Field Crops Research 270 (2021) 108209

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Impact of management practices on weed infestation, water productivity, rice yield and grain quality in irrigated systems in Côte d'Ivoire

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ARTICLE INFO

Keywords:
Alternate wetting and drying
Grain quality
Soil
Lowland weeds
Rice

ABSTRACT

Management practices that simultaneously enhance rice yield, water productivity, labor productivity, and grain quality are needed for improving crop production and mitigating the negative impact of water scarcity on food security. The objectives of this on-farm study were to evaluate the effects of water management practices including the safe alternate wetting and drying (AWD) method of irrigation on rice yield, water productivity, weed biomass, and grain quality, and identify the factors associated with their variabilities in the fields with AWD. On-farm trials were conducted over two years in 30 fields within two irrigation schemes in the region of Bouake, central Côte d'Ivoire. Before rice cultivation, in each field, three plots consisting of water management practices were established: continuous flooding (CF), safe AWD, and farmers' practice (FP). Lowland weeds were dominant in rice fields in this study area. Large variations in weed biomass, rice yield, and water productivity were found across fields for each water management practice. Weed biomass and irrigation water input were lower under safe AWD than CF due to higher soil drying while there was no significant difference in rice yield between safe AWD and CF. Water productivity was higher under safe AWD than CF and FP. Rice milling recovery, head yield, and chalkiness were not significantly different among water management practices. Higher rice yield and water productivity in the safe AWD fields were associated with higher soil pH and nitrogen (N) fertilizer rate and better congruence between nitrogen fertilizer application and crop N demand. Milling recovery, head yield, and chalkiness in the safe AWD fields were strongly affected by the choice of rice variety. Combination of safe AWD with varieties having good grain quality characteristics and improved nutrient management practices could be recommended to the smallholder rice farmers to improve rice yield, water productivity, and grain quality and reduce labour requirement for irrigation and weeding particularly in schemes where lowland weeds are dominant.

1. Introduction

About 27 % of the calories in the world's developing countries are obtained from rice (Barker and Dawe, 2002; Pandey et al., 2010). While rice consumption per capita has stabilized in most Asian countries and declined in some of the high-income countries in Asia, it is still rapidly rising in sub-Saharan Africa (SSA) (Reardon and Timmer, 2014). However, local rice production is not able to keep pace with the sharp increase in rice consumption and the region increasingly depends on imports (FAOSTAT, 2020). Rice production can be increased in two ways: expansion of cultivation area and increase in land productivity (e.g. yield) (Tanaka et al., 2017). Among the major rice production systems in SSA (irrigated lowland, rainfed lowland, and rainfed upland), average rice yield is higher in the irrigated system (3.6 t/ha) than in rainfed lowland (2.8 t/ha) and rainfed upland (1.6 t/ha) (Tanaka et al., 2017). About 22 % of the total rice area in SSA is irrigated (Diagne et al., 2013a) contributing to 40 % of the total rice production (FAOSTAT, 2020). Achieving rice self-sufficiency in SSA requires an increase in irrigated rice production (Saito et al., 2015; van Oort et al., 2015). Major challenges to irrigated rice production in SSA included i) less-than-optimum input use (Niang et al., 2017; Saito et al., 2015, 2019), ii) poor soil fertility (Haefele et al., 2014), iii) poor weed management (Becker et al., 2002; Rodenburg et al., 2019), iv) unreliable water supply (Becker et al., 2002; Mdemu et al., 2017; Tanaka et al., 2015, 2017), and v) farmers' limited access to inputs and credit (Diagne et al., 2013b). Besides, climate change is anticipated to decrease the irrigation potentials of water resources by 10–40% (Sylla et al., 2018), and hence adds to farmers' burden and is likely to compromise the future productivity and

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https://doi.org/10.1016/j.fcr.2021.108209
Received 7 October 2020; Received in revised form 4 June 2021; Accepted 16 June 2021
Available online 24 June 2021

sustainability of irrigated systems in many African countries (van Oort and Zwart, 2018).

Among the water-saving technologies that were developed in recent decades, the alternate wetting and drying (AWD) method of irrigation is widely advocated for its potential to increase water productivity while maintaining rice yield compared to continuous flooding (Bouman and Tuong, 2001; Lampayan et al., 2015). Under AWD, fields are subjected to intermittent flooding where irrigation is interrupted, and water is allowed to subside until the water table falls down to a threshold below the soil surface, after which the field is re-flooded (Bouman and Tuong, 2001). Previous studies indicated an increase in water productivity by 19–29% under AWD compared to continuous flooding (Bouman and Tuong, 2001; Lampayan et al., 2015; Liang et al., 2016; Yang et al., 2017). Other co-benefits of AWD were reported such as a decrease in methane emissions by 32–75% (Jiang et al., 2019), a decrease in the concentration of arsenic in grains by 14–26% (Norton et al., 2017) and an increase in the internal phosphorus use efficiency by 3–5 % (Song et al., 2018).

