	6.12E-04
Age |Young adult	-0.035	0.329	-0.046	0.294	-0.074	0.113	**-0.083**	0.027	-0.055	0.344
Age|Senior adult	**0.087**	0.019	0.001	0.986	-0.015	0.663	**0.101**	0.024	-0.065	0.155
Education |Primary school	0.012	0.695	0.042	0.289	**-0.081**	0.027	-0.019	0.619	**-0.086**	0.036
Education|High school	-0.028	0.499	-0.038	0.466	0.047	0.444	-0.050	0.363	-0.021	0.774
Farm type |MRE	-0.008	0.760	**0.074**	0.025	0.023	0.442	0.020	0.570	0.015	0.715
Farm type |HRE	-0.054	0.483	0.117	0.269	0.075	0.442	-0.113	0.104	0.046	0.707
Rice field size	0.008	0.750	0.008	0.797	0.025	0.675	0.033	0.326	-0.087	0.058
Rice farming experience	0.001	0.681	-0.002	0.255	0.001	0.462	-0.001	0.477	-0.002	0.430
Main income source |Trade	**-0.155**	1.08E-36	0.157	0.071	-0.133	0.053	0.097	0.252	0.148	0.183
Main income source|Other	**0.119**	3.40E-01	0.097	0.415	-0.137	0.227	0.005	0.967	0.110	0.425
Ratio of rice production sold	0.001	0.279	4.72E-04	0.364	-0.001	0.169	0.000	0.394	**0.002**	0.008
Irrigation water paid	-1.70E-08	0.990	-3.98E-07	0.790	**8.58E-06**	7.38E-06	**-3.42E-06**	0.024	6.88E-07	0.702
Irrigation frequency in DS | < once a week	**-0.107**	0.003	0.082	0.191	0.019	0.698	-0.026	0.662	**-0.227**	6.90E-07
Irrigation frequency in DS | Very scarce	**-0.094**	0.023	**-0.171**	1.29E-28	**0.198**	2.27E-44	**-0.191**	1.07E-31	**-0.277**	3.61E-07
Irrigation water availability in DS | Very bad & Bad	**0.174**	7.33E-07	**-0.152**	1.28E-04	0.041	0.275	**-0.088**	0.039	**0.178**	3.28E-04
Irrigation water availability in DS | Very good & Good	-1.91E-02	0.494	2.88E-02	0.529	-0.04	0.31	-1.81E-02	0.663	9.04E-02	0.065
Frequency of water scarcity	**-0.035**	1.48E-04	**0.026**	0.042	-0.010	0.382	-0.021	0.089	0.023	0.101
χ^2	187.9 ***	< 2.2E-16	87.47 ***	9.19E-10	201.7 ***	< 2.2E-16	75.23 ***	9.68E-08	96.88 ***	2.26E-11
Log likelihood	-246.59		-264.32		-271.89		-242.2		-353.17	
Nagelkerke Pseudo R^2	0.49		0.24		0.49		0.21		0.23	

Bold values indicate the coefficients are statistically significant at a p-value less than 0.05.
The reference or base category of each explanatory variable is presented in Table 2.

Table S12 Estimated parameters of binomial logistic models: Determinants of farmers' passive adaptation strategies to water scarcity in irrigated rice fields (n = 572)

Explanatory variables	No rice cultivation		Reduction of the cultivated rice field size	
	Coefficient	P-value	Coefficient	P-value
Intercept	-4.93	0.012	-1.56	0.463
Climatic zone |Sudano-Sahelian	**4.69**	0.004	1.28	0.448
Texture|Loamy	-0.87	0.332	-17.63	0.992
Texture|Sandy	-15.19	0.995	1.93	0.068
Farming association |Yes	-0.71	0.176	0.07	0.944
Gender| Female	-7.02E-04	0.999	0.35	0.708
Age |Young adult	0.47	0.394	-1.47	0.148
Age|Senior adult	-0.31	0.660	1.28	0.227
Education |Primary school	0.10	0.860	1.55	0.049
Education|High school	-16.83	0.994	-16.31	0.997
Farm type |MRE	-0.75	0.173	-0.54	0.518
Farm type |HRE	-16.67	0.997	-16.70	0.998
Rice field size	0.54	0.809	0.80	0.611
Rice farming experience	0.02	0.492	-0.08	0.091
Main income source |Trade	0.11	0.866	-18.47	0.997
Main income source|Other	0.68	0.676	-17.96	0.998
Ratio of rice production sold	9.97E-06	0.999	4.42E-03	0.704
Irrigation water paid	**-1.29E-04**	0.035	-6.43E-05	0.384
Irrigation frequency in DS | < once a week	-0.90	0.287	-17.81	0.995
Irrigation frequency in DS | Very scarce	-17.50	0.996	-16.31	0.998
Irrigation water availability in DS | Very bad & Bad	**1.65**	0.038	-0.74	0.419
Irrigation water availability in DS | Very good & Good	0.97	0.165	-0.17	0.847
Frequency of water scarcity	-0.17	0.387	-0.31	0.307
χ^2	84.22 ***	3.23E-09	31.10 ^{ns}	0.09
Log likelihood	-117.42		-54.28	
Nagelkerke Pseudo R^2	0.44		0.31	

Bold values indicate the coefficients are statistically significant at a p-value less than 0.05.
The reference or base category of each explanatory variable is presented in Table 2.

Table S13

Average marginal effects (AME) of binomial logistic models: Determinants of farmers' passive adaptation strategies to water scarcity in irrigated rice fields (n = 572)

Explanatory variables	No rice cultivation		Reduction of the cultivated rice field size	
	Coefficient	P-value	Coefficient	P-value
Climatic zone |Sudano-Sahelian	0.153	0.075	0.024	0.512
Texture|Loamy	-0.029	0.218	-0.022	0.056
Texture|Sandy	**-0.057**	2.17E-09	0.081	0.268
Farming association |Yes	-0.028	0.168	0.001	0.943
Gender| Female	-2.80E-05	0.999	0.006	0.717
Age |Young adult	0.020	0.406	0.043	0.339
Age|Senior adult	-0.011	0.641	-0.020	0.137
Education |Primary school	0.004	0.862	0.037	0.116
Education|High school	**-0.054**	6.99E-08	**-0.013**	0.013
Farm type |MRE	-0.029	0.154	-0.009	0.493
Farm type |HRE	**-0.067**	2.91E-06	**-0.023**	0.005
Rice field size	0.021	0.809	0.014	0.613
Rice farming experience	0.001	0.492	-0.001	0.110
Main income source |Trade	0.005	0.869	**-0.022**	4.99E-04
Main income source|Other	0.032	0.719	**-0.022**	4.99E-04
Ratio of rice production sold	0.000	0.999	7.63E-05	0.704
Irrigation water paid	**-5.14E-06**	0.031	-1.11E-06	0.391
Irrigation frequency in DS | < once a week	-0.030	0.170	**-0.022**	3.59E-04
Irrigation frequency in DS | Very scarce	**-0.058**	7.10E-10	**-0.022**	3.59E-04
Irrigation water availability in DS | Very bad & Bad	**0.061**	0.034	-0.012	0.39
Irrigation water availability in DS | Very good & Good	2.84E-02	0.117	-3.30E-03	0.845
Frequency of water scarcity	-6.90E-03	0.385	-5.33E-03	0.32
χ^2	84.22 ***	3.23E-09	31.10 ^{ns}	0.09
Log likelihood	-117.42		-54.28	
Nagelkerke Pseudo R^2	0.44		0.31	

Bold values indicate the coefficients statistically significant at a p-value less than 0.05.

Appendix B: Supplementary material for Chapter 3

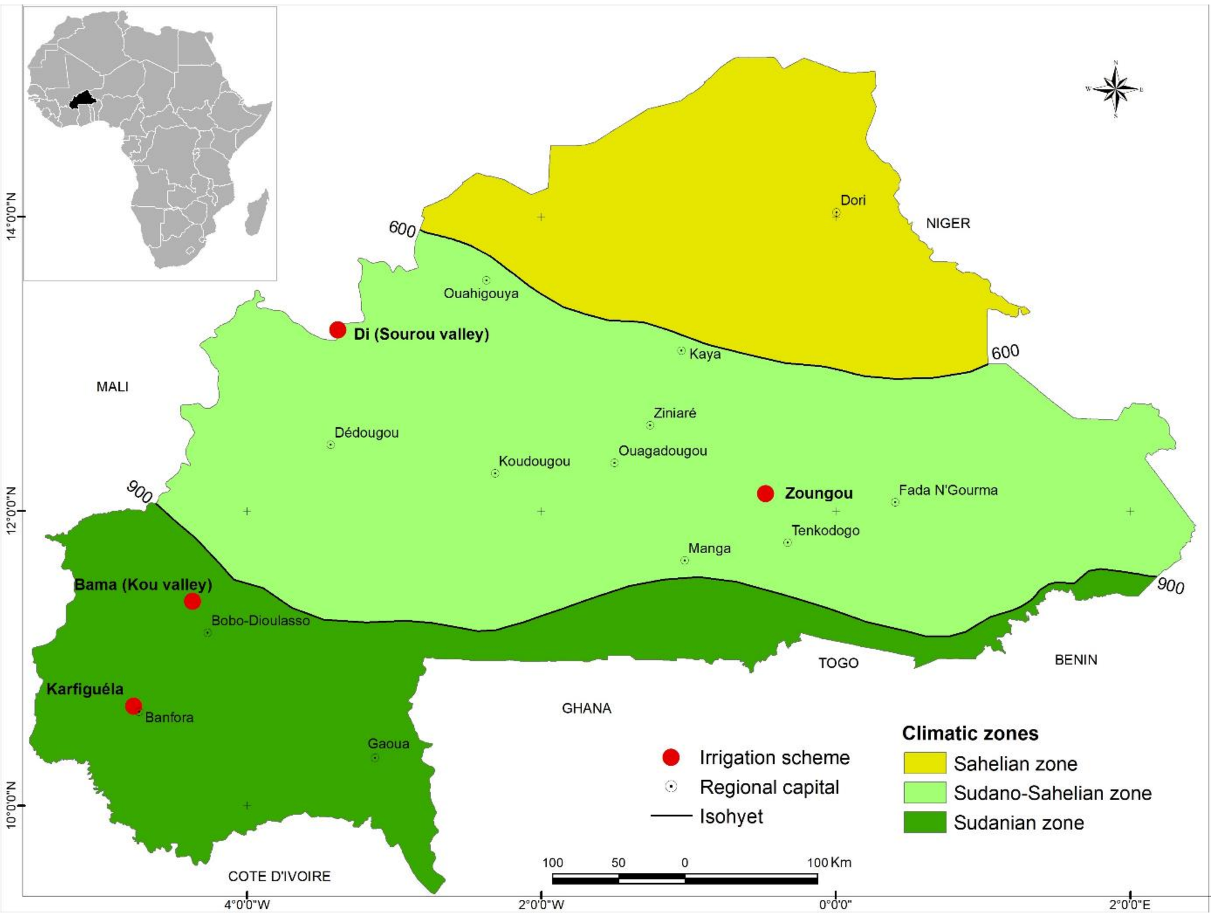

Fig. S1. Map of Burkina Faso showing climatic zones delimitation and study sites.

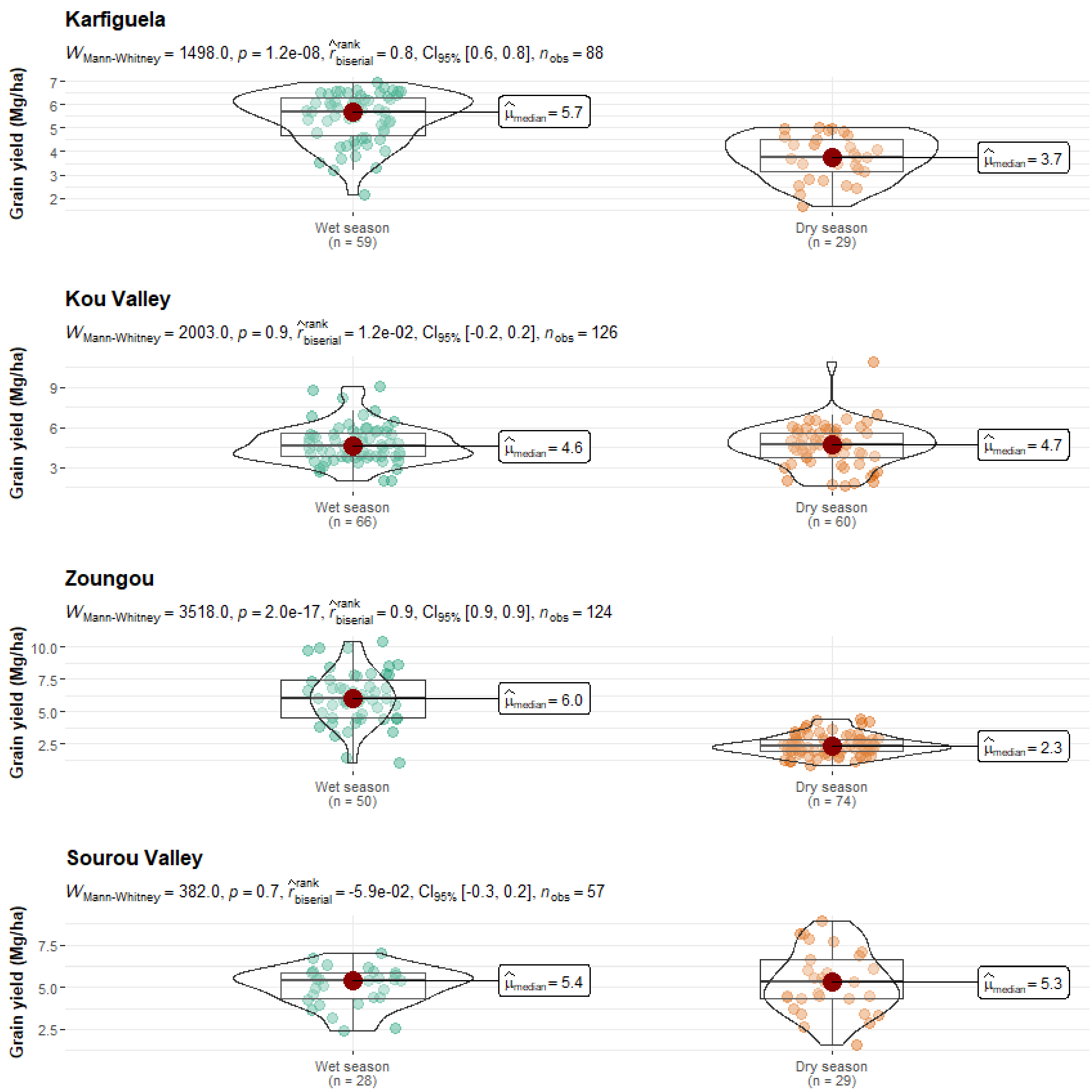

Fig. S2. Yield in wet and dry seasons in different irrigation schemes in Burkina Faso in 2018-2020.