Allowing the soil to dry periodically under AWD may, however, promote weed growth (Haden et al., 2007), and increase the competition for soil nutrients (de Vries et al., 2010). Earlier studies on weeds in rice production systems in West Africa showed a higher weed biomass in rainfed lowland than irrigated lowland, which was attributed to a better water control in irrigated lowland, particularly to continuous flooding (Becker and Johnson, 1999, 2001; Kent and Johnson, 2001; Becker et al., 2003). Upon the soil rewetting in the soil drying and wetting cycles, loss of nitrogen through nitrification and denitrification was reported to be higher under AWD compared to continuous flooding which may reduce nitrogen uptake by rice plants (Pandey et al., 2014; Jiang et al., 2019). In a meta-analysis of 56 studies in 528 pairwise comparisons, rice yield was found to be reduced in many cases under AWD compared to continuous flooding with an average reduction of 5.4–22.6% (Carrijo et al., 2017). There have been limited studies on AWD in Africa that focused on yield and water productivity (de Vries et al., 2010; Krupnik et al., 2012; Djaman et al., 2018). Globally, investigations on the impact of AWD on grain quality are limited. Graham-Acquaah et al. (2019) reported a negative effect of AWD on grain quality due to an increase in chalkiness and a decrease in setback viscosity in Northeast Arkansas, USA while Cheng et al. (2003) reported an increase in grain quality with AWD due to an increase in protein content in Zhejiang, China. Besides, most of the studies on AWD were conducted on research stations, and only a few studies were carried out on farmers' fields (Carrijo et al., 2017; Jiang et al., 2019). Little is known about the factors that determine variabilities in weed biomass, rice yield, water productivity, and grain quality in farmers' fields with AWD practice of irrigation. Therefore, the objectives of this study were to assess the effects of water management practices on weed biomass, rice yield, water productivity and grain quality in farmers' fields, and to identify the determinants of their variability in farmers' fields with AWD in irrigated systems in central Côte d'Ivoire.

2. Materials and methods

2.1. Study site

On-farm multi-location trials were conducted from March to June in 2018 and 2019 in 30 fields at two irrigation schemes, i.e., Mbe (7°53′58″ N, 5°3′33″' W) and Lokakpli (7°51′47″ N, 5°3′35″ W) in the region of Bouake in central Côte d'Ivoire. The two schemes were 5 km away from each other. The scheme of Mbe was poorly developed with traditional irrigation and drainage canals dug into the earth, while the scheme of Lokapkli was moderately developed with concrete irrigation and drainage canals constructed in the framework of a collaborative project between the governments of Côte d'Ivoire and Japan. In both schemes, surface water from a dam located upstream was conveyed through gravity to the main irrigation canal, and to secondary canals from which water is diverted to farmers' fields. Small dikes (also called as bunds) were constructed using soil to restrict surface runoff and store water in fields. The scheme of Mbe was developed in the 1980s while the scheme of Lokapkli was developed in 1998.

The two irrigation schemes belong to the derived savannah agro-ecological zone of West Africa (Becker and Johnson, 2001; Erenstein, 2006). The climate is tropical with two dry seasons from November to March and from July to August and two rainy seasons from April to June and from September to October. Mean minimum and maximum air temperatures and solar radiation in the 2018 and 2019 growing seasons were similar and within the medium-term range (2010–2019) (Table 1). Seasonal rainfall was 515 mm in 2018 and 520 mm in 2019 and both were within the medium-term range (Table 1). The on-farm trials were conducted during the first rainy season in 2018 and 2019 because water is supplied from dams and water shortage is one of the major constraints to rice cultivation during the first rainy season. However, during the second rainy season, implementation of AWD is not suitable due to more rains and poor drainage systems in these two schemes. Thus, we did not implement on-farm studies in the second rainy season.

2.2. Treatments and plot size

The 30 farmers were selected based on their willingness to participate in the experiment in both years. Fifteen farmers were selected in each of the two schemes. Fields of selected farmers were located at different positions within each scheme with 4, 7, and 4 farmers' fields located close, at middle distance, and far from the secondary canal, hereafter referred to as water source. Each farmer's field (300 m^2) was subdivided into three plots of 100 m^2 consisting of three water management practices: a) continuous flooding (CF), b) safe alternate wetting and drying (AWD) and c) farmers' practice of irrigation (FP). Perforated field water tubes were installed to a depth of 15 cm in every plot to monitor water depth. In CF, standing water of 2–5 cm depth was maintained from transplanting to 7 days before harvest. In the safe AWD treatment, field water depth was kept at 2–5 cm during the first 10 days after transplanting (DAT), and afterward, the timing of irrigation was based on the water depth in the field water tube. When the water disappeared in the tube, the plot was irrigated to a depth of 5 cm above the soil surface. At the flowering stage, the field was re-flooded, and thereafter the AWD cycles were repeated until 7 days before harvest. In FP, each farmer implemented its own water management practice. But farmers tended to maintain a shallow water depth of 2 cm in the fields during the first week after transplanting, and thereafter, farmers irrigated when the standing water disappeared. Thus, their water

Table 1
Weather data during rice growing seasons in 2018 (Year 1) and 2019 (Year 2) as means of daily values (temperature and solar radiation) and cumulated daily values (rainfall) compared to the 2010 – 2019 average in Mbe, Bouake, Côte d'Ivoire. Interquartile values are presented in the bracket.

Month	March	April	May	June	March - June
Minimum temperature (C)					
2018	22.3	22.3	21.9	21.7	22.1
2019	21.3	22.9	22.7	22.3	22.3
2010–2019	21.9 (1.0)	22.3 (1.2)	22.1 (1.1)	22.2 (0.6)	22.1 (0.7)
Maximum temperature (C)					
2018	31.6	31.5	30.6	29.4	30.8
2019	33.7	31.6	30.9	28.7	31.2
2010–2019	33.8 (2.0)	33.2 (1.8)	32.4 (2.4)	30.7 (2.7)	32.6 (2.1)
Solar radiation (MJ/m^2/day)					
2018	20	21	21	17	20
2019	21	22	20	15	20
2010 - 2019	23 (1)	23 (3)	22 (1)	17 (2)	21 (2)
Rainfall (mm)					
2018	92	159	68	197	515
2019	51	181	186	102	520
2010 - 2019	114 (86)	170 (27)	188 (108)	145 (135)	618 (129)

management practices are similar at some extent to AWD, although farmers did not use standard approach for irrigation timing. There was large variation in water conditions across farmers' fields. For the three water management practices, irrigation was stopped for 2–3 days to have a saturated field condition before each weeding and fertilizer application. Under such a saturated field condition, farmers can easily remove weeds manually and ensure that fertilizer is uniformly applied in the fields. To prevent lateral water flow, the plots were separated with double bunds and all bunds were covered with plastic film installed to a depth of 30 cm below the soil surface. At a given field, all crop management practices other than water management practices were operated based on the farmers' own practices and they are same across the three water management treatments to evaluate the effect of water management. No instruction was provided to farmers on crop management practices, variety, and fertilizer application.

2.3. Data collection

Before the start of the experiment, composites of 12 individual auger samples (0–20 cm) per field were mixed, air-dried, and sieved (2 mm) for analysis of sand and clay contents, pH, and soil organic carbon. Sand and clay contents were determined with the Robinson pipette method. The soil pH was determined using a soil-water ratio of 1–2.5 with a pH meter (pH 2700; Eutech Instruments Pte Ltd.) The soil organic carbon was determined by chromic acid digestion.

The altitude of each farmer's field was determined using a handheld Garmin GPS receiver with ±5 m positional accuracy. In each field, agricultural practices other than water management were based on the selected farmer's practices. Information on farmers' agricultural practices was collected through weekly field visits and interviews with farmers. Agricultural practices considered were land preparation (tillage, straw management), planting material, establishment method, date of transplanting, age of seedling, frequency and dates of fertilizer applications, frequency and dates of weeding operations. We had conversations with farmers on fertilizer application and provided farmers with the quantity of fertilizer that they usually apply. In the case of nitrogen, it varied with year, but not among farmers in a given year. All the farmers applied 144 and 68 kg/ha of nitrogen in 2018 and 2019, respectively. The rates of phosphorus and potassium fertilizers were 44 and 42 kg/ha and did not vary between years and among farmers.

Every two days, field water depth in the tubes and field water status (1: ponded water and 2: no ponded water) were recorded between 10.00 a.m. and 11.00 a.m. Soil dryness index was calculated as the ratio between number of days without ponded water at the soil surface and total number of recording days, and separated in (1) the number of days during the growing season (from transplanting to harvest), (2) the vegetative stage (from transplanting to panicle initiation), (3) the reproductive stage (from panicle initiation to flowering) and (4) the ripening stage (from flowering to harvest). A soil dryness index of 0 indicates that the field has been continuously flooded, while a soil dryness index of 1 indicates that the field has been continuously unflooded.

In both years, weed biomass was assessed in two 2-m^2 in the center of each plot when farmers were about to weed their field. Weed biomass at each weeding intervention was determined after oven-drying at 70 °C for 48 h. At each growing season, the total weed biomass of each plot was determined as the sum of the weed biomass at the different weeding operations practiced by farmers. Weed species were identified in each plot during each weeding operation in both years of experiment, and grouped per plant family, weed group (broad-leaved, grasses and sedges), and ecological preference (hydromorphic, lowland or both) following Johnson and Kent (2002). Except for weed biomass and weed species frequency, other weed related variables such as weed density, coverage, number of people involved, and the duration of each weeding operation were not recorded in this study.

A 45° V-notch was established at the inlet of each plot to determine the discharge of water following Shen (1981) (Eq. 1). For each irrigation, the water above the crotch of the V-notch, usually referred to as hydraulic head, was recorded at 2-min intervals for each water management plot. The discharge (Q) for each 2-min interval was computed using Eq. 1, and the duration of each irrigation was recorded. The discharge was multiplied by the duration of each irrigation and cumulated for all irrigations over the growing season period to estimate the irrigation water input.

$$Q = 4.28 * Ce * tan\left(\frac{\theta}{2}\right) * (H + k)^{2.5} \quad (1)$$

with Q the discharge in m^3/s, Ce = 0.580174504, k = 0.004921221, θ = 45°, and H is the water above the crotch of the V-notch in m (Shen, 1981).