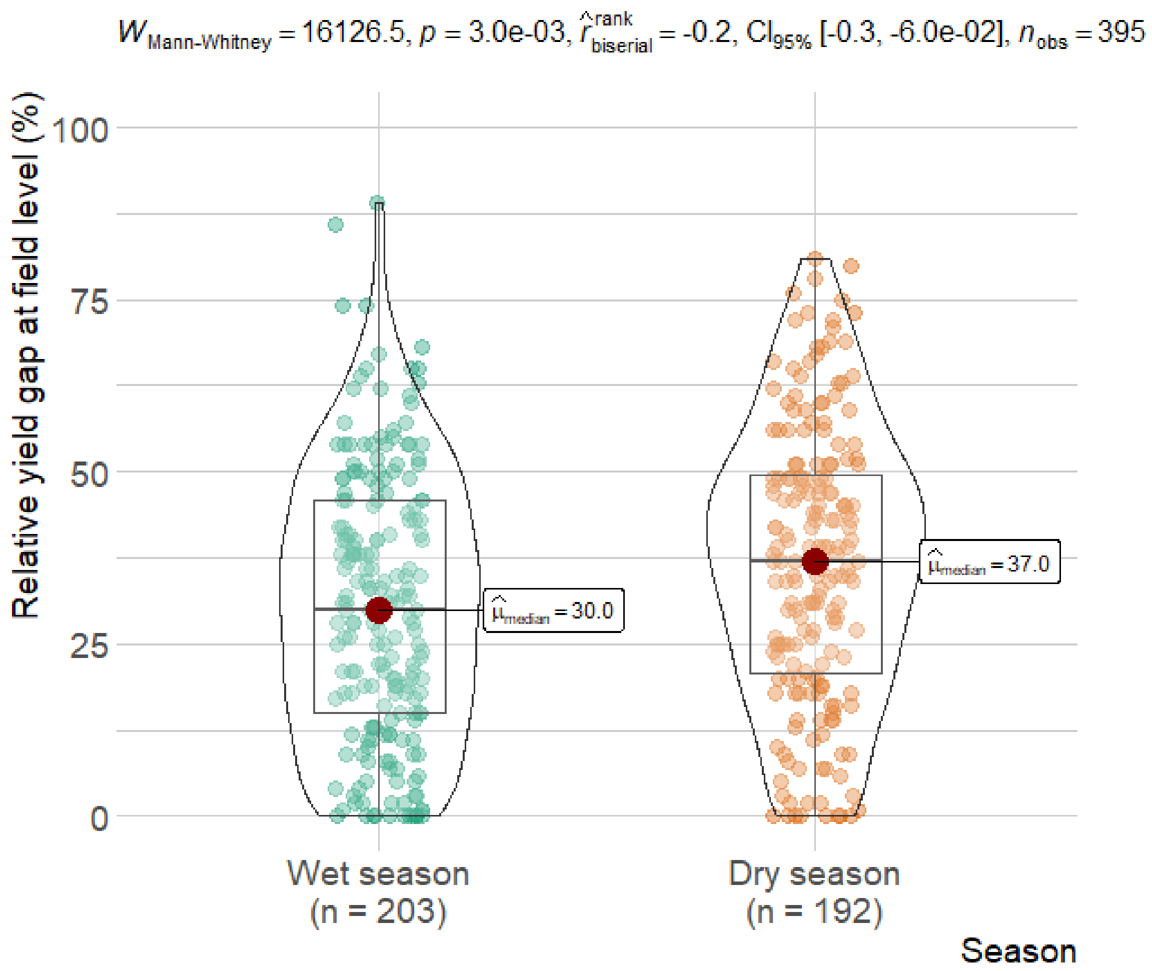

Fig. S3. Relative yield gap at field level in wet and dry seasons across irrigation schemes in Burkina Faso in 2018-2020.

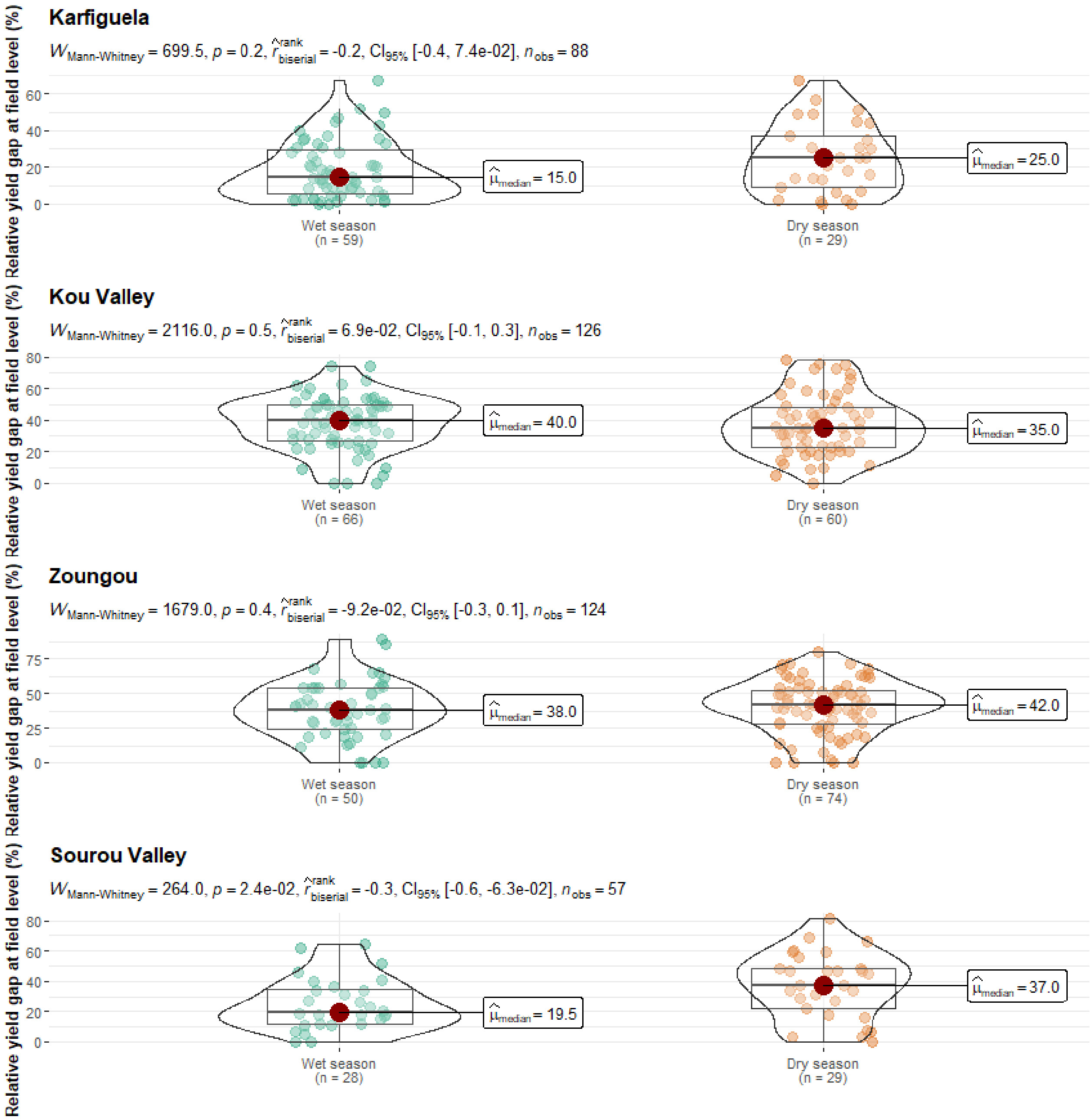

Fig. S4. Relative yield gap at field level in wet and dry seasons in different irrigation schemes in Burkina Faso in 2018-2020.

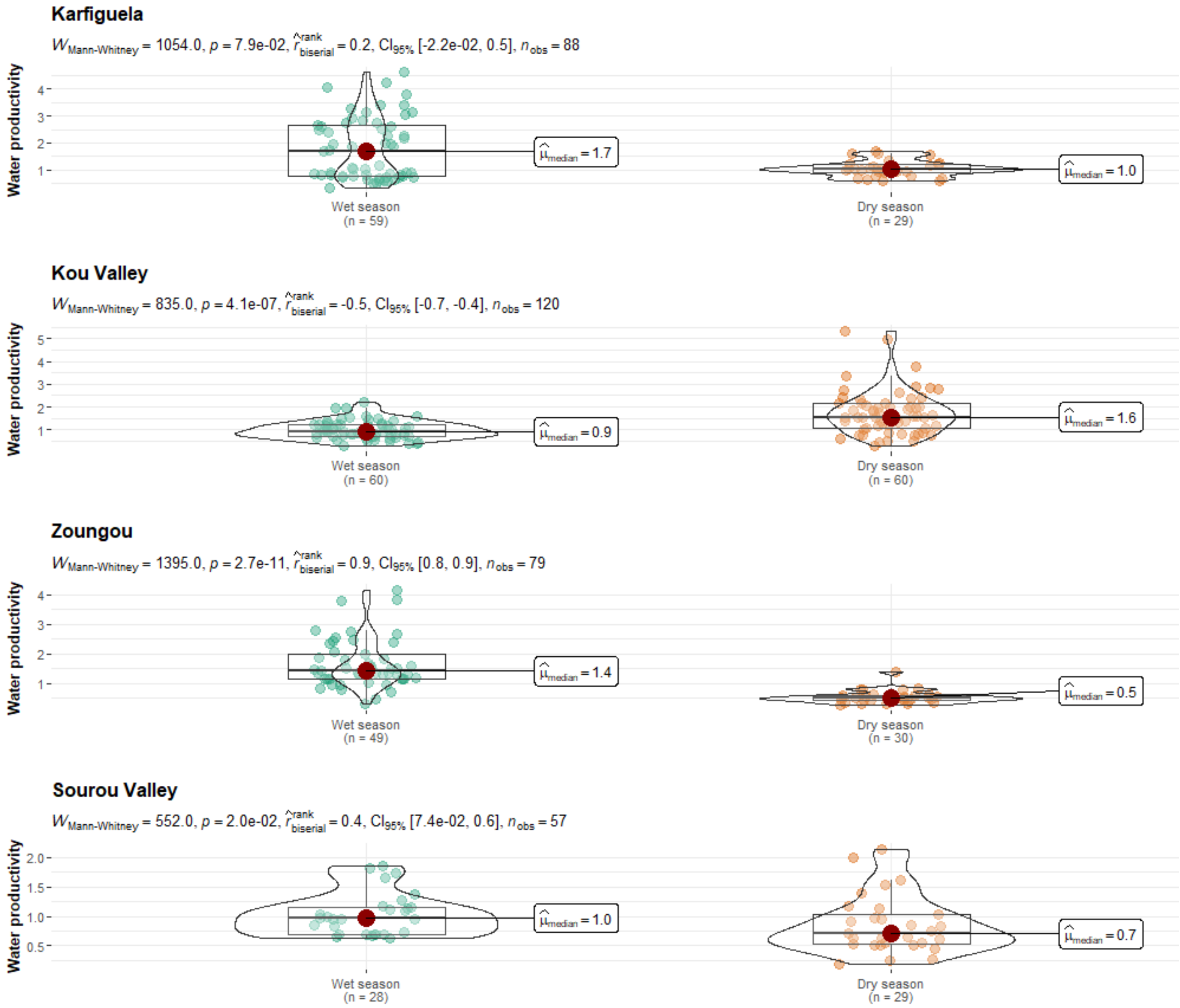

Fig. S5. Water productivity (kg grain m^{-3} of water) in wet and dry seasons in different irrigation schemes in Burkina Faso in 2018-2020.

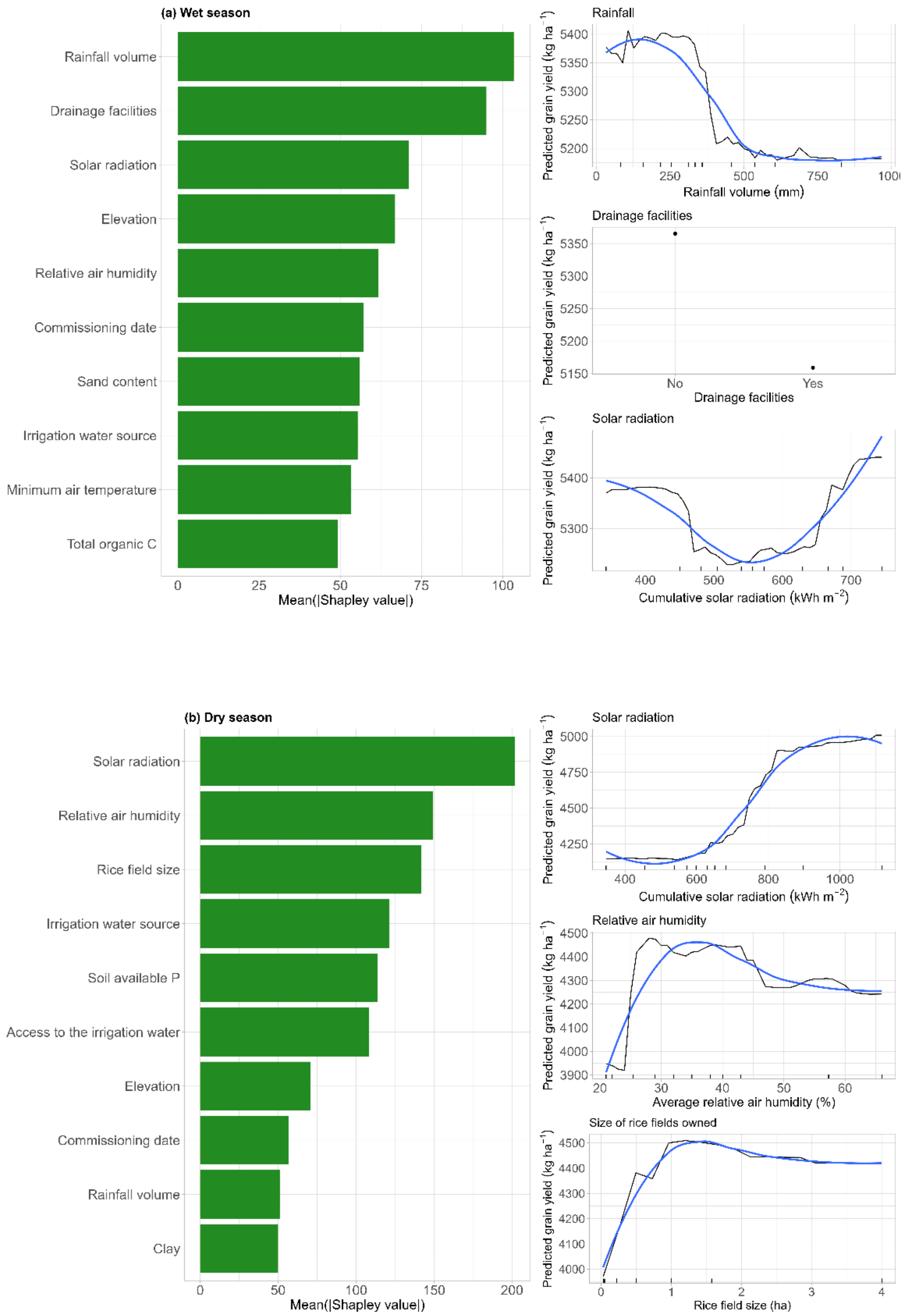

Fig. S6. Non-manageable factors explaining yield variability and their effect on the variation of yield in **(a)** wet season, and **(b)** dry season in irrigated lowland systems in Burkina Faso in 2018-2020. Results are from random forest models. Only the top 10 most important factors are displayed. The variable importance is expressed as the mean of the absolute Shapley values. Only partial dependence plots (PDPs) of the three top-ranked predictor variables of yield variability are displayed. Each PDP (black line) is overlaid by a Locally Estimated Scatterplot Smoothing (LOESS) curve (blue line). The Y-axis of each plot indicates the average effect of different values or categories of the X predictor on the predicted yield (kg ha^{-1}).

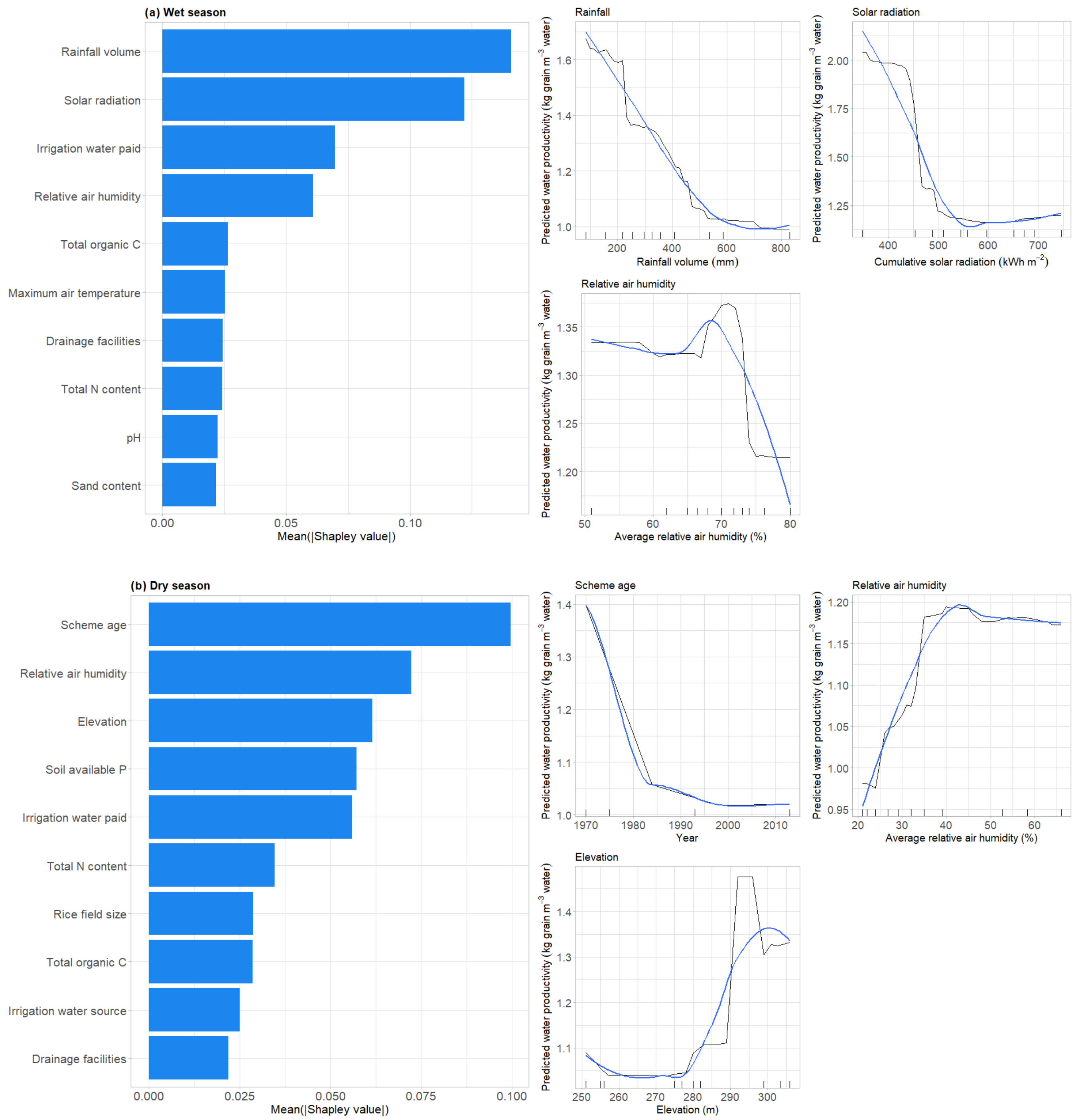

Fig. S7. Non-manageable factors explaining water productivity variability and their effect on the variation of water productivity in **(a)** wet season, and **(b)** dry season in irrigated lowland systems in Burkina Faso in 2018-2020. Results are from random forest models. Only the top 10 most important factors are displayed. The variable importance is expressed as the mean of the absolute Shapley values. Only partial dependence plots (PDPs) of the three top-ranked predictor variables of water productivity variability are displayed. Each PDP (black line) is overlaid by a Locally Estimated Scatterplot Smoothing (LOESS) curve (blue line). The Y-axis of each plot indicates the average effect of different values or categories of the X predictor on the predicted water productivity (kg grain m^{-3} water).

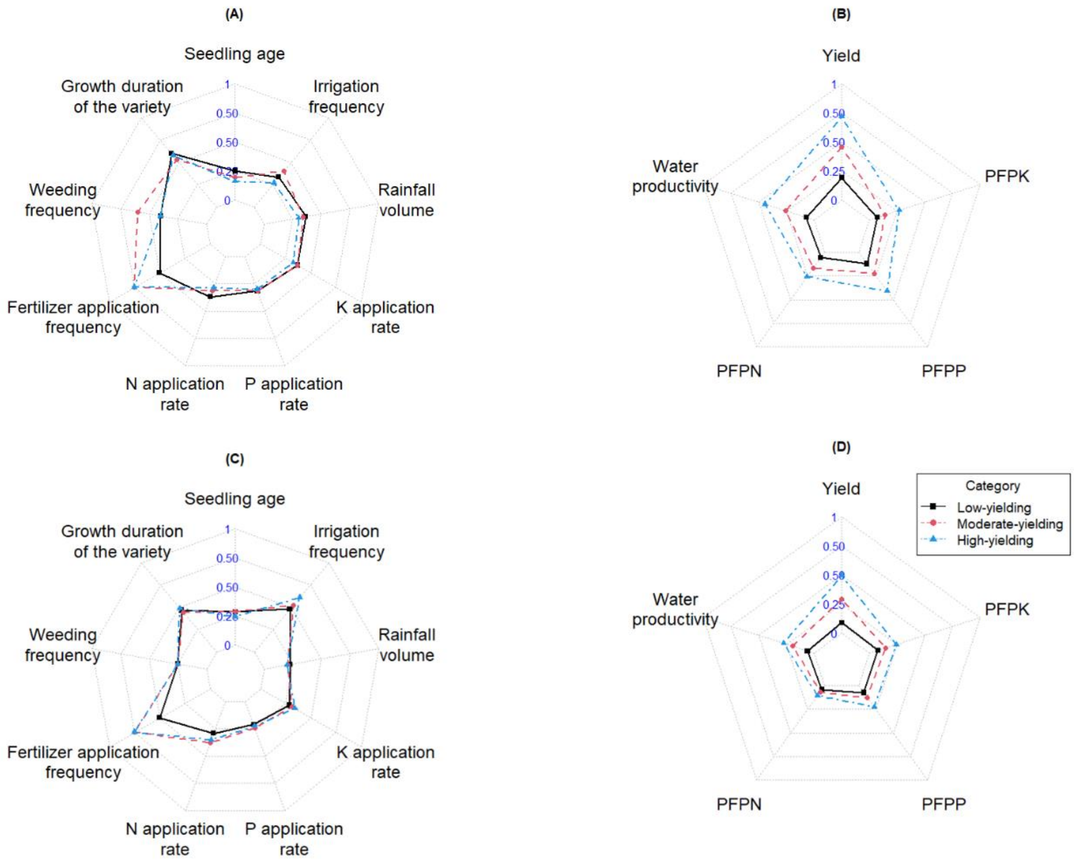

Fig. S8. Trade-offs/Synergies within the wet season between different (**a**) production inputs, and (**b**) grain yield and the indicators of resource-use efficiency (WP- Total water productivity; PFPN – Partial factor productivity of applied N; PFPP – Partial factor productivity of applied P; PFPK – Partial factor productivity of applied K); and within the dry season between different (**c**) production inputs, and (**d**) Grain yield and the indicators of resource-use efficiency in irrigated lowland systems in Burkina Faso in 2018-2020. The three categories of farmers were delineated by the grain yield performance.

Table S1 Sites, climatic zones, and number of fields surveyed per season and year

Irrigation scheme	Climatic zone	2018		2019		2020		Total
		Dry season	Wet season	Dry season	Wet season	Dry season	Wet season	
Karfiguela	Sudanian	0	29	29	30	0	0	88
Kou Valley	Sudanian	28	34	26	32	6	0	126
Zoungou	Sudano-sahelian	44	22	30	28	0	0	124
Sourou Valley	Sudano-sahelian	0	0	29	28	0	0	57

Table S2 Information on the planting material

Variety	Variety type	Growth duration of the variety	Growth duration category	Potential yield (Mg/ha)	Source #
Orylux6	Indica	100	Short duration	6.5	Comité nationale des semences (2014)
TS2	Indica	120	Medium duration	6.5	Comité nationale des semences (2014)
IT	Indica	130	Long duration	7.0	Comité nationale des semences (2014)
Gambiaka	Indica	140	Long duration	5.0	Comité nationale des semences (2014)
FKR19 (TOX 728-1)	Tropical japonica	115	Medium duration	6.0	Comité nationale des semences (2014)
Samangrin (TOX 729)	Tropical japonica	95	Short duration	6.0	Comité nationale des semences (2014)
Nerica4	Upland NERICA	100	Short duration	4.0	Comité nationale des semences (2014)
FKR45N	Upland NERICA	95	Short duration	4.0	Comité nationale des semences (2014)
FKR62N	Lowland NERICA	118	Medium duration	7.0	Comité nationale des semences (2014)
FKR60N	Lowland NERICA	115	Medium duration	7.0	Comité nationale des semences (2014)

[#] Comité nationale des semences (2014) Catalogue national des espèces et variétés agricoles du Burkina Faso. Ouagadougou, Burkina Faso. 81 p. http://fagri-burkina.com/Docs/BF_2014_Catalogue_especes_varietes_agricoles_BF_Final.pdf

Table S3 Variation of weather conditions in the rice fields during the growth period across irrigation schemes in Burkina Faso (2018-2020)

	Karfiguela (n = 88)	Kou Valley (n = 126)	Zoungou (n=124)	Sourou Valley (n= 57)	Overall	Test statistic
Cumulative solar radiation (kWh.m^{-2})						<0.001
Mean (SD)	486 (71)	575 (72)	571 (84)	781 (138)	584 (125)	Kruskal-Wallis
Median (IQR)	485 (95)	569 (74)	571 (149)	745 (216)	559 (150)	
Average maximum temperature (°C)						<0.001
Mean (SD)	34 (1)	35 (2)	37 (2)	36 (1)	35 (2)	Kruskal-Wallis
Median (IQR)	33 (3)	35 (5)	38 (3)	37 (3)	35 (4)	
Average minimum temperature (°C)						0.001
Mean (SD)	24 (2)	25 (2)	24 (1)	25 (1)	24 (1)	Kruskal-Wallis
Median (IQR)	23 (3)	24 (3)	24 (1)	24 (1)	24 (2)	
Average relative air humidity (%)						<0.001
Mean (SD)	68 (8)	55 (17)	42 (18)	46 (17)	53 (19)	Kruskal-Wallis
Median (IQR)	72 (13)	61 (33)	31 (30)	33 (35)	59 (38)	
Rainfall volume (mm)*						<0.001
Mean (SD)	313 (177)	272 (257)	102 (141)	124 (111)	206 (210)	Kruskal-Wallis
Median (IQR)	225 (333)	162 (449)	33 (194)	27 (227)	156 (297)	

SD: Standard deviation

IQR: Interquartile range

* 1 mm of rain = 10 m^3 ha^{-1}

Table S4 Variation of climatic factors in the rice fields during the growth period in wet and dry seasons in irrigated rice in Burkina Faso (2018-2020)

	Wet season (n = 203)	Dry season (n = 192)	Test statistic
Cumulative solar radiation (kWh.m^{-2})			0.005
Mean (SD)	558 (86)	611 (151)	Wilcoxon rank-sum
Median (IQR)	554 (120)	584 (168)	
Average maximum temperature (°C)			<0.001
Mean (SD)	34 (1)	38 (1)	Wilcoxon rank-sum
Median (IQR)	34 (2)	38 (2)	
Average minimum temperature (°C)			<0.001
Mean (SD)	23(1)	25 (1)	Wilcoxon rank-sum
Median (IQR)	23 (1)	25 (2)	
Average relative air humidity (%)			<0.001
Mean (SD)	68 (7)	36 (11)	Wilcoxon rank-sum
Median (IQR)	70 (8)	32 (11)	
Cumulative rainfall volume (mm)			<0.001
Mean (SD)	353 (193)	51 (65)	Wilcoxon rank-sum
Median (IQR)	321 (306)	26 (57)	

Table S5 Soil fertility attributes of the rice fields across irrigation schemes in Burkina Faso (2018-2020)

	Karfiguela	Kou Valley	Zoungou	Sourou Valley	Overall	Test statistic
pH H_2O						<0.001
Mean (SD)	5.3 (0.5)	5.7 (0.4)	6.7 (0.8)	7.6 (0.4)	6.2 (1.0)	Kruskal-Wallis
Median (IQR)	5.3 (0.6)	5.7 (0.5)	6.5 (1.2)	7.7 (0.6)	6.0 (1.5)	
Total N (%)						<0.001
Mean (SD)	0.06 (0.03)	0.09 (0.03)	0.08 (0.03)	0.05 (0.01)	0.08 (0.03)	Kruskal-Wallis
Median (IQR)	0.06 (0.03)	0.09 (0.03)	0.08 (0.04)	0.05 (0.02)	0.07 (0.04)	
Total C (%)						<0.001
Mean (SD)	0.76 (0.34)	1.08 (0.32)	1.12 (0.37)	0.65 (0.15)	0.95 (0.38)	Kruskal-Wallis
Median (IQR)	0.66 (0.37)	1.02 (0.40)	1.05 (0.55)	0.62 (0.19)	0.88 (0.53)	
C:N ratio						<0.001
Mean (SD)	12 (1)	12 (1)	14 (3)	12 (1)	12 (2)	Kruskal-Wallis
Median (IQR)	12 (2)	12 (2)	13 (3)	12 (1)	12 (2)	
Available P (Bray-2) (mg/kg)						<0.001
Mean (SD)	11 (9)	16 (14)	10 (1)	5 (3)	11 (11)	Kruskal-Wallis
Median (IQR)	8 (8)	12 (12)	7 (10)	4 (3)	8 (11)	
Clay content (%)						<0.001
Mean (SD)	14 (6)	25 (7)	29 (7)	26 (6)	24 (9)	Kruskal-Wallis
Median (IQR)	14 (7)	25 (9)	29 (9)	26 (6)	24 (12)	
Silt content (%)						<0.001
Mean (SD)	10 (5)	16 (3)	18 (6)	8 (1)	24 (9)	Kruskal-Wallis
Median (IQR)	9 (7)	15 (3)	18 (6)	8 (2)	24 (12)	
Sand content (%)						<0.001
Mean (SD)	76 (10)	59 (7)	53 (10)	66 (6)	62 (12)	Kruskal-Wallis
Median (IQR)	77 (13)	60 (10)	52 (13)	66 (7)	63 (16)	

Table S6 Soil fertility attributes of the rice fields in wet and dry seasons in Burkina Faso (2018-2020)

	Wet season	Dry season	Test statistic
pH H_2O			<0.001
Mean (SD)	6.0 (0.9)	6.4 (1.0)	Wilcoxon rank-sum
Median (IQR)	5.8 (0.9)	6.1 (1.9)	
Total N (%)			0.049
Mean (SD)	0.07 (0.03)	0.08 (0.03)	Wilcoxon rank-sum
Median (IQR)	0.07 (0.04)	0.07 (0.04)	
Total C (%)			<0.001
Mean (SD)	0.87 (0.32)	1.04 (0.41)	Wilcoxon rank-sum
Median (IQR)	0.84 (0.39)	0.97 (0.58)	
C:N ratio			<0.001
Mean (SD)	12 (1)	13 (2)	Wilcoxon rank-sum
Median (IQR)	12 (1)	13 (2)	
Available P (Bray-2) (mg/kg)			0.66
Mean (SD)	11 (11)	12 (11)	Wilcoxon rank-sum
Median (IQR)	8 (9)	8 (19)	
Clay content (%)			0.002
Mean (SD)	23 (8)	25 (9)	t-test
Median (IQR)	22 (12)	26 (12)	
Silt content (%)			0.002
Mean (SD)	13 (5)	15 (6)	t-test
Median (IQR)	13 (8)	15 (7)	
Sand content (%)			<0.001
Mean (SD)	65 (11)	60 (13)	t-test
Median (IQR)	64 (13)	59 (18)	

Table S7 Socio-economic characteristics of smallholder rice farmers across irrigation schemes in Burkina Faso (2018-2020)

	Karfiguela (n = 88)	Kou Valley (n = 126)	Zoungou (n = 124)	Sourou Valley (n = 57)	Overall	Test statistic
(Row %)(Col %)						
Gender						<0.001
Female	3 (4.55%) (3.41%)	0 (0.00%) (0.00%)	63 (95.45%) (50.81%)	0 (0.00%) (0.00%)	66 (100%) (16.71%)	Chi-square
Male	85 (25.84%) (96.59%)	126 (38.30%) (100.00%)	61 (18.54%) (49.19%)	57 (17.33%) (100.00%)	329 (100%) (83.29%)	
Education						<0.001
Illiterate	59 (24.08%) (67.05%)	54 (22.04%) (42.86%)	96 (39.18%) (77.42%)	36 (14.69%) (63.16%)	245 (100%) (62.03%)	Chi-square
Primary school	27 (21.95%) (30.68%)	59 (47.97%) (46.83%)	22 (17.89%) (17.74%)	15 (12.20%) (26.32%)	123 (100%) (31.14%)	
Secondary School	2 (7.41%) (2.27%)	13 (48.15%) (10.32%)	6 (22.22%) (4.84%)	6 (22.22%) (10.53%)	27 (100%) (6.84%)	
Number of farm workers						0.396
Mean (SD)	6.15 (3.36)	6.81 (6.61)	7.23 (6.45)	7.28 (5.62)	6.86 (5.83)	Kruskal-Wallis
Median (IQR)	5.50 (2.25)	5.00 (4.00)	6.00 (5.62)	7.00 (4.50)	5.50 (4.00)	
Rice field size (ha)						<0.001
Mean (SD)	0.45 (0.30)	0.84 (0.24)	0.12 (0.08)	1.58 (0.88)	0.63 (0.62)	Kruskal-Wallis
Median (IQR)	0.50 (0.25)	1.00 (0.50)	0.10 (0.15)	1.50 (1.00)	0.50 (0.80)	
Herd size (TLU)						0.005
Mean (SD)	3.06 (4.57)	4.37 (8.67)	3.99 (3.93)	9.86 (27.69)	4.75 (12.12)	Kruskal-Wallis
Median (IQR)	1.46 (2.88)	1.94 (5.24)	3.10 (3.76)	2.70 (9.25)	2.25 (4.45)	
Number of farm machines						<0.001
Mean (SD)	0.00 (0.00)	0.21 (0.61)	0.31 (0.64)	1.07 (2.07)	0.32 (0.98)	Kruskal-Wallis
Median (IQR)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (1.00)	0.00 (0.00)	
Rice farming experience (Years)						<0.001
Mean (SD)	30 (12)	25 (12)	18 (9)	9 (10)	22 (13)	Kruskal-Wallis
Median (IQR)	30 (17)	22 (19)	20 (15)	4.00 (8.00)	20 (19)	
Main income source						<0.001
Agriculture	85 (23.68%) (96.59%)	117 (32.59%) (92.86%)	106 (29.53%) (85.48%)	51 (14.21%) (89.47%)	359 (100%) (90.89%)	Chi-square
Trade	0 (0.00%) (0.00%)	0 (0.00%) (0.00%)	16 (100.00%) (12.90%)	0 (0.00%) (0.00%)	16 (100%) (4.05%)	
Other	3 (15.00%) (3.41%)	9 (45.00%) (7.14%)	2 (0.00%) (1.61%)	6 (30.00%) (10.53%)	20 (100%) (5.06%)	