At maturity, grain yield was determined from two areas of 4-m^2 in the center of each plot and adjusted to 14 % grain moisture content. Water productivity was calculated as the ratio between grain yield and total water input (rainfall + total irrigation amount). Grains collected from each plot were subjected to grain quality analysis. Two hundred grams of paddy were used for proper husking and milling. Husking was done with a testing rice husker (THU-34A Satake testing rice husker, Satake, Hiroshima, Japan). Brown rice was polished with a rice polisher (Recipal 32 rice whitener, Yamamoto Co., Higashine, Japan). Milling recovery, head rice yield, and chalkiness were determined following Ndindeng et al. (2015). Milling recovery was determined as the percentage ratio of polished rice to brown rice on a weight basis. Head rice comprises whole grains excluding discolored and damaged grains. A grain is considered whole if the grain length is 75%–100% whole. Head rice yield was expressed as a percentage ratio of the head rice to the paddy rice on a weight basis. Percentage of chalky grains was determined on a 50-g sample using the S21 rice statistical analyzer (LKL Technologia, Santa Cruz do Rio Pardo, Brazil), calibrated with the reference sample (Tinto) supplied by the manufacturer.

2.4. Statistical analyses

Before the statistical analyses, field data where safe AWD was not applied as instructed (10 fields in year 2) were removed from the database. Analyses of variance were conducted to evaluate the effects of year, site, field position, and water management on weed biomass, irrigation water input, number of irrigations, rice yield, water productivity, milling recovery, head yield, and chalkiness. To meet the assumptions of the analysis of variance, weed biomass, irrigation water input, and rice chalkiness were subjected to logarithm transformations. Mean values were tested for significant differences by using the Tukey's Honest significant difference test.

Multiple linear regressions were applied to evaluate the effect of soil dryness indices on weed biomass across water management practices. Five models (Models 1–5) specified in Table 2 were applied, fitted, and ranked based on the lowest Akaike's Information Criterion (AIC).

To identify the factors affecting variabilities in weed biomass, rice yield, water productivity, milling recovery, head rice yield, and chalkiness in the rice fields managed with safe AWD, 20 models (Models 6–25) specified in Table 2 were applied, fitted, and ranked based on the lowest AIC. Fig. 1 and Table 3 were used to identify the predictors that would be used to build the models. Among the predictors that varied significantly in farmers' fields (coefficient of variation greater than 10 %) were the soil dryness index during the growing season (Fig. 1), soil organic carbon, transplanting date, seedling age, timing of the first weeding operation, timing of the third fertilizer application, and rice variety (Table 3). Tillage method, crop residue management, crop establishment method, weeding method, timing of first and second splits of fertilizer application, fertilizer application frequency, weeding operation frequency, and timing of second weeding operation were not included in the models because they did not largely vary significantly in farmers' fields (coefficient of variation lower than 10 %) (Table 3).

Table 2
Models and variables used to explain variability in weed biomass in field with continuous flooding and safe alternate wetting and drying irrigation method (safe AWD) (Models 1 – 5), weed biomass, rice yield, water productivity, milling recovery, head rice yield, and chalkiness in fields with safe AWD irrigation method (Models 6 – 25) and soil dryness index during the growing season in fields with safe AWD and farmers' practices of irrigation (Models 26 – 28).

Model	Variables
• Model 1	soil dryness index during the vegetative stage
• Model 2	soil dryness indices during the vegetative and reproductive stages
• Model 3	soil dryness indices during the vegetative and the ripening stages
• Model 4	soil dryness indices during the reproductive and ripening stages
• Model 5	soil dryness index during the growing season
• Model 6	variety
• Model 7	variety, age of seedling
• Model 8	variety, timing of the first weeding operation
• Model 9	soil pH, variety
• Model 10	soil organic carbon, variety
• Model 11	soil pH, variety, nitrogen (N) fertilizer input
• Model 12	soil pH, N fertilizer input, timing of third fertilizer application
• Model 13	soil pH, variety, timing of third fertilizer application
• Model 14	soil pH, variety, N fertilizer input, age of seedling
• Model 15	soil pH, variety, N fertilizer input, age of seedling, transplanting date
• Model 16	soil pH, age of seedling, transplanting date, N fertilizer input, timing of third fertilizer application
• Model 17	soil pH, soil organic carbon, N fertilizer input
• Model 18	soil pH, soil organic carbon, N fertilizer input, timing of third fertilizer application, transplanting date
• Model 19	soil pH, soil organic carbon, N fertilizer input, variety
• Model 20	soil pH, soil organic carbon, N fertilizer input, variety, age of seedling, transplanting date
• Model 21	soil pH, soil organic carbon, N fertilizer input, variety, timing of third fertilizer application
• Model 22	soil pH, soil organic carbon, variety, age of seedling, N fertilizer input, timing of third fertilizer application
• Model 23	soil pH, soil organic carbon, variety, age of seedling, transplanting date, N fertilizer input, timing of third fertilizer application
• Model 24	soil pH, soil organic carbon, variety, age of seedling, transplanting date, timing of the first weeding operation, N fertilizer input, timing of third fertilizer application
• Model 25	soil dryness during the growing season, soil organic carbon, soil pH, N fertilizer input, timing of third fertilizer application, transplanting date
• Model 26	soil organic carbon
• Model 27	field altitude
• Model 28	soil organic carbon, field altitude