Table S8 Farm management practices in the rice fields across irrigation schemes in Burkina Faso (2018-2020)

	Karfiguela	Kou Valley	Zoungou	Sourou Valley	Overall	Test statistic
Growth duration of the variety						<0.001
Mean (SD)	120 (7)	110 (11)	113 (6)	140 (3)	118 (12)	Kruskal-Wallis
Median (IQR)	118 (2)	115 (20)	115 (0)	140.00 (0)	118 (5)	
Sowing date in nursery						<0.001
Mean (SD)	164.59 (70.54)	113.56 (98.96)	86.05 (104.29)	85.19 (109.08)	112.20 (101.13)	Kruskal-Wallis
Median (IQR)	201.00 (144.00)	132.50 (194.75)	6.00 (193.50)	4.00 (212.00)	147.00 (202.50)	
Age of the seedlings at transplanting (days)						<0.001
Mean (SD)	23.05 (4.72)	22.06 (6.49)	20.38 (6.46)	37.44 (9.85)	23.97 (8.76)	Kruskal-Wallis
Median (IQR)	22.00 (5.00)	20.50 (8.00)	20.00 (10.00)	37.00 (12.00)	21.00 (10.00)	
Planting density (hill/m²)						<0.001
Mean (SD)	25.86 (3.66)	31.40 (10.56)	20.38 (7.16)	22.30 (7.77)	26.01 (9.17)	Kruskal-Wallis
Median (IQR)	25.00 (0.00)	28.00 (14.00)	20.00 (12.00)	20.00 (10.00)	25.00 (11.00)	
Number of seedlings per hill						<0.001
Mean (SD)	2.67 (0.92)	2.91 (1.17)	1.96 (0.79)	2.53 (0.71)	2.51 (1.02)	Kruskal-Wallis
Median (IQR)	3.00 (1.00)	3.00 (2.00)	2.00 (1.00)	2.00 (1.00)	2.00 (1.00)	
Weeding frequency						0.669
Mean (SD)	2.32 (0.84)	2.40 (1.03)	2.42 (0.88)	2.54 (0.91)	2.41 (0.92)	Kruskal-Wallis
Median (IQR)	2.00 (1.00)	2.00 (1.00)	2.00 (1.00)	2.00 (1.00)	2.00 (1.00)	
Inorganic fertilizer application frequency						<0.001
Mean (SD)	2.44 (0.54)	2.66 (0.52)	2.19 (0.67)	3.02 (0.77)	2.51 (0.67)	Kruskal-Wallis
Median (IQR)	2.00 (1.00)	3.00 (1.00)	2.00 (1.00)	3.00 (2.00)	3.00 (1.00)	
N application rate (kg N/ha)						<0.001
Mean (SD)	118.86 (36.57)	126.59 (36.27)	120.07 (62.81)	148.25 (52.21)	125.94 (49.28)	Kruskal-Wallis
Median (IQR)	120.00 (3.05)	123.00 (50.40)	120.80 (72.30)	142.00 (66.00)	121.00 (52.20)	
P application rate (kg P/ha)						<0.001
Mean (SD)	22.10 (6.63)	14.21 (4.30)	17.70 (11.53)	16.39 (6.77)	17.39 (8.49)	Kruskal-Wallis
Median (IQR)	20.10 (0.00)	13.10 (3.30)	17.20 (15.30)	16.00 (9.20)	16.40 (7.00)	
K application rate (kg K/ha)						<0.001

Mean (SD)	22.89 (8.01)	26.01 (7.57)	24.55 (15.18)	26.05 (11.21)	24.86 (11.13)	Kruskal-Wallis
Median (IQR)	23.20 (0.00)	24.90 (2.80)	23.90 (17.80)	24.10 (14.50)	24.15 (8.20)	
Insect and disease control frequency						<0.001
Mean (SD)	0.67 (0.74)	1.89 (1.13)	0.31 (0.48)	0.84 (0.82)	0.97 (1.06)	Kruskal-Wallis
Median (IQR)	1.00 (1.00)	2.00 (2.00)	0.00 (1.00)	1.00 (1.00)	1.00 (2.00)	
Irrigation frequency						<0.001
Mean (SD)	5 (3)	10 (6)	12 (8)	14 (6)	10 (7)	Kruskal-Wallis
Median (IQR)	5 (4)	9 (9)	9 (16)	15 (110)	8 (10)	
Irrigation water input (m^3/ha)						<0.001
Mean (SD)	944 (738)	1641 (1275)	3032 (2192)	5146 (3717)	2363 (2478)	Kruskal-Wallis
Median (IQR)	670 (1090)	1341 (1532)	2205 (3267)	4305 (3805)	1715 (2272)	
(Row %)(Col %)						
Source of seeds						<0.001
Certified	58 (34.52%) (65.91%)	32 (19.05%) (25.40%)	75 (44.64%) (60.48%)	3 (1.79%) (5.26%)	168 (100.00%) (42.53%)	Chi-square
Non-certified	30 (13.22%) (34.09%)	94 (41.41%) (74.60%)	49 (21.59%) (39.52%)	54 (23.79%) (94.74%)	227 (100.00%) (57.47%)	
Straw management						<0.001
Removing	36 (17.31%) (41.38%)	25 (12.02%) (19.84%)	115 (55.29%) (92.74%)	32 (15.38%) (56.14%)	208 (100.00%) (52.79%)	Chi-square
Burning	21 (25.61%) (24.14%)	45 (54.88%) (35.71%)	2 (2.44%) (1.61%)	14 (17.07%) (24.56%)	82 (100.00%) (20.81%)	
Grazing *in-situ*	10 (18.18%) (11.49%)	41 (74.55%) (32.54%)	3 (5.45%) (2.42%)	1 (1.82%) (1.75%)	55 (100.00%) (13.96%)	
Mulching	7 (23.33%) (8.05%)	12 (40.00%) (9.52%)	3 (10.00%) (2.42%)	8 (26.67%) (14.04%)	30 (100.00%) (7.61%)	
Incorporation	13 (68.42%) (14.94%)	3 (15.79%) (2.38%)	1 (5.26%) (0.81%)	2 (10.53%) (3.51%)	19 (100.00%) (4.82%)	
Residue management						<0.001
Removing	15 (28.85%) (17.44%)	2 (3.85%) (1.60%)	10 (19.23%) (8.06%)	25 (48.08%) (43.86%)	52 (100.00%) (13.27%)	Chi-square
Burning	19 (65.52%) (22.09%)	2 (6.90%) (1.60%)	6 (20.69%) (4.84%)	2 (6.90%) (3.51%)	29 (100.00%) (7.40%)	
Mulching	1 (3.33%) (1.16%)	2 (6.67%) (1.60%)	27 (90.00%) (21.77%)	0 (0.00%) (0.00%)	30 (100.00%) (7.65%)	
Incorporation	51 (18.15%) (59.30%)	119 (42.35%) (95.20%)	81 (28.83%) (65.32%)	30 (10.68%) (52.63%)	281 (100.00%) (71.68%)	
Tillage method						<0.001
No-tillage	0 (0.00%) (0.00%)	5 (100.00%) (3.97%)	0 (0.00%) (0.00%)	0 (0.00%) (0.00%)	5 (100.00%) (1.27%)	Chi-square
Manual	1 (1.75%) (1.14%)	0 (0.00%) (0.00%)	56 (98.25%) (45.53%)	0 (0.00%) (0.00%)	57 (100.00%) (14.47%)	
Animal	87 (30.96%) (98.86%)	119 (42.35%) (94.44%)	67 (23.84%) (54.47%)	8 (2.85%) (14.04%)	281 (100.00%) (71.32%)	
Mechanical	0 (0.00%) (0.00%)	2 (3.92%) (1.59%)	0 (0.00%) (0.00%)	49 (96.08%) (85.96%)	51 (100.00%) (12.94%)	

Land levelling						<0.001
Poor	44 (26.04%) (50.00%)	5 (2.96%) (3.97%)	92 (54.44%) (77.97%)	28 (16.57%) (49.12%)	169 (100.00%) (43.44%)	Chi-square
Good	44 (20.00%) (50.00%)	121 (55.00%) (96.03%)	26 (11.82%) (22.03%)	29 (13.18%) (50.88%)	220 (100.00%) (56.56%)	
Herbicide use						<0.001
No	6 (6.32%) (6.82%)	26 (27.37%) (20.63%)	58 (61.05%) (46.77%)	5 (5.26%) (8.77%)	95 (100.00%) (24.05%)	Chi-square
Yes	82 (27.33%) (93.18%)	100 (33.33%) (79.37%)	66 (22.00%) (53.23%)	52 (17.33%) (91.23%)	300 (100.00%) (75.95%)	
Mechanical weeding						<0.001
No	83 (29.86%) (94.32%)	18 (6.47%) (14.29%)	122 (43.88%) (98.39%)	55 (19.78%) (96.49%)	278 (100.00%) (70.38%)	Chi-square
Yes	5 (4.27%) (5.68%)	108 (92.31%) (85.71%)	2 (1.71%) (1.61%)	2 (1.71%) (3.51%)	117 (100.00%) (29.62%)	
Application of organic manure						<0.001
No	51 (16.78%) (57.95%)	90 (29.61%) (71.43%)	107 (35.20%) (87.70%)	56 (18.42%) (98.25%)	304 (100.00%) (77.35%)	Chi-square
Yes	37 (41.57%) (42.05%)	36 (40.45%) (28.57%)	15 (16.85%) (12.30%)	1 (1.12%) (1.75%)	89 (100.00%) (22.65%)	
Application of inorganic fertilizer in nursery						<0.001
No	88 (31.32%) (100.00%)	12 (4.27%) (9.52%)	124 (44.13%) (100.00%)	57 (20.28%) (100.00%)	281 (100.00%) (71.14%)	Chi-square
Yes	0 (0.00%) (0.00%)	114 (100.00%) (90.48%)	0 (0.00%) (0.00%)	0 (0.00%) (0.00%)	114 (100.00%) (28.86%)	
Birds control						<0.001
No	74 (29.72%) (84.09%)	57 (22.89%) (45.24%)	113 (45.38%) (91.13%)	5 (2.01%) (8.77%)	249 (100.00%) (63.04%)	Chi-square
Yes	14 (9.59%) (15.91%)	69 (47.26%) (54.76%)	11 (7.53%) (8.87%)	52 (35.62%) (91.23%)	146 (100.00%) (36.96%)	

Table S9 Farm management practices in the rice fields in wet and dry seasons in Burkina Faso (2018-2020)

	Wet season	Dry season	Overall	Test statistic
Growth duration of the variety				<0.001
Mean (SD)	120(11)	115 (13)	118 (12)	Wilcoxon rank-sum
Median (IQR)	118 (5)	115 (20)	118 (5)	
Sowing date in nursery				<0.001
Mean (SD)	207 (23)	12 (29)	112 (101)	Wilcoxon rank-sum
Median (IQR)	208 (30)	6 (29)	147 (202)	
Age of the seedlings at transplanting (days)				0.223
Mean (SD)	23 (8)	25 (9)	24 (9)	Wilcoxon rank-sum
Median (IQR)	21 (5)	22 (13)	21 (10)	
Planting density				0.004
Mean (SD)	25 (10)	27 (8)	26 (9)	Wilcoxon rank-sum
Median (IQR)	25 (13)	25 (7)	25 (11)	
Number of seedlings per hill				0.555
Mean (SD)	3 (1)	2 (1)	3 (1)	Wilcoxon rank-sum
Median (IQR)	2 (1)	2 (1)	2 (1)	
Weeding frequency				0.044
Mean (SD)	3 (1)	2 (1)	2 (1)	Wilcoxon rank-sum
Median (IQR)	2 (1)	2 (1)	2 (1)	
Inorganic fertilizer application frequency				0.409
Mean (SD)	3 (1)	2 (1)	3 (1)	Wilcoxon rank-sum
Median (IQR)	3 (1)	2 (1)	3 (1)	
N application rate (kg N/ha)				0.193
Mean (SD)	124 (44)	128 (54)	126 (49)	Wilcoxon rank-sum
Median (IQR)	121(44)	123 (55)	121 (52)	
P application rate (kg P/ha)				<0.001
Mean (SD)	19 (8)	16 (8)	17 8)	Wilcoxon rank-sum
Median (IQR)	20 (7)	16 (10)	16 (7)	
K application rate (kg K/ha)				0.186
Mean (SD)	26 (10)	24 (12)	25(11)	Wilcoxon rank-sum
Median (IQR)	25 (6)	23 (14)	24 (8)	
Insect and disease control frequency				<0.001
Mean (SD)	1.19 (1.11)	0.73 (0.95)	0.97 (1.06)	Wilcoxon rank-sum
Median (IQR)	1.00 (2.00)	0.00 (1.00)	1.00 (2.00)	
Irrigation frequency				<0.001
Mean (SD)	5 (3)	16(5)	10 (7)	Wilcoxon rank-sum
Median (IQR)	5 (4)	16 (9)	8 (10)	
Irrigation water input (m^3/ha)				<0.001
Mean (SD)	1189.82 (1113.50)	3916.24 (2901.57)	2362.81 (2478.01)	Wilcoxon rank-sum
Median (IQR)	905.00 (1337.05)	3021.66 (3453.16)	1715.00 (2272.18)	
Source of seeds				<0.001
Certified	104 (61.90%) (51.23%)	64 (38.10%) (33.33%)	168 (100%) (42.53%)	Chi-square
Non-certified	99 (43.61%) (48.77%)	128 (56.39%) (66.67%)	227 (100%) (57.47%)	
Straw management				0.072
Removing	97 (46.63%) (48.02%)	111 (53.37%) (57.81%)	208 (100%) (52.79%)	Chi-square
Burning	39 (47.56%) (19.31%)	43 (52.44%) (22.40%)	82 (100%) (20.81%)	
Grazing *in-situ*	34 (61.82%) (16.83%)	21 (38.18%) (10.94%)	55 (100%) (13.96%)	
Mulching	20 (66.67%) (9.90%)	10 (33.33%) (5.21%)	30 (100%) (7.61%)	
Incorporation	12 (63.16%) (5.94%)	7 (36.84%) (3.65%)	19 (100%) (4.82%)	
Residue management				0.031
Removing	18 (34.62%) (8.96%)	34 (65.38%) (17.80%)	52 (100%) (13.27%)	Chi-square
Burning	15 (51.72%) (7.46%)	14 (48.28%) (7.33%)	29 (100%) (7.40%)	
Mulching	20 (66.67%) (9.95%)	10 (33.33%) (5.24%)	30 (100%) (7.65%)	
Incorporation	148 (52.67%) (73.63%)	133 (47.33%) (69.63%)	281 (100%) (71.68%)	
Tillage method				<0.001

No-tillage	5 (100%) (2.46%)	0 (0.00%) (0.00%)	5 (100%) (1.27%)	Chi-square
Manual	4 (7.02%) (1.97%)	53 (92.98%) (27.75%)	57 (100%) (14.47%)	
Animal	172 (61.21%) (84.73%)	109 (38.79%) (57.07%)	281 (100%) (71.32%)	
Mechanical	22 (43.14%) (10.84%)	29 (56.86%) (15.18%)	51 (100%) (12.94%)	
Land levelling				0.089
Poor	97 (57.40%) (47.78%)	72 (42.60%) (38.71%)	169 (100%) (43.44%)	Chi-square
Good	106 (48.18%) (52.22%)	114 (51.82%) (61.29%)	220 (100%) (56.56%)	
Weeding frequency				0.044
Mean (SD)	2.50 (0.95)	2.32 (0.89)	2.41 (0.92)	Wilcoxon rank-sum
Median (IQR)	2.00 (1.00)	2.00 (1.00)	2.00 (1.00)	
Herbicide use				<0.001
No	7 (7.37%) (3.45%)	88 (92.63%) (45.83%)	95 (100%) (24.05%)	Chi-square
Yes	196 (65.33%) (96.55%)	104 (34.67%) (54.17%)	300 (100%) (75.95%)	
Mechanical weeding				0.935
No	142 (51.08%) (69.95%)	136 (48.92%) (70.83%)	278 (100%) (70.38%)	Chi-square
Yes	61 (52.14%) (30.05%)	56 (47.86%) (29.17%)	117 (100%) (29.62%)	
Application of organic manure				0.712
No	155 (50.99%) (76.35%)	149 (49.01%) (78.42%)	304 (100%) (77.35%)	Chi-square
Yes	48 (53.93%) (23.65%)	41 (46.07%) (21.58%)	89 (100%) (22.65%)	
Application of mineral fertilizer in nursery				0.671
No	142 (50.53%) (69.95%)	139 (49.47%) (72.40%)	281 (100%) (71.14%)	Chi-square
Yes	61 (53.51%) (30.05%)	53 (46.49%) (27.60%)	114 (100.00%) (28.86%)	
Birds control				<0.001
No	149 (59.84%) (73.40%)	100 (40.16%) (52.08%)	249 (100%) (63.04%)	Chi-square
Yes	54 (36.99%) (26.60%)	92 (63.01%) (47.92%)	146 (100%) (36.96%)	

Table S10 Pest incidence in the rice fields across irrigation schemes in Burkina Faso (2018-2020)

	Karfiguela	Kou Valley	Zoungou	Sourou Valley	Overall	Test statistic
Weed infestation above the canopy at flowering						<0.001
Mean (SD)	0.07 (0.25)	0.48 (0.60)	0.07 (0.29)	0.14 (0.35)	0.22 (0.46)	Kruskal-Wallis
Median (IQR)	0.00 (0.00)	0.00 (1.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	
Weed infestation below the canopy at flowering						<0.001
Mean (SD)	1.44 (0.68)	1.02 (0.71)	1.02 (0.79)	0.91 (0.47)	1.10 (0.72)	Kruskal-Wallis
Median (IQR)	1.00 (1.00)	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)	
Insect damage at maturity						<0.001
(Row %)(Col %)						Chi-square
No	85 (25.45%) (96.59%)	112 (33.53%) (90.32%)	107 (32.04%) (86.99%)	30 (8.98%) (52.63%)	334 (100.00%) (85.20%)	
Mild	3 (5.36%) (3.41%)	10 (17.86%) (8.06%)	16 (28.57%) (13.01%)	27 (48.21%) (47.37%)	56 (100.00%) (14.29%)	
Moderate	0 (0.00%) (0.00%)	2 (100.00%) (1.61%)	0 (0.00%) (0.00%)	0 (0.00%) (0.00%)	2 (100.00%) (0.51%)	
Disease damage at maturity						<0.001
(Row %)(Col %)						Chi-square
No	81 (29.14%) (92.05%)	33 (11.87%) (26.61%)	107 (38.49%) (87.70%)	57 (20.50%) (100.00%)	278 (100.00%) (71.10%)	
Mild	7 (9.59%) (7.95%)	53 (72.60%) (42.74%)	13 (17.81%) (10.66%)	0 (0.00%) (0.00%)	73 (100.00%) (18.67%)	
Moderate	0 (0.00%) (0.00%)	34 (94.44%) (27.42%)	2 (5.56%) (1.64%)	0 (0.00%) (0.00%)	36 (100.00%) (9.21%)	
Severe	0 (0.00%) (0.00%)	4 (100.00%) (3.23%)	0 (0.00%) (0.00%)	0 (0.00%) (0.00%)	4 (100.00%) (1.02%)	

Table S11 Pest incidence in the rice fields in wet and dry seasons in Burkina Faso (2018-2020)

	Wet season	Dry season	Overall	Test statistic
(Row %)(Col %)				
Weed infestation above the canopy at flowering				0.175
Mean (SD)	0.18 (0.41)	0.25 (0.50)	0.22 (0.46)	Wilcoxon rank-sum
Median (IQR)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	
Weed infestation below the canopy at flowering				0.587
Mean (SD)	1.08 (0.77)	1.11 (0.66)	1.10 (0.72)	Wilcoxon rank-sum
Median (IQR)	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)	
Insect damage at maturity				0.224
No	166 (49.70%) (83.00%)	168 (50.30%) (87.50%)	334 (100.00%) (85.20%)	Chi-square
Mild	32 (57.14%) (16.00%)	24 (42.86%) (12.50%)	56 (100.00%) (14.29%)	
Moderate	2 (100.00%) (1.00%)	0 (0.00%) (0.00%)	2 (100.00%) (0.51%)	
Disease damage at maturity				<0.001
No	140 (50.36%) (70.00%)	138 (49.64%) (72.25%)	278 (100.00%) (71.10%)	Chi-square
Mild	23 (31.51%) (11.50%)	50 (68.49%) (26.18%)	73 (100.00%) (18.67%)	
Moderate	33 (91.67%) (16.50%)	3 (8.33%) (1.57%)	36 (100.00%) (9.21%)	
Severe	4 (100.00%) (2.00%)	0 (0.00%) (0.00%)	4 (100.00%) (1.02%)	

Table S12 Total water input and field water condition indices in the rice fields across irrigation schemes in Burkina Faso (2018-2020)

	Karfiguela	Kou Valley	Zoungou	Sourou Valley	Overall	Test statistic
Total water input (m^3/ha)						<0.001
Mean (SD)	4069.03 (1811.02)	4128.01 (1775.76)	4626.83 (1444.31)	6386.32 (3243.17)	4601.67 (2190.49)	Kruskal-Wallis
Median (IQR)	3588.50 (2973.25)	3756.50 (2844.50)	4437.50 (1968.00)	5569.00 (2848.00)	4251.70 (2745.75)	
Soil flooding index (%)						<0.001
Mean (SD)	62.38 (24.23)	53.70 (19.93)	55.50 (22.04)	77.96 (14.11)	60.24 (22.41)	Kruskal-Wallis
Median (IQR)	64.00 (40.75)	52.00 (30.00)	52.50 (30.50)	79.00 (16.00)	61.50 (35.00)	
Soil dryness index (%)						<0.001
Mean (SD)	0.23 (1.23)	0.68 (3.19)	10.11 (12.38)	0.95 (3.11)	2.77 (7.51)	Kruskal-Wallis
Median (IQR)	0.00 (0.00)	0.00 (0.00)	6.00 (14.00)	0.00 (0.00)	0.00 (0.00)	

Table S13 Total water input and field water condition in the rice fields in wet and dry seasons in Burkina Faso (2018-2020)

	Wet season	Dry season	Overall	Test statistic
Total water input (m^3/ha)				0.088
Mean (SD)	4620.06 (1760.55)	4577.32 (2661.43)	4601.67 (2190.49)	Wilcoxon rank-sum
Median (IQR)	4510.75 (2522.75)	3893.50 (2613.88)	4251.70 (2745.75)	
Soil flooding index (%)				<0.001
Mean (SD)	65.02 (21.23)	53.65 (22.40)	60.24 (22.41)	Wilcoxon rank-sum
Median (IQR)	67.00 (38.50)	53.00 (34.50)	61.50 (35.00)	
Soil dryness index (%)				<0.001
Mean (SD)	2.53 (8.52)	3.10 (5.84)	2.77 (7.51)	Wilcoxon rank-sum
Median (IQR)	0.00 (0.00)	0.00 (4.00)	0.00 (0.00)	

Table S14 Productivity and sustainability indicators of smallholder rice farming production across irrigation schemes in Burkina Faso (2018-2020)

	Karfiguela	Kou Valley	Zoungou	Sourou Valley	Overall	Test statistic
Grain yield (Mg/ha)						<0.001
Mean (SD)	4.88 (1.30)	4.70 (1.50)	3.87 (2.32)	5.15 (1.54)	4.55 (1.82)	Kruskal-Wallis
Median (IQR)	4.93 (2.06)	4.72 (1.78)	3.12 (3.49)	5.32 (1.60)	4.50 (2.57)	
WP (kg grain/m^3 of water)						<0.001
Mean (SD)	1.53 (1.01)	1.38 (0.83)	1.23 (0.86)	0.94 (0.44)	1.31 (0.86)	Kruskal-Wallis
Median (IQR)	1.05 (1.40)	1.21 (0.86)	1.14 (1.00)	0.86 (0.50)	1.06 (0.90)	
PFPN (kg grain/kg N)						0.022
Mean (SD)	45 (21)	43 (43)	41.73 (36.49)	38.83 (17.30)	43 (34)	Kruskal-Wallis
Median (IQR)	43 (23)	37 (21)	33.30 (36.60)	36.80 (23.10)	37 (27)	
PFPP (kg grain/kg P)						<0.001
Mean (SD)	234 (82)	368 (219)	260.53 (179.14)	366.25 (178.59)	305 (187)	Kruskal-Wallis
Median (IQR)	228 (108)	329 (157)	230.20 (198.75)	360.60 (147.80)	276 (166)	
PFPK (kg grain/kg K)						0.002
Mean (SD)	207 (69)	201 (118)	188 (128)	238 (163)	204 (121)	Kruskal-Wallis
Median (IQR)	206 (91)	180 (91)	164 (145)	207 (101)	187 (111)	

Table S15 Productivity and sustainability indicators of smallholder rice farming production in wet and dry seasons in Burkina Faso (2018-2020)

	Wet season	Dry season	Test statistic
Grain yield (Mg/ha)			<0.001
Mean (SD)	5.32 (1.56)	3.73 (1.73)	Wilcoxon rank-sum
Median (IQR)	5.38 (1.93)	3.45 (2.37)	
WP (kg grain/m^3 of water)			0.004
Mean (SD)	1.40 (0.86)	1.19 (0.83)	Wilcoxon rank-sum
Median (IQR)	1.14 (0.96)	0.98 (0.96)	
PFPN (kg grain/kg N)			<0.001
Mean (SD)	49 (27)	36 (38)	Wilcoxon rank-sum
Median (IQR)	44 (25)	30 (21)	
PFPP (kg grain/kg P)			0.002
Mean (SD)	322 (165)	286 (206)	Wilcoxon rank-sum
Median (IQR)	293 (1460)	249 (198)	
PFPK (kg grain/kg K)			<0.001
Mean (SD)	229 (127)	177 (109)	Wilcoxon rank-sum
Median (IQR)	209 (106)	164 (103)	

Table S16 Socio-economic characteristics of household's head managing rice fields from various yielding categories in the wet season in Burkina Faso (2018-2020)

	Low-yielding	Moderate-yielding	High-yielding	Test statistic
(Row %)(Col %)				
Gender				0.09
Female	3 (27%) (14%)	6 (55%) (4%)	2 (18%) (10%)	Chi-square
Male	18 (9%) (86%)	155 (81%) (96%)	19 (10%) (90%)	
Education				0.615
Illiterate	10 (9%) (48%)	90 (79%) (56%)	14 (12%) (67%)	Chi-square
Primary school	8 (11%) (38%)	59 (82%) (37%)	5 (7%) (24%)	
Secondary school	3 (18%) (14%)	12 (71%) (7%)	2 (12%) (10%)	
Number of farm workers				0.136
Mean (SD)	5 (3)	7 (5)	9 (10)	Kruskal-Wallis
Median (IQR)	5 (3)	6 (4)	7 (4)	
Rice field size (ha)				0.773
Mean (SD)	1 (0)	1 (1)	1 (0)	Kruskal-Wallis
Median (IQR)	0 (1)	0 (1)	0 (1)	
Herd size (TLU)				0.237
Mean (SD)	3 (3)	6 (17)	6 (10)	Kruskal-Wallis
Median (IQR)	2 (2)	2 (5)	3 (4)	
Number of farm machines				0.351
Mean (SD)	0 (0)	0 (1)	0 (1)	Kruskal-Wallis
Median (IQR)	0 (0)	0 (0)	0 (1)	
Rice farming experience (Years)				0.118
Mean (SD)	22 (12)	24 (13)	30 (14)	Kruskal-Wallis
Median (IQR)	22 (9)	23 (18)	30 (18)	
Main income source				0.109
Agriculture	18 (9%) (86%)	155 (80%) (96%)	20 (10%) (95%)	Chi-square
Other	3 (30%) (14%)	6 (60%) (4%)	1 (10%) (5%)	
Trade	-	-	-	

Low-yielding, Moderate-yielding, and High-yielding represent the Bottom 10%, Middle 80%, and Top 10% of the sample, respectively.

SD: Standard deviation. IQR: Interquartile range

Table S17 Socio-economic characteristics of household's head managing rice fields from various yielding categories in the dry season in Burkina Faso (2018-2020)

	Low-yielding	Moderate-yielding	High-yielding	Test statistic
(Row %)(Col %)				
Gender				0.664
Female	6 (11%) (30%)	45 (82%) (30%)	4 (7%) (20%)	Chi-square
Male	14 (10%) (70%)	107 (78%) (70%)	16 (12%) (80%)	
Education				0.793
Illiterate	14 (11%) (70%)	101 (77%) (66%)	16 (12%) (80%)	Chi-square
Primary school	5 (10%) (25%)	43 (84%) (28%)	3 (6%) (15%)	
Secondary school	1 (10%) (5%)	8 (80%) (5%)	1 (10%) (5%)	
Number of farm workers				0.776
Mean (SD)	7 (4)	7 (6)	7 (2)	Kruskal-Wallis
Median (IQR)	6 (6)	6 (4)	6 (2)	
Rice field size (ha)				0.808
Mean (SD)	1 (1)	1 (1)	1 (1)	Kruskal-Wallis
Median (IQR)	0 (1)	0 (1)	0 (1)	
Herd size (TLU)				0.208
Mean (SD)	3 (3)	4 (8)	4 (3)	Kruskal-Wallis
Median (IQR)	2 (2)	2 (4)	4 (5)	
Number of farm machines				0.887
Mean (SD)	0 (1)	0 (1)	0 (2)	Kruskal-Wallis
Median (IQR)	0 (0)	0 (0)	0 (0)	
Rice farming experience (Years)				0.556
Mean (SD)	20 (13)	19 (12)	16 (11)	Kruskal-Wallis
Median (IQR)	21 (22)	20 (18)	14 (11)	
Main income source				0.639
Agriculture	16 (10%) (80%)	131 (79%) (86%)	19 (11%) (95%)	Chi-square
Other	2 (20%) (10%)	8 (80%) (5%)	0 (0%) (0%)	
Trade	2 (12%) (10%)	13 (81%) (9%)	1 (6%) (5%)	

Low-yielding, Moderate-yielding, and High-yielding represent the Bottom 10%, Middle 80%, and Top 10% of the sample, respectively.

SD: Standard deviation. IQR: Interquartile range

Table S18 Soil fertility attributes of fields from different rice-yielding categories in the wet season in Burkina Faso (2018-2020)

	Low-yielding	Moderate-yielding	High-yielding	Test statistic
pH H_2O				0.683
Mean (SD)	6.2 (0.9)	6.0 (0.9)	6.1 (0.8)	Kruskal-Wallis
Median (IQR)	6.0 (0.9)	5.8 (0.9)	6.1 (1.1)	
Total N				0.839
Mean (SD)	0.077 (0.030)	0.073 (0.027)	0.070 (0.026)	Kruskal-Wallis
Median (IQR)	0.073 (0.036)	0.071 (0.035)	0.068 (0.038)	
Total C				0.693
Mean (SD)	0.909 (0.323)	0.870 (0.324)	0.827 (0.305)	Kruskal-Wallis
Median (IQR)	0.810 (0.383)	0.853 (0.394)	0.762 (0.435)	
C:N ratio				0.837
Mean (SD)	12 (1)	12 (1)	12 (1)	Kruskal-Wallis
Median (IQR)	12 (2)	12 (2)	12 (2)	
Available P (Bray-2)				0.516
Mean (SD)	9.4 (8.3)	10.6 (10.1)	16.0 (21.5)	Kruskal-Wallis
Median (IQR)	7.5 (9.5)	7.7 (8.7)	6.8 (12.2)	
Clay content (%)				0.244
Mean (SD)	25 (9)	22 (8)	24 (8)	Kruskal-Wallis
Median (IQR)	25 (14)	22 (11)	27 (9)	
Silt content (%)				0.873
Mean (SD)	13 (5)	13 (5)	13 (6)	Kruskal-Wallis
Median (IQR)	14 (6)	13 (8)	14 (9)	
Sand content (%)				0.271
Mean (SD)	63 (12)	65 (11)	63 (12)	Kruskal-Wallis
Median (IQR)	60 (11)	65 (13)	59 (16)	

Low-yielding, Moderate-yielding, and High-yielding represent the Bottom 10%, Middle 80%, and Top 10% of the sample, respectively.