Among the timing of the three splits of fertilizer application, only the timing of the third split of fertilizer application had large variation (coefficient of variation greater than 10 %) (Table 3). Therefore, only the timing of the third split of fertilizer application was included in the models. The amount of nitrogen fertilizer applied by farmers was considered as predictor because it varied with year. Soil properties such as sand and clay contents were not considered because they were highly correlated with soil organic carbon ($r > 0.75$, $p < 0.001$). As the distributions of minimum and maximum temperatures and solar radiation were similar during the growing season in 2018 and 2019 (Table 1), minimum and maximum temperatures and solar radiation were not included as predictors in the models.

As the soil dryness indices were in a standard unit interval and asymmetric (Cribari-Neto and Zeileis, 2010), beta regression was used to evaluate the determinants of their variabilities in AWD and FP fields. Three models (Models 26–28) specified in Table 2 were applied, fitted, and ranked based on the lowest AIC. All the statistical analyses were performed with the R software (R Core Team, 2018).

3. Results

3.1. Rice growing environment, crop management, weeds, rice yield, water productivity, grain quality and soil dryness indices during the study period

The weather parameters during the study period are presented in Table 1. They were generally similar between two years except for rainfall in some months. Monthly average minimum air temperature ranged from 21.7–22.3 °C in Year 1 and from 21.3 to 22.9 °C in Year 2. Similarly, monthly average maximum air temperature ranged from 29.4–31.6 °C in Year 1 and from 28.7–33.7 °C in Year 2. Monthly average solar radiation ranged from 17 to 21 MJ/m^2/day in Year 1 and from 15 to 22 MJ/m^2/day in Year 2. Monthly rainfall ranged from 68 to 197 mm in Year 1 and from 51 to 186 mm in Year 2 (Table 1). Rainfall was smaller in May, but higher in June in Year 1 than those in Year 2. Total rainfall during the rice-growing season was similar between the two years.

There was large variation in soil properties in rice fields except the soil pH (Table 3). Soil texture varied from sandy loam to sandy clay, while soil organic carbon ranged from 1.5 to 3.8 %. Field altitude ranged from 260 to 276 m above mean sea level. Regarding the agricultural practices, those that differed largely among farmers (CV $\geq$ 10 %) were the date of transplanting, age of seedling, timing of the first weeding operation, and timing of the third split of fertilizer application (Table 3). Varieties used by farmers changed with year of experiment. In Year 1, JT11, ORYLUX6, and WITA9 were used by 20, 7, and 73 % of the farmers, while in Year 2, these varieties were used by 70, 10, and 20 % of the farmers, respectively. Other agricultural practices such as tillage method, crop residue management, crop establishment method, weeding method, timing of the first and second splits of fertilizer application, frequency of fertilizer application, and frequency of weeding operations were similar among farmers. All farmers manually returned crop residue during the tillage operation, used transplanting as crop establishment method, applied fertilizer in three split doses, applied the first split of fertilizer application on the date of transplanting, used two manual weeding operations and did not apply any herbicide.

Soil dryness index ranged from 0 to 1 in Year 1 and from 0 to 0.83 in Year 2 (Fig. 1). On average, soil dryness index was 0.40 in Year 1 and 0.38 in Year 2. Each year, soil dryness index varied with phenological stage and water management practice. Across year and water management practices, the soil dryness index ranged from 0.05 to 0.87 during the vegetative stage, from 0 to 0.20 during the reproductive stage, from 0 to 1 during the ripening stage, and from 0.03 to 0.67 during the growing season. On average, the soil dryness index was 0.48 during the vegetative stage, 0.01 during the reproductive stage, and 0.50 during the ripening stage. Across years and phenological stages, the soil dryness index during the growing season ranged from 0.33 to 0.64 in safe AWD fields, from 0.03 to 0.25 in CF fields and from 0.45 to 0.67 in FP fields. On average, the soil dryness index was 0.50 in safe AWD fields, 0.14 in CF fields, and 0.55 in FP fields (Fig. 1). The soil dryness index during the growing season in the FP fields was significantly affected by site and field location (Table 4). The soil dryness index during the growing season in FP was lower in the Lokapkli scheme than in Mbe (Fig. 2A), and in the fields far from the water source than in fields located close to and in the middle distance to the water source (Fig. 2B). In the fields with safe AWD and FP, there was a positive relationship between the soil dryness index during the growing season and field altitude (Table 5).