SD: Standard deviation. IQR: Interquartile range

Table S19 Soil fertility attributes of fields from different rice-yielding categories in the dry season in Burkina Faso (2018-2020)

	Low-yielding	Moderate-yielding	High-yielding	Test statistic
pH H_2O				0.391
Mean (SD)	6.3 (1.1)	6.5 (1.1)	6.1 (0.7)	Kruskal-Wallis
Median (IQR)	6.2 (1.7)	6.1 (2.0)	6.0 (0.6)	
Total N				**0.017**
Mean (SD)	0.084 (0.041)	0.079 (0.033)	0.102 (0.033)	Kruskal-Wallis
Median (IQR)	0.071 (0.030)	0.071 (0.042)	0.108 (0.048)	
Total C				0.096
Mean (SD)	1.077 (0.476)	1.006 (0.393)	1.234 (0.421)	Kruskal-Wallis
Median (IQR)	0.859 (0.472)	0.957 (0.568)	1.379 (0.599)	
C:N ratio				0.239
Mean (SD)	13 (2)	13 (2)	12 (1)	Kruskal-Wallis
Median (IQR)	13 (2)	13 (2)	12 (2)	
Available P (Bray-1)				0.539
Mean (SD)	13 (13)	11 (11)	13 (9)	Kruskal-Wallis
Median (IQR)	7 (12)	8 (12)	11 (11)	
Clay content (%)				0.533
Mean (SD)	27 (10)	25 (8)	26 (10)	Kruskal-Wallis
Median (IQR)	24 (12)	26 (12)	26 (11)	
Silt content (%)				0.899
Mean (SD)	16 (7)	15 (6)	15 (5)	Kruskal-Wallis
Median (IQR)	16 (5)	15 (9)	16 (6)	
Sand content (%)				0.471
Mean (SD)	57 (15)	60 (13)	59 (14)	Kruskal-Wallis
Median (IQR)	58 (14)	60 (17)	58 (19)	

Low-yielding, Moderate-yielding, and High-yielding represent the Bottom 10%, Middle 80%, and Top 10% of the sample, respectively.

SD: Standard deviation. IQR: Interquartile range

Table S20 Production inputs in various rice-yielding categories in the wet season in irrigated lowland systems in Burkina Faso (2018-2020)

	Low-yielding	Moderate-yielding	High-yielding	Test statistic
Growth duration of the variety				0.515
Mean (SD)	122 (10)	119 (11)	121 (9)	Kruskal-Wallis
Median (IQR)	120 (15)	118 (5)	118 (5)	
Age of the seedlings at transplanting (days)				0.476
Mean (SD)	26 (13)	23 (7)	21 (5)	Kruskal-Wallis
Median (IQR)	21 (6)	21 (6)	21 (6)	
Number of seedlings per hill				**0.036**
Mean (SD)	3 (1)	3 (1)	2 (1)	Kruskal-Wallis
Median (IQR)	3 (2)	2 (1)	2 (2)	
Weeding frequency				0.459
Mean (SD)	2 (1)	3 (1)	2 (1)	Kruskal-Wallis
Median (IQR)	2 (1)	2 (1)	2 (2)	
Application of organic manure				**0.015**
No	13 (8%) (62%)	130 (84%) (81%)	12 (8%) (57%)	Chi-square
Yes	8 (17%) (38%)	31 (65%) (19%)	9 (19%) (43%)	
Inorganic fertilizer application frequency				0.436
Mean (SD)	2 (1)	3 (1)	3 (1)	Kruskal-Wallis
Median (IQR)	2 (1)	3 (1)	3 (1)	
N application rate (kg N/ha)				0.06
Mean (SD)	144 (71)	123 (40)	112 (29)	Kruskal-Wallis
Median (IQR)	136 (34)	121 (38)	119 (30)	
P application rate (kg P/ha)				0.326
Mean (SD)	19 (13)	19 (8)	18 (8)	Kruskal-Wallis
Median (IQR)	13 (7)	20 (7)	20 (7)	
K application rate (kg K/ha)				0.626
Mean (SD)	26 (16)	26 (10)	23 (9)	Kruskal-Wallis
Median (IQR)	25 (4)	25 (6)	23 (2)	
Birds control				0.402
No	18 (12%) (86%)	116 (78%) (72%)	15 (10%) (71%)	Chi-square
Yes	3 (6%) (14%)	45 (83%) (28%)	6 (11%) (29%)	
Irrigation frequency				0.142
Mean (SD)	5 (3)	6 (3)	4 (3)	Kruskal-Wallis
Median (IQR)	5 (3)	5 (3)	4 (4)	
Irrigation water input (m3/ha)				0.441
Mean (SD)	1060 (832)	1217 (1082)	1118 (1555)	Kruskal-Wallis
Median (IQR)	805 (1081)	948 (1275)	690 (1292)	
Total water input (m^3/ha)				0.499
Mean (SD)	4802 (1956)	4641 (1709)	4285 (1973)	Kruskal-Wallis
Median (IQR)	4014 (2438)	4622 (2628)	4180 (2718)	
Soil flooding index (%)				0.338
Mean (SD)	67 (22)	64 (21)	71 (22)	Kruskal-Wallis
Median (IQR)	72 (24)	65 (37)	63 (35)	
Soil dryness index (%)				0.88
Mean (SD)	3 (10)	2 (8)	4 (11)	Kruskal-Wallis
Median (IQR)	0 (0)	0 (0)	0 (0)	

Low-yielding, Moderate-yielding, and High-yielding represent the Bottom 10%, Middle 80%, and Top 10% of the sample, respectively.
Significant effects ($p < 0.05$) are indicated in bold.
SD: Standard deviation.
IQR: Interquartile range

Table S21 Production inputs in various rice-yielding categories in the dry season in irrigated lowland systems Burkina Faso (2018-2020)

	Low-yielding	Moderate-yielding	High-yielding	Test statistic
Growth duration of the variety				0.691
Mean (SD)	116 (13)	115 (13)	117 (12)	Kruskal-Wallis
Median (IQR)	115 (9)	115 (20)	115 (5)	
Age of the seedlings at transplanting (days)				0.474
Mean (SD)	25 (13)	25 (9)	23 (9)	Kruskal-Wallis
Median (IQR)	18 (16)	24 (10)	21 (11)	
Number of seedlings per hill				0.831
Mean (SD)	2 (1)	2 (1)	2 (1)	Kruskal-Wallis
Median (IQR)	2 (1)	2 (1)	2 (1)	
Weeding frequency				0.275
Mean (SD)	2 (1)	2 (1)	2 (1)	Kruskal-Wallis
Median (IQR)	2 (0)	2 (1)	2 (1)	
Application of organic manure				0.963
No	16 (11%) (80%)	117 (79%) (78%)	16 (11%) (80%)	Chi-square
Yes	4 (10%) (20%)	33 (80%) (22%)	4 (10%) (20%)	
Inorganic fertilizer application frequency				**0.05**
Mean (SD)	2 (1)	3 (1)	3 (1)	Kruskal-Wallis
Median (IQR)	2 (1)	3 (1)	2 (1)	
N application rate (kg N/ha)				0.108
Mean (SD)	101 (63)	132 (53)	122 (50)	Kruskal-Wallis
Median (IQR)	120 (86)	128 (48)	118 (74)	
P application rate (kg P/ha)				0.759
Mean (SD)	14 (9)	16 (8)	15 (6)	Kruskal-Wallis
Median (IQR)	13 (12)	16 (10)	16 (9)	
K application rate (kg K/ha)				0.494
Mean (SD)	22 (14)	24 (12)	26 (10)	Kruskal-Wallis
Median (IQR)	23 (14)	23 (14)	23 (13)	
Birds control				0.602
No	9 (9%) (45%)	82 (82%) (54%)	9 (9%) (45%)	Chi-square
Yes	11 (12%) (55%)	70 (76%) (46%)	11 (12%) (55%)	
Irrigation frequency				0.236
Mean (SD)	15 (5)	16 (5)	18 (6)	Kruskal-Wallis
Median (IQR)	16 (6)	16 (9)	18 (10)	
Irrigation water input (m3/ha)				0.288
Mean (SD)	4256 (3828)	3608 (2222)	5435 (4761)	Kruskal-Wallis
Median (IQR)	2580 (2480)	2834 (3416)	4190 (3987)	
Total water input (m^3/ha)				0.244
Mean (SD)	5061 (3494)	4282 (1942)	5925 (4626)	Kruskal-Wallis
Median (IQR)	3853 (2338)	3781 (2606)	4592 (3165)	
Soil flooding index (%)				**0.027**
Mean (SD)	37 (24)	54 (22)	60 (22)	Kruskal-Wallis
Median (IQR)	32 (31)	51 (34)	64 (30)	
Soil dryness index (%)				0.111
Mean (SD)	8 (10)	3 (5)	3 (4)	Kruskal-Wallis
Median (IQR)	3 (10)	0 (3)	0 (4)	

Low-yielding, Moderate-yielding, and High-yielding represent the Bottom 10%, Middle 80%, and Top 10% of the sample, respectively.
Significant effects ($p < 0.05$) are indicated in bold.
SD: Standard deviation.
IQR: Interquartile range

Appendix C: Supplementary material for Chapter 4

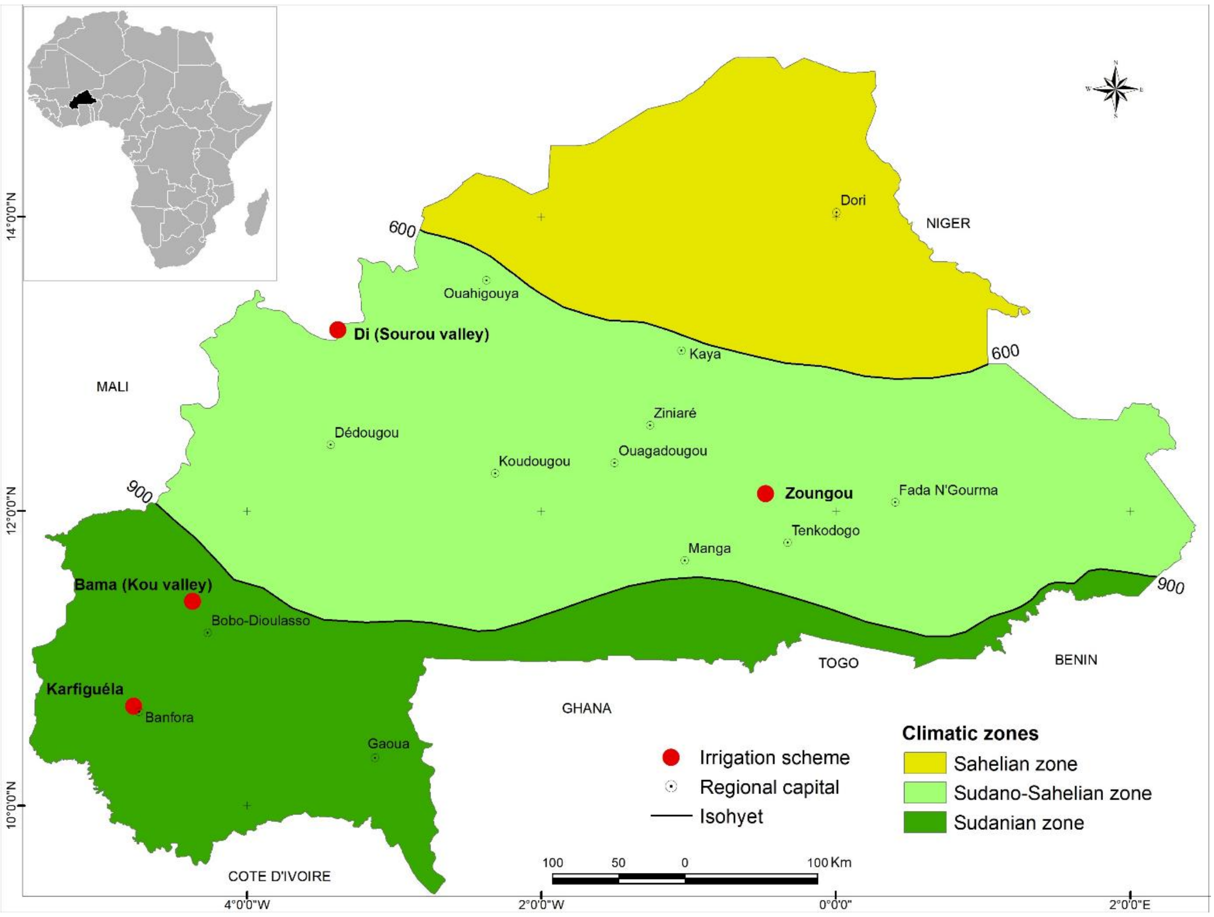

Fig. S1. Map of Burkina Faso showing climatic zones delimitation and study sites

Table S1 Sites, climatic zones, and number of on-farm trials per season and per year

Irrigation scheme	Climatic zone	2018		2019		Total
		Dry season	Wet season	Dry season	Wet season	
Karfiguela	Sudanian	0	6	13	25	44
Kou Valley	Sudanian	12	9	10	4	35
Zoungou	Sudano-sahelian	0	4	13	7	24
Sourou Valley	Sudano-sahelian	0	0	28	23	51

Table S2 Overview of the data collected

N°	Explanatory variables	Units	Variable type	Modalities	Data collection method
	Weather conditions				
1	Cumulative solar radiation	kWh m^{-2}	Quantitative		aWhere data platform
2	Average maximum air temperature	°C	Quantitative		aWhere data platform
3	Average minimum air temperature	°C	Quantitative		aWhere data platform
4	Average relative air humidity	%	Quantitative		aWhere data platform
5	Rainfall water volume	mm	Quantitative		aWhere data platform
	Irrigation scheme and terrain attributes				
6	Position within the irrigation scheme		Categorical	Head-end; Middle reaches; Tail-end	Field survey & observation
7	Access to the irrigation water		Categorical	Easy; Intermediate; Difficult	Field survey & observation
	Soil fertility				
8	pH H_2O	-	Quantitative		Laboratory analyses
9	Total N	%	Quantitative		Laboratory analyses$
10	Total C	%	Quantitative		Laboratory analyses$
11	Available P (Bray-2)	mg kg^{-1}	Quantitative		Laboratory analyses
12	Clay content	%	Quantitative		Laboratory analyses$
13	Sand content	%	Quantitative		Laboratory analyses$
	Genetic factors of the planting material				
14	Growth duration of the variety	days	Quantitative		Literature review
15	Yield potential of the variety	Mg ha^{-1}	Quantitative		Literature review
16	Variety type		Categorical	Tropical *japonica*; *indica*; Lowland NERICA	Literature review
	Crop management practices				
17	Source of the seeds		Categorical	Non-certified; Certified	Field survey & observation
18	Straw management		Categorical	Removing; Burning; Grazing *in-situ*; Mulching; Incorporation	Field survey & observation
19	Residue management		Categorical	Removing; Burning; Mulching; Incorporation	Field survey & observation
20	Tillage method		Categorical	No-tillage; Manual; Animal traction; Mechanical	Field survey & observation
21	Land levelling		Categorical	Poor; Good	Field survey & observation
22	Sowing date in the nursery		Quantitative		Field survey & observation

23	Age of the seedlings at transplanting	days	Quantitative		Field survey & observation
24	Planting density	hills m^{-2}	Quantitative		Field survey & observation
25	Number of seedlings per hill		Quantitative		Field survey & observation
26	Weeding frequency		Quantitative		Field survey & observation
27	Herbicide use		Categorical	No; Yes	Field survey & observation
28	Mechanical weeding		Categorical	No; Yes	Field survey & observation
29	Application of organic manure in the main field		Categorical	No; Yes	Field survey & observation
30	Application of mineral fertilizer in the nursery		Quantitative	No; Yes	Field survey & observation
31	Split of N fertilizer application		Quantitative		Field survey & observation
32	N application rate	kg N ha^{-1}	Quantitative		Field survey & observation
33	P application rate	kg P ha^{-1}	Quantitative		Field survey & observation
34	K application rate	kg K ha^{-1}	Quantitative		Field survey & observation
35	Insect and disease control frequency		Quantitative		Field survey & observation
36	Bird control		Categorical	No; Yes	Field survey & observation
37	Irrigation frequency		Quantitative		Field survey & observation
38	Irrigation water input	m^3 ha^{-1}	Quantitative		Field survey & observation
	Pest incidence				
39	Weed infestation above the canopy at flowering		Quantitative	0 = no weed; 1 = weed cover less than or equal to 10% of ground cover; 2 = weed cover more than 10% and less than or equal to 30% of ground cover; 3 = weed cover more than 30%; 4 = Weed cover more than 60%	Field survey & observation
40	Weed infestation below the canopy at flowering		Quantitative	0 = no weed; 1 = weed cover less than or equal to 10% of ground cover; 2 = weed cover more than 10% and less than or equal to 30% of ground cover; 3 = weed cover more than 30%; 4 = Weed cover more than 60%	Field survey & observation
41	Insect damage at maturity		Categorical	No; Mild; Moderate	Field survey & observation
42	Disease damage at maturity		Categorical	No; Mild; Moderate; Severe	Field survey & observation
	Field water conditions and total water input				
43	Total volume of water input (Rainfall + Irrigation)	m^3 ha^{-1}	Quantitative		Field survey & aWhere
44	Soil flooding index	%	Quantitative		Field survey & observation
45	Soil dryness index	%	Quantitative		Field survey & observation

$ Clay and sand contents were assessed using the Robinson pipette method, and total N and C contents by dry combustion

Table S3 Information on the planting material

Variety	Varietal type	Growth duration of the variety	Growth duration category	Potential yield (Mg/ha)	Source *
Orylux6	Indica	100	Short duration	6.5	Comité nationale des semences (2014)
TS2	Indica	120	Medium duration	6.5	Comité nationale des semences (2014)
IET 2885	Indica	130	Long duration	7.0	Comité nationale des semences (2014)
Gambiaka	Indica	140	Long duration	5.0	Comité nationale des semences (2014)
FKR19 (TOX 728-1)	Tropical japonica	115	Medium duration	6.0	Comité nationale des semences (2014)
Samangrin (TOX 729)	Tropical japonica	95	Short duration	6.0	Comité nationale des semences (2014)
FKR62N	Lowland NERICA	118	Medium duration	7.0	Comité nationale des semences (2014)
FKR60N	Lowland NERICA	115	Medium duration	7.0	Comité nationale des semences (2014)

* Comité nationale des semences (2014) Catalogue national des espèces et variétés agricoles du Burkina Faso. Ouagadougou, Burkina Faso. 81 p.
http://fagri-burkina.com/Docs/BF_2014_Catalogue_especes_varietes_agricoles_BF_Final.pdf

Table S4 Weather conditions in the rice fields during the wet season across the studied irrigation schemes

	Karfiguela (n=31)	Kou Valley (n=13)	Zoungou (n=11)	Sourou Valley (n=23)	Overall (n = 78)
Cumulative solar radiation (kWh m^{-2})					
Mean (SD)	523 (52)	558 (37)	617 (60)	660 (66)	583 (81)
Median (IQR)	519 (63)	558 (26)	642 (100)	680 (60)	558 (131)
Average maximum temperature (°C)					
Mean (SD)	32 (0)	33 (1)	34 (1)	35 (1)	34 (1)
Median (IQR)	32 (1)	34 (1)	34 (1)	35 (0)	34 (2)
Average minimum temperature (°C)					
Mean (SD)	23 (0)	23 (0)	24 (0)	24 (0)	23 (0)
Median (IQR)	23 (0)	23 (1)	24 (0)	24 (0)	23 (1)
Average relative air humidity (%)					
Mean (SD)	75 (3)	68 (4)	64 (5)	63 (4)	69 (7)
Median (IQR)	75 (4)	67 (5)	65 (6)	65 (5)	69 (10)
Rainfall volume (mm)					
Mean (SD)	496 (148)	390 (123)	280 (92)	230 (59)	370 (163)
Median (IQR)	537 (137)	363 (149)	321 (158)	254 (20)	321 (283)

SD: Standard deviation
IQR: Interquartile range

Table S5 Weather conditions in the rice fields during the dry season across the studied irrigation schemes

	Karfiguela (n=13)	Kou Valley (n=22)	Zoungou (n=13)	Sourou Valley (n=28)	Overall (n=76)
Cumulative solar radiation (kWh m^{-2})					
Mean (SD)	481 (91)	607 (94)	611 (42)	897 (86)	678 (186)
Median (IQR)	485 (126)	602 (112)	606 (50)	898 (91)	636 (298)
Average maximum temperature (°C)					
Mean (SD)	36 (0)	38 (1)	38 (0)	37 (0)	37 (1)
Median (IQR)	36 (1)	38 (2)	38 (0)	37 (0)	37 (1)
Average minimum temperature (°C)					
Mean (SD)	27 (0)	26 (1)	25 (0)	25 (1)	26 (1)
Median (IQR)	27 (0)	26 (1)	25 (0)	25 (1)	26 (2)
Average relative air humidity (%)					
Mean (SD)	59 (3)	38 (4)	23 (1)	29 (2)	37 (13)
Median (IQR)	59 (3)	38 (6)	22 (1)	29 (4)	33 (17)
Rainfall volume (mm)					
Mean (SD)	189 (26)	53 (29)	20 (18)	25 (6)	70 (70)
Median (IQR)	172 (36)	46 (31)	33 (37)	27 (2)	37 (73)

SD: Standard deviation
IQR: Interquartile range

Table S6 Farm management practices in the rice fields in wet and dry seasons in Burkina Faso (2018-2019)

	Wet season (n = 78)	Dry season (n = 76)	Overall	Test statistic
(Row %)(Col %)				
Growth duration of the variety (days)				Wilcoxon rank-sum
Mean (SD)	124 (12)	122 (15)	123 (14)	0.453
Median (IQR)	120 (22)	120 (25)	120 (25)	
Source of seeds				Chi-square
Certified	38 (69%) (49%)	17 (31%) (21%)	55 (100%) (34%)	**<0.001**
Non-certified	40 (38%) (51%)	65 (62%) (79%)	105 (100%) (66%)	
Straw management				Chi-square
Removing from the field	32 (42%) (41%)	44 (58%) (54%)	76 (100%) (48%)	0.268
Burning	19 (54%) (24%)	16 (46%) (20%)	35 (100%) (22%)	
Grazed by animals	8 (42%) (10%)	11 (58%) (13%)	19 (100%) (12%)	
Mulching in the field	13 (68%) (17%)	6 (32%) (7%)	19 (100%) (12%)	
Incorporation in the field	6 (55%) (8%)	5 (45%) (6%)	11 (100%) (7%)	
Residue management				Chi-square
Removing from the field	8 (24%) (10%)	26 (76%) (32%)	34 (100%) (21%)	**0.005**
Burning	6 (43%) (8%)	8 (57%) (10%)	14 (100%) (9%)	
Mulching in the field	7 (70%) (9%)	3 (30%) (4%)	10 (100%) (6%)	
Incorporation in the field	57 (56%) 73%)	45 (44%) (55%)	102 (100%) (64%)	
Tillage method				Chi-square
No-tillage	1 (100%) (1%)	0 (0%) (0%)	1 (100%) (1%)	**0.019**
Manual	2 (15%) (3%)	11 (85%) (13%)	13 (100%) (8%)	
Animal	56 (56%) (72%)	44 (44%) (54%)	100 (100%) (62%)	
Mechanical	19 (41%) (24%)	27 (59%) (33%)	46 (100%) (29%)	
Land leveling				Chi-square
Poor	41 (61%) (53%)	26 (39%) (32%)	67 (100%) (42%)	**0.012**
Good	37 (40%) (47%)	56 (60%) (68%)	93 (100%) (58%)	
Age of the seedlings at transplanting (days)				Wilcoxon rank-sum
Mean (SD)	25 (8)	29 (11)	27 (10)	**0.039**
Median (IQR)	22 (10)	26 (17)	25 (11)	
Planting density (hills m^{-2})				Wilcoxon rank-sum
Mean (SD)	23 (8)	26 (8)	25 (8)	**<0.001**
Median (IQR)	25 (8)	25 (10)	25 (6)	
Number of seedlings per hill				Wilcoxon rank-sum

Mean (SD)	3 (1)	2 (1)	3 (1)	0.146
Median (IQR)	3 (1)	2 (1)	2 (1)	
Weeding frequency				Wilcoxon rank-sum
Mean (SD)	3 (1)	2 (1)	2 (1)	0.551
Median (IQR)	3 (1)	2 (1)	2 (1)	
Herbicide use				Chi-square
No	3 (10%) (4%)	28 (90%) (34%)	31 (100%) (19%)	**<0.001**
Yes	75 (58%) (96%)	54 (42%) (66%)	129 (100%) (81%)	
Mechanical weeding				Chi-square
No	61 (50%) (78%)	61 (50%) (74%)	122 (100%) (76%)	0.703
Yes	17 (45%) (22%)	21 (55%) (26%)	38 (100%) (24%)	
Application of organic manure				Chi-square
No	62 (48%) (79%)	68 (52%) (83%)	130 (100%) (81%)	0.723
Yes	16 (53%) (21%)	14 (47%) (17%)	30 (100%) (19%)	
Application of mineral fertilizer in nursery				Chi-square
No	65 (51%) (83%)	62 (49%) (76%)	127 (100%) (79%)	0.312
Yes	13 (39%) (17%)	20 (61%) (24%)	33 (100%) (21%)	
Mineral fertilizer application frequency				Wilcoxon rank-sum
Mean (SD)	3 (1)	3 (1)	3 (1)	0.851
Median (IQR)	3 (1)	3 (1)	3 (1)	
N application rate (kg N ha^{-1})				Wilcoxon rank-sum
Mean (SD)	121 (35)	134 (49)	128 (43)	0.101
Median (IQR)	121 (35)	130 (58)	122 (50)	
P application rate (kg P ha^{-1})				Wilcoxon rank-sum
Mean (SD)	19 (6)	16 (7)	18 (7)	**0.003**
Median (IQR)	20 (6)	16 (9)	20 (7)	
K application rate (kg K ha^{-1})				Wilcoxon rank-sum
Mean (SD)	25 (9)	25 (10)	25 (9)	**0.776**
Median (IQR)	23 (4)	23 (10)	23 (6)	
Insect and disease control frequency				Wilcoxon rank-sum
Mean (SD)	1 (1)	1 (1)	1 (1)	0.06
Median (IQR)	1 (2)	1 (1)	1 (2)	
Bird control				Chi-square
No	56 (67%) (72%)	28 (33%) (34%)	84 (100%) (52%)	**<0.001**
Yes	22 (29%) (28%)	54 (71%) (66%)	76 (100%) (48%)	

SD: Standard deviation

Significant effects ($p < 0.05$) are indicated in bold.

Table S7 Sowing dates (mean + standard deviation) in irrigation schemes in Burkina Faso in wet and dry seasons 2018-2019

	Karfiguela	Kou Valley	Zoungou	Sourou Valley
Sowing date in the nursery				
In wet season	21 July ± 15 days	7 August ± 11 days	24 July ± 17 days	13 July ± 11 days
In dry season	7 March ± 12 days	13 January ± 19 days	31 December ± 8 days	11 December ± 11 days

Table S8 Productivity indicators of smallholder rice farming production in wet and dry seasons in Burkina Faso (2018-2019)

	Wet season (n = 78)	Dry season (n = 76)	Overall	Test statistic
Grain yield (Mg ha^{-1})				Wilcoxon rank-sum
Mean (SD)	5.21 (1.45)	4.54 (1.81)	4.88 (1.67)	**<0.001**
Median (IQR)	5.30 (1.90)	4.27 (2.11)	4.75 (2.20)	
Total water productivity (kg grain m^{-3} of water)				Wilcoxon rank-sum
Mean (SD)	1.12 (0.51)	1.29 (0.92)	1.20 (0.74)	0.712
Median (IQR)	0.96 (0.64)	1.02 (0.86)	0.97 (0.78)	
Irrigation water productivity (kg grain m^{-3} of water)				Wilcoxon rank-sum
Mean (SD)	8.16 (7.79)	1.78 (1.53)	5.00 (6.48)	**<0.001**
Median (IQR)	4.58 (9.70)	1.32 (1.55)	2.43 (4.19)	
Partial factor productivity of N (kg grain kg^{-1} N)				Wilcoxon rank-sum
Mean (SD)	50 (35)	36 (17)	43 (28)	**<0.001**
Median (IQR)	44 (27)	34 (17)	39 (25)	
Partial factor productivity of P (kg grain kg^{-1} P)				Wilcoxon rank-sum
Mean (SD)	295 (117)	328 (165)	311 (144)	0.179
Median (IQR)	271 (129)	300 (199)	276 (162)	
Partial factor productivity of K (kg grain kg^{-1} K)				Wilcoxon rank-sum
Mean (SD)	219 (84)	193 (83)	206 (85)	**0.003**
Median (IQR)	208 (98)	184 (90)	194 (93)	

SD: Standard deviation
Significant effects ($p < 0.05$) are indicated in bold.

Table S9 Productivity indicators of smallholder rice farming production across the studied irrigation schemes in Burkina Faso (2018-2019)

	Karfiguela	Kou Valley	Zoungou	Sourou Valley	Overall	Test statistic
Grain yield (Mg ha^{-1})						1-way ANOVA
Mean (SD)	4.78 (1.09)	4.52 (1.91)	4.75 (2.10)	5.27 (1.62)	4.88 (1.67)	**0.024**
Median (IQR)	4.77 (1.60)	4.23 (2.09)	4.36 (3.34)	5.37 (1.96)	4.75 (2.20)	
Water productivity (kg grain m^{-3} of water)						Kruskal-Wallis
Mean (SD)	1.10 (0.52)	1.57 (1.10)	1.12 (0.61)	1.07 (0.57)	1.20 (0.74)	**0.029**
Median (IQR)	0.94 (0.48)	1.16 (1.31)	1.02 (0.93)	0.96 (0.67)	0.97 (0.78)	
Irrigation water productivity (kg grain m^{-3} of water)						Kruskal-Wallis
Mean (SD)	10.57 (8.77)	4.16 (4.14)	3.21 (3.98)	1.61 (1.17)	5.00 (6.48)	**<0.001**
Median (IQR)	8.36 (12.27)	3.00 (2.75)	1.20 (2.97)	1.30 (1.22)	2.43 (4.19)	
Partial factor productivity of N (kg grain kg^{-1} N)						Kruskal-Wallis
Mean (SD)	43 (17)	38 (19)	60 (56)	39 (18)	43 (28)	**0.003**
Median (IQR)	41 (22)	34 (21)	46 (34)	36 (24)	39 (25)	
Partial factor productivity of P (kg grain kg^{-1} P)						Kruskal-Wallis
Mean (SD)	229 (74)	341 (172)	301 (121)	365 (147)	311 (144)	**<0.001**
Median (IQR)	225 (82)	310 (152)	274 (163)	348 (172)	276 (162)	
Partial factor productivity of K (kg grain kg^{-1} K)						Kruskal-Wallis
Mean (SD)	203 (61)	187 (92)	197 (103)	226 (84)	206 (85)	**0.001**
Median (IQR)	197 (65)	180 (83)	182 (105)	216 (99)	194 (93)	

SD: Standard deviation

Significant effects ($p < 0.05$) are indicated in bold.

Table S10 Effect of alternate wetting and drying irrigation (AWD) (%) on yield, water productivity, and irrigation water productivity across the studied irrigation schemes in Burkina Faso (2018-2019)

	Karfiguela (n = 44)	Kou Valley (n = 35)	Zoungou (n = 24)	Sourou Valley (n = 51)	Overall	Test statistic
AWD effect on grain yield (%)						1-way ANOVA
Mean (SD)	5 (13)	5 (24)	5 (16)	7 (19)	6 (18)	0.947
Median (IQR)	4 (5)	1 (16)	6 (19)	3 (24)	3 (15)	
AWD effect on total water productivity (%)						Kruskal-Wallis
Mean (SD)	12 (18)	33 (34)	32 (29)	40 (34)	29 (31)	**<0.001**
Median (IQR)	11 (15)	21 (54)	31 (32)	40 (49)	22 (39)	
AWD effect on irrigation water productivity (%)						Kruskal-Wallis
Mean (SD)	98 (98)	57 (49)	45 (32)	49 (53)	64 (69)	0.138
Median (IQR)	60 (139)	44 (54)	44 (24)	48 (51)	48 (56)	

SD: Standard deviation

Significant effects ($p < 0.05$) are indicated in bold.