Sixteen weed species were frequently (>10 % occurrence) observed in farmers' fields, of which 67 % were broad-leaved compared to 21 % sedges and 23 % grasses (Table 6). Of the weed species frequently observed, 60 % preferred lowland conditions while 15 % preferred hydromorphic conditions and 35 % preferred both lowland and

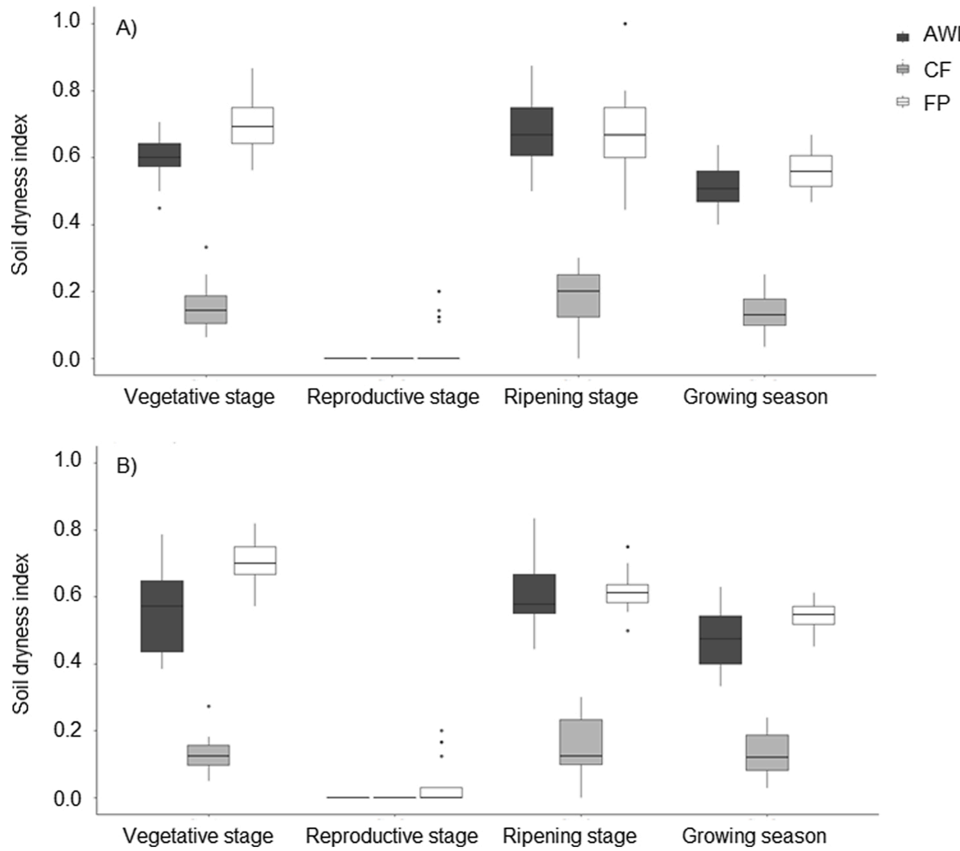

Fig. 1. Soil dryness index during the vegetative, reproductive, ripening, and the growing season in the fields managed with safe alternate wetting and drying (AWD), continuous flooding (CF), and farmers' practices of irrigation (FP) in year 1 (A) and year 2 (B).

hydromorphic conditions (Table 6). The three most dominant weed species were *Heteranthera callifolia*, *Leptochloa caerulescens*, and *Sphenoclea zeylanica* and were evenly distributed across field positions (Table 6). However, their frequency was different among water management practice (Table 6). *Heteranthera callifolia* and *Sphenoclea zeylanica* were the most dominant under CF, while *Leptochloa caerulescens* was the dominant under FP. The frequency of weeds that preferred lowland conditions was the highest under CF, while the frequency of weeds that preferred both lowland and hydromorphic conditions was the highest under FP (Table 6). Field-to-field variations in weed biomass, rice yield, water productivity, and grain quality, except for milling recovery were large in each of safe AWD, CF, and FP fields (Table 3).

3.2. Effects of water management and field position on weed biomass, irrigation water input, number of irrigations, rice yield, water productivity and grain quality

Weed biomass was significantly higher in year 1 (197 g/m^2) than in year 2 (144 g/m^2) (Tables 7 and 8). The effect of field position on weed biomass varied by site (Table 7). In Mbe, the highest weed biomass (201 g/m^2) was recorded in fields located at a middle distance from the water source, while in Lokapkli, the highest weed biomass (274 g/m^2) was recorded in fields located far from the water source (Fig. 3). Compared to CF, weed biomass was reduced by 36 % under safe AWD (Tables 7 and 8). No significant difference in weed biomass was found between CF and FP (Table 8). Lower weed biomass in safe AWD fields compared to CF fields was related to the higher soil dryness index under safe AWD (Table 9) causing the reduction of broad-leaved and lowland weeds particularly of *Heteranthera callifolia* and *Sphenoclea zeylanica* (Table 6).

Water management had a significant effect on irrigation water input with the lowest irrigation water input under safe AWD (190 mm) and the highest under CF (403 mm) (Tables 7 and 8). There was a significant site by year interaction effect on irrigation water input (Table 7). While no significant difference was found in the irrigation water input between the two schemes in Year 1, irrigation water input in Year 2 was higher in Mbe than in Lokapkli (Fig. 4a). Irrigation water input was significantly higher in Year 2 (419 mm) than in Year 1 (218 mm) (Tables 7 and 8). This could be attributed to the fact that the duration of the crop growing cycle was longer in Year 2 than Year 1, as most of the farmers used variety having longer duration (JT11) in Year 2.

Similarly, the total water input (irrigation + rainfall) was affected by water management (Tables 7 and 8). The lowest total water input (707 mm) was found under safe AWD, while the highest water input (920 mm) was found under CF (Tables 7 and 8). The interaction between site and year on total water input was significant (Table 7). While no significant difference was found in the total water input between the two sites in Year 1 (Fig. 4B), irrigation water input in Year 2 was higher in Mbe than in Lokapkli (Fig. 4B).

The number of irrigations was higher in Year 2 (7) than in Year 1 (6) (Tables 7 and 8). Water management had a significant effect on the number of irrigations. Compared to CF, the number of irrigations was reduced by 25 % under FP and 50 % under safe AWD (Table 8). The effect of field position on the number of irrigations varied by site (Table 7). While in Mbe, there was no significant difference in the number of irrigations among field positions, in Lokapkli the number of irrigations was higher in the fields located far from the water source than in those located close and at a middle distance from the water source (Fig. 5).

Rice yield was significantly higher in Year 1 (6.0 t/ha) than in Year 2 (5.0 t/ha) (Tables 7 and 8). There was a significant site by year interaction effect on rice yield (Table 7). While in Year 1, rice yield was lower in Mbe than in Lokapkli, no significant difference in rice yield was found

Table 3
Soil properties and field altitude, farmers' crop management practices by year and weed biomass, rice yield, water productivity, milling recovery, head rice yield and rice chalkiness by water management practice in the farmers' fields.

	Average	Range	CV [a] (%)
Soil properties			
pH	5.8	5.4 – 6.2	3
Soil organic carbon (%)	2.9	1.5 – 3.8	23
Sand (%)	31	15 – 53	31
Clay (%)	54	22 – 74	21
Field altitude above mean sea level (m)	267	260 – 276	2
Transplanting date (Julian day) [b]			
Year 1 (n = 30)	89	57 – 144	40
Year 2 (n = 20)	90	63 – 114	47
Age of seedling (day)			
Year 1 (n = 30)	25	16 – 35	17
Year 2 (n = 20)	24	16 – 30	13
Timing of the first weeding operation (DAT) [c]			
Year 1 (n = 30)	24	21 – 35	17
Year 2 (n = 20)	23	21 – 28	12
Timing of the second weeding operation (DAT)			
Year 1 (n = 30)	52	51 – 54	2
Year 2 (n = 20)	54	51 – 60	4
Timing of the second split of fertilizer application (DAT)			
Year 1 (n = 30)	22	19 – 24	4
Year 2 (n = 20)	22	19 – 23	4
Timing of the third split of fertilizer application (DAT)			
Year 1 (n = 30)	45	35 – 57	14
Year 2 (n = 20)	42	30 – 57	15
Growing cycle duration (day) [d]			
Year 1 (n = 30)	98	81 – 123	12
Year 2 (n = 20)	113	93 – 136	9
Weed biomass (g/m^2)			
Safe AWD	133	24 – 385	59
CF	208	47 – 418	49
FP	186	40 – 532	53
Rice yield (t/ha)			
Safe AWD	5.6	2.9 – 8.8	25
CF	5.9	3.3 – 8.9	24
FP	5.2	2.6 – 8.2	26
Water productivity (kg/m^3/ha)			
Safe AWD	0.81	0.34 – 1.31	30
CF	0.67	0.30 – 1.08	30
FP	0.66	0.25 – 1.15	32
Milling recovery (%)			
Safe AWD	63	55 – 68	6
CF	64	58 – 68	5
FP	63	50 – 69	7
Head rice yield (%)			
Safe AWD	51	32 – 60	16
CF	53	42 – 59	10
FP	52	41 – 61	11
Chalkiness (%)			
Safe AWD	5.5	0.2–45.9	199
CF	4.2	0.1 – 28.7	166
FP	3.9	0.6 – 26.2	161

[a] CV: coefficient of variation.
[b] Difference between each farmers' rice transplanting date and first farmers' transplanting date in each year was used to calculate the CV. The number of farmers involved in the experiment in Year 1 (n = 30) and Year 2 (n = 20) was presented.
[c] Timing of the first weeding operation was expressed in number of days after transplanting (DAT). Agricultural practices such as tillage method, crop residue management, crop establishment method, the timing of the first split of fertilizer application, frequency of fertilizer application, frequency of weeding operations were similar among farmers and were not presented in this table.
[d] Growing cycle duration was estimated from transplanting to harvest.

Table 4
p-value from the analysis of variance for the soil dryness index during the growing season of different field positions evaluated at two sites and for two years.

Source of variation	Degree of freedom	F-value
Year (Y)	1	0.280
Site (S)	1	0.004**
Position (P)	2	0.045*
Y x S	1	0.897
Y x P	2	0.166
S x P	2	0.363
S x Y x P	2	0.444

between the two schemes in Year 2 (Fig. 6A). Field position effects on rice yield varied by year and by site (Table 7). Field position had a significant effect on rice yield in Year 2, but not in Year 1 (Fig. 6B). Besides, field position had a significant effect on rice yield in Mbe, but not in Lokapkli (Fig. 6C). Among water management practices, rice yield was lower under FP than safe AWD and CF while there was no significant difference between rice yield of safe AWD and CF (Table 8). No relationship was observed between the soil dryness index during the growing season and rice yield in fields with safe AWD and CF (Fig. 7), but a negative relationship was found in fields with FP (Fig. 7).