Appendix D: Supplementary material for Chapter 5

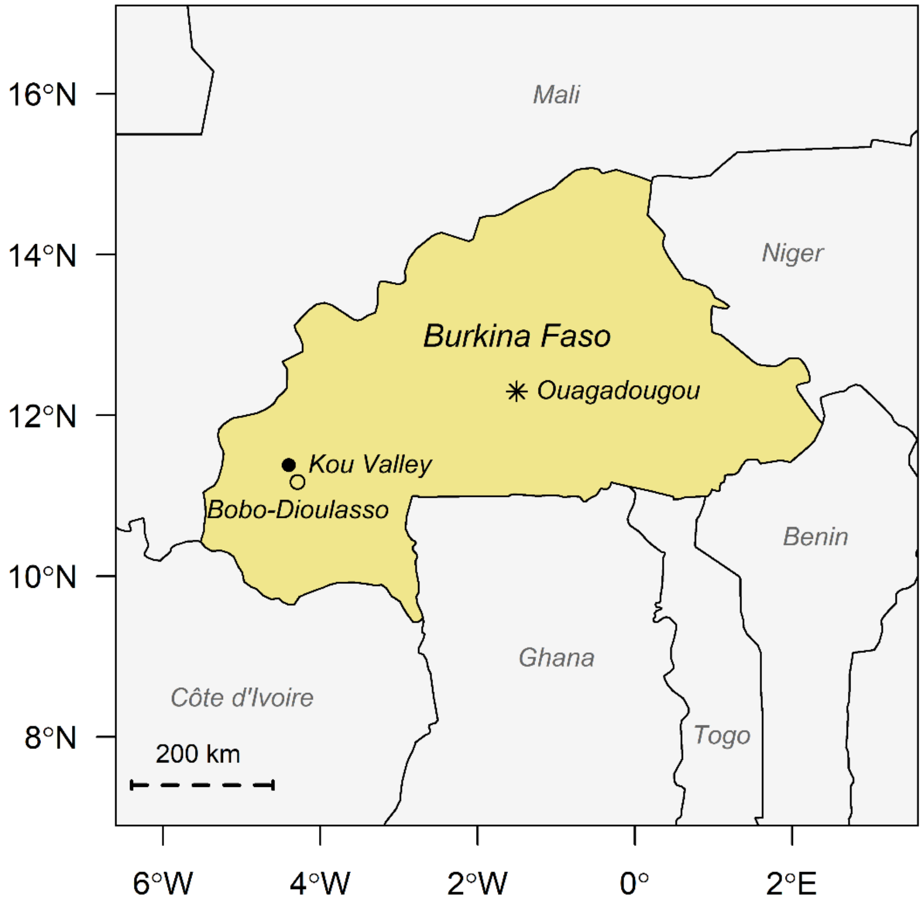

Fig. S1. Location of the study site (Kou Valley irrigation scheme, Burkina Faso)

Table S1 Overview of the primary and secondary data collected

N°	Variables	Units	Type	Modalities	Data collection method
	Weather conditions				
1	Cumulative solar radiation	kWh m^{-2}	Quantitative		aWhere data platform
2	Average maximum air temperature	°C	Quantitative		aWhere data platform
3	Average minimum air temperature	°C	Quantitative		aWhere data platform
4	Average relative air humidity	%	Quantitative		aWhere data platform
5	Cumulative rainfall volume	mm	Quantitative		aWhere data platform
	Soil fertility				
6	pH H_2O	-	Quantitative		Laboratory analyses
7	Total N	%	Quantitative		Laboratory analyses
8	Total C	%	Quantitative		Laboratory analyses
9	Available P (Bray-2)	mg kg^{-1}	Quantitative		Laboratory analyses
10	Clay content	%	Quantitative		Laboratory analyses
11	Silt content	%	Quantitative		Laboratory analyses
12	Sand content	%	Quantitative		Laboratory analyses
	Crop management practices				
13	Source of the seeds		Categorical	Non-certified; Certified	Field survey & observation
14	Straw management		Categorical	Removing from the field; Burning; Grazing *in-situ*; Mulching in the field; Incorporation in the field	Field survey & observation
15	Residue management		Categorical	Removing from the field; Burning; Mulching in the field; Incorporation in the field	Field survey & observation
16	Tillage method		Categorical	No-tillage; Manual; Animal; Mechanical	Field survey & observation
17	Land leveling		Categorical	Poor; Good	Field survey & observation
18	Sowing date in the nursery		Quantitative		Field survey & observation
19	Age of the seedlings at transplanting	days	Quantitative		Field survey & observation
20	Planting density	hills m^{-2}	Quantitative		Field survey & observation
21	Number of seedlings per hill		Quantitative		Field survey & observation
22	Weeding frequency		Quantitative		Field survey & observation
23	Herbicide use		Categorical	No; Yes	Field survey & observation
24	Mechanical weeding		Categorical	No; Yes	Field survey & observation

25	Application of organic manure in the main field		Categorical	No; Yes	Field survey & observation
26	Application of mineral fertilizer in the nursery		Quantitative	No; Yes	Field survey & observation
27	Mineral fertilizer application frequency		Quantitative		Field survey & observation
28	N application rate	kg N ha^{-1}	Quantitative		Field survey & observation
29	P application rate	kg P ha^{-1}	Quantitative		Field survey & observation
30	K application rate	kg K ha^{-1}	Quantitative		Field survey & observation
31	Insect and disease control frequency		Quantitative		Field survey & observation
32	Bird and rat control		Categorical	No; Yes	Field survey & observation
33	Irrigation frequency		Quantitative		Field survey & observation
34	Irrigation water input	m^3 ha^{-1}	Quantitative		Field survey & observation
	Pest incidence				
35	Weed infestation above the canopy at flowering		Quantitative	0 = No weed; 1 = weed cover less than or equal to 10% of ground cover; 2 = weed cover more than 10% and less than or equal to 30% of ground cover; 3 = weed cover more than 30%.	Field survey & observation
36	Weed infestation below the canopy at flowering		Quantitative	0 = No weed; 1 = weed cover less than or equal to 10% of ground cover; 2 = weed cover more than 10% and less than or equal to 30% of ground cover; 3 = weed cover more than 30%.	Field survey & observation
37	Insect damage at maturity		Categorical	No; Mild; Moderate	Field survey & observation
38	Disease damage at maturity		Categorical	No; Mild; Moderate; Severe	Field survey & observation
	Soil water conditions and water input				
39	Total water input	m^3 ha^{-1}	Quantitative		Field survey & aWhere
40	Soil flooding index	%	Quantitative		Field survey & observation
41	Soil dryness index	%	Quantitative		Field survey & observation
	Yield, yield components, and growth parameters				
42	Tiller number from 6 hills at harvest		Quantitative		Field survey & observation
43	Panicle number from 6 hills at harvest		Quantitative		Field survey & observation
44	Grain yield	Mg ha^{-1}	Quantitative		Field survey & observation

Table S2 Weather conditions in the rice fields during the wet and dry seasons in Kou Valley, Burkina Faso (2019-2020)

	Wet season (n = 12)	Dry season (n = 18)	Overall (n = 30)	Test statistic
Cumulative solar radiation (kWh m^{-2})				t-test
Mean (SD)	556 (65)	639 (73)	605 (81)	**0.003**
Average maximum temperature (°C)				t-test
Mean (SD)	34 (0)	37 (1)	36 (2)	**<0.001**
Average minimum temperature (°C)				Wilcoxon rank-sum
Mean (SD)	23 (1)	26 (1)	25 (2)	**<0.001**
Average relative air humidity (%)				t-test
Mean (SD)	64 (5)	39 (4)	49 (13)	**<0.001**
Cumulative rainfall volume (mm)				Wilcoxon rank-sum
Mean (SD)	258 (88)	60 (27)	139 (114)	**<0.001**

SD: Standard deviation
Significant effects ($p < 0.05$) are indicated in bold

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Table S3 Soil fertility attributes of the rice fields during the wet and dry seasons in Kou Valley, Burkina Faso (2019-2020)

	Wet season (n = 12)	Dry season (n = 18)	Overall (n = 30)	Test statistic
pH H_2O				t-test
Mean (SD)	5.7 (0.3)	5.7 (0.2)	5.7 (0.2)	>0.999
Total N (%)				Wilcoxon rank-sum
Mean (SD)	0.085 (0.024)	0.115 (0.035)	0.103 (0.034)	**0.011**
Total C (%)				Wilcoxon rank-sum
Mean (SD)	0.992 (0.249)	1.316 (0.310)	1.186 (0.325)	**0.003**
C:N ratio				t-test
Mean (SD)	12 (1)	12 (1)	12 (1)	0.827
Available P (Bray-1) (mg kg^{-1})				Wilcoxon rank-sum
Mean (SD)	20 (24)	20 (10)	20 (17)	0.138
Clay content (%)				t-test
Mean (SD)	25 (6)	25 (8)	25 (7)	0.883
Silt content (%)				Wilcoxon rank-sum
Mean (SD)	16 (3)	17 (5)	17 (4)	0.831
Sand content (%)				Wilcoxon rank-sum
Mean (SD)	59 (7)	58 (9)	58 (8)	0.915

SD: Standard deviation

Table S4 Synopsis of farm management practices in the rice fields during the wet and dry seasons in Kou Valley, Burkina Faso (2019-2020)

	Wet season	Dry season	Overall	Test statistic
(Row %)(Col %)				
Growth duration of the variety (days)				Wilcoxon rank-sum
Mean (SD)	110 (11)	108 (12)	109 (11)	0.618
Source of seeds				Chi-square
Certified	0 (0%) (0%)	2 (100%) (11%)	2 (100%) (7%)	0.654
Non-certified	12 (43%) (100%)	16 (57%) (89%)	28 (100%) (93%)	
Straw management				Chi-square
Removing from the field	5 (62%) (42%)	3 (38%) (17%)	8 (100%) (27%)	0.519
Burning	5 (36%) (42%)	9 (64%) (50%)	14 (100%) (47%)	
Grazing *in-situ*	2 (33%) (17%)	4 (67%) (22%)	6 (100%) (20%)	
Mulching in the field	0 (0%) (0%)	1 (100%) (6%)	1 (100%) (3%)	
Incorporation in the field	0 (0%) (0%)	1 (100%) (6%)	1 (100%) (3%)	
Residue management				Chi-square
Removing	0 (0%) (0%)	1 (100%) (6%)	1 (100%) (3%)	0.345
Mulching	1 (100%) (8%)	0 (0%) (0%)	1 (100%) (3%)	
Incorporation	11 (41%) (92%)	16 (59%) (94%)	27 (100%) (93%)	
Tillage method				Chi-square
No tillage	3 (100%) (25%)	0 (0%) (0%)	3 (100%) (10%)	0.065
Animal	9 (35%) (75%)	17 (65%) (94%)	26 (100%) (87%)	
Mechanical	0 (0%) (0%)	1 (100%) (6%)	1 (100%) (3%)	
Land levelling				Chi-square
Poor	1 (100%) (8%)	0 (0%) (0%)	1 (100%) (3%)	0.836
Good	11 (38%) (92%)	18 (62%) (100%)	29 (100%) (97%)	
Sowing date in nursery				
Mean (SD)	226 (16)	13 (20)	98 (107)	
Age of the seedlings at transplanting (days)				Wilcoxon rank-sum
Mean (SD)	24 (7)	26 (10)	25 (8)	0.815

Planting density (hills m^{-2})				Wilcoxon rank-sum
Mean (SD)	30 (9)	30 (7)	30 (8)	0.65
Number of seedlings per hill				Wilcoxon rank-sum
Mean (SD)	4 (1)	3 (1)	3 (1)	0.527
Weeding frequency				Wilcoxon rank-sum
Mean (SD)	3 (1)	3 (1)	3 (1)	0.132
Herbicide use				Chi-square
No	0 (0%) (0%)	1 (100%) (6%)	1 (100%) (3%)	>0.999
Yes	12 (41%) (100%)	17 (59%) (94%)	29 (100%) (97%)	
Application of organic manure				Chi-square
No	10 (43%) (83%)	13 (57%) (72%)	23 (100%) (77%)	0.792
Yes	2 (29%) (17%)	5 (71%) (28%)	7 (100%) (23%)	
Application of mineral fertilizer in nursery				Chi-square
No	0 (0%) (0%)	1 (100%) (6%)	1 (100%) (3%)	>0.999
Yes	12 (41%) (100%)	17 (59%) (94%)	29 (100%) (97%)	
Mineral fertilizer application frequency				Wilcoxon rank-sum
Mean (SD)	2 (0)	3 (1)	2 (1)	0.25
N application rate (kg N ha^{-1})				Wilcoxon rank-sum
Mean (SD)	119 (18)	128 (26)	125 (23)	0.23
P application rate (kg P ha^{-1})				Wilcoxon rank-sum
Mean (SD)	16 (4)	13 (3)	14 (3)	**0.042**
K application rate (kg K ha^{-1})				Wilcoxon rank-sum
Mean (SD)	29 (7)	25 (5)	27 (6)	0.114
Insect and disease control frequency				Wilcoxon rank-sum
Mean (SD)	2 (1)	2 (1)	2 (1)	0.051
Bird control				Chi-square
No	6 (75%) (50%)	2 (25%) (11%)	8 (100%) (27%)	0.053
Yes	6 (27%) (50%)	16 (73%) (89%)	22 (100%) (73%)	

SD: Standard deviation

Significant effects ($p < 0.05$) are indicated in bold.

Table S5 Grain yield, water productivity and partial factor productivity of applied nutrients during the wet and dry seasons in Kou Valley, Burkina Faso (2019-2020)

	Wet season	Dry season	Overall	Test statistic
Grain yield (Mg ha^{-1})				t-test
Mean (SD)	4.83 (1.48)	4.33 (1.31)	4.53 (1.39)	0.187
Median (IQR)	4.30 (2.05)	4.42 (1.79)	4.32 (1.87)	
Total water productivity (kg grain m^{-3} of water)				Wilcoxon rank-sum
Mean (SD)	1.40 (0.29)	1.81 (0.86)	1.64 (0.72)	**0.028**
Median (IQR)	1.41 (0.32)	1.69 (1.06)	1.53 (0.75)	
Irrigation water productivity (kg grain m^{-3} of water)				Wilcoxon rank-sum
Mean (SD)	6.38 (3.54)	2.56 (1.71)	4.09 (3.19)	**<0.001**
Median (IQR)	5.65 (4.97)	2.09 (1.79)	3.08 (3.39)	
Partial factor productivity of N (kg grain kg^{-1} N)				Wilcoxon rank-sum
Mean (SD)	42 (16)	34 (9)	37 (13)	0.126
Median (IQR)	38 (25)	36 (10)	36 (13)	
Partial factor productivity of P (kg grain kg^{-1} P)				Wilcoxon rank-sum
Mean (SD)	318 (115)	339 (122)	331 (119)	0.378
Median (IQR)	284 (131)	332 (124)	322 (143)	
Partial factor productivity of K (kg grain kg^{-1} K)				Wilcoxon rank-sum
Mean (SD)	175 (62)	178 (64)	177 (63)	0.81
Median (IQR)	164 (78)	174 (65)	174 (77)	

SD: Standard deviation

Significant effects ($p < 0.05$) are indicated in bold.

Table S6 Grain yield, yield components, water productivity, and nutrient uptake in non-fertilized plots under two water management practices: farmers practices (FP) and alternate wetting and severe soil drying (AWD30) irrigation during the wet and dry seasons in Kou Valley, Burkina Faso (2019-2020)

	Wet season			Dry season		
	FP	AWD30	Test statistic	FP	AWD30	Test statistic
Tiller number$ from 6 hills at harvest			LMM			LMM
Mean (SD)	62 (18)	56 (11)	0.188	65 (11)	68(10)	0.426
Panicle number from 6 hills at harvest			LMM			LMM
Mean (SD)	58 (17)	53 (10)	0.227	65 (11)	67 (10)	0.483
Grain yield (Mg/ha)			LMM			LMM
Mean (SD)	2.48 (1.14)	1.83 (0.63)	0.058	3.20 (1.09)	2.93 (0.99)	0.317
Total water productivity (kg grain/m^3)			LMM			LMM
Mean (SD)	0.74 (0.28)	0.72 (0.11)	0.856	1.33 (0.52)	1.67 (0.57)	0.078
Irrigation water productivity (kg grain/m^3)			LMM			LMM
Mean (SD)	2.78 (3.03)	4.52 (2.57)	0.123	1.86 (0.84)	2.93 (1.75)	0.108
N uptake (kg N/ha)			LMM			LMM
Mean (SD)	36 (16)	23 (7)	**0.036**	39 (15)	37 (10)	0.582
P uptake (kg P/ha)			LMM			LMM
Mean (SD)	9 (3)	6 (2)	**0.020**	11 (5)	10 (5)	0.565
K uptake (kg K/ha)			LMM			LMM
Mean (SD)	52 (26)	42 (14)	0.180	67 (22)	64 (14)	0.576

$ This count includes both stems and tillers.

SD: Standard deviation

LMM stands for linear mixed effect model

Significant effects ($p < 0.05$) are indicated in bold.

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