Water productivity was higher in Year 1 (0.82 kg/m^3/ha) than in Year 2 (0.54 kg/m^3/ha) (Tables 7 and 8). There was a significant site by year interaction effect on water productivity (Table 7). While in Year 1, water productivity was higher in Lokapkli than in Mbe (Fig. 8A), no significant difference in water productivity between the two schemes was found in Year 2 (Fig. 8A). Field position effects on water productivity varied by year and by site (Table 7). Field position had a significant effect on water productivity in Year 2, but not in Year 1 (Fig. 8B). Besides, field position had a significant effect on water productivity in Mbe, but not in Lokapkli (Fig. 8C). Water management had a significant effect on water productivity (Tables 7 and 8). Compared to CF, water productivity was 23 % higher under safe AWD while there was no significant difference in the water productivity between CF and FP (Table 8).

Rice milling recovery was significantly higher in Lokapkli (66 %) than in Mbe (62 %) (Tables 7 and 8). No significant effect of field position and water management practice on rice milling recovery was found (Table 7). Head rice yield was 52 % on average (Table 8). No significant effect of water management on head rice yield was found (Table 7). The interaction effects of field position and site on head rice yield and chalkiness were significant (Table 7). Field position had a significant effect on head rice yield and chalkiness in Lokapkli, but not in Mbe (Fig. 9).

3.3. Factors affecting weed biomass, rice yield, water productivity, milling recovery, head rice yield and chalkiness in the fields with the safe alternate wetting and drying method of irrigation

Table 10 shows the most important variables that explained variability in weed biomass, rice yield, water productivity, milling recovery, head rice yield, and chalkiness in the fields with the safe AWD method of irrigation. Among the models used to explain weed biomass in the safe AWD fields, model 8 provided the best fit with an AIC of 564. This model considers the timing of the first weeding operation and rice variety for explaining 33 % of the variability in weed biomass. There was a positive relationship between the timing of the first weeding operation and weed biomass (Table 10). Model 18 provided the best fit for explaining rice yield in the safe AWD fields with an AIC of 159 (Table 10). This model considers soil pH, soil organic carbon, nitrogen fertilizer input, date of transplanting, and timing of third fertilizer application and explained 45 % of the variability in rice yield. There was a positive relationship between rice yield and soil pH, nitrogen fertilizer input, and the timing of the third fertilizer application (Table 10). For the factors explaining

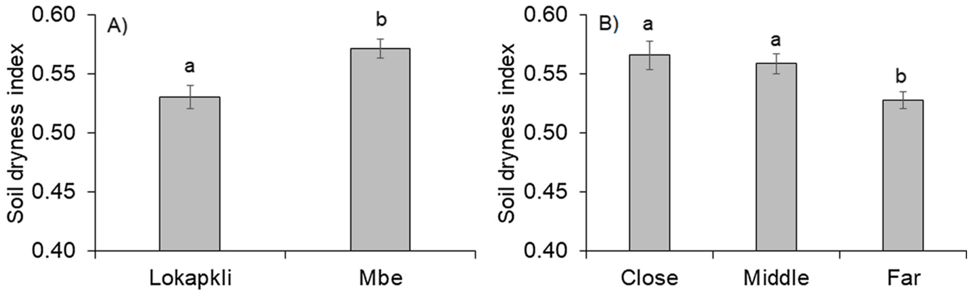

Fig. 2. Soil dryness during the growing season in the irrigation schemes of Mbe and Lokapkli (A) and in the fields located close, at a middle distance and far from the water source (B). Means with different lower-case letters across schemes (A) and positions (B) are significantly different at p ≤ 0.05. The error bars represent the standard error.

Table 5
Model parameters explaining variability in the soil dryness indices during the growing season in the fields with the safe alternate wetting and drying (safe AWD) and farmer's practice (FP) of irrigation.

Variable	Estimate	95 % confidence interval		P-value
		Lower	Upper	
Soil dryness index (P – H) [a]				
Fields with safe AWD – Model 28				
Intercept	−13.534	−1.789	0.147	<0.001
Field elevation	0.051	−0.032	0.015	<0.001
Soil organic carbon	−0.014	0.002	0.009	0.827
Fields with FP – Model 28				
Intercept	−5.354	−1.789	0.147	0.004
Field elevation	0.021	−0.032	0.015	0.002
Soil organic carbon	−0.035	0.002	0.009	0.440

[a] Soil dryness index (P - H): soil dryness index measured from planting (P) to harvest (H).

variability in water productivity, model 12 provided the best fit with an AIC of -35 (Table 10). This model considers soil pH, nitrogen fertilizer input, and timing of the third fertilizer application for explaining 68 % of the variability in water productivity. There was a positive relationship between water productivity and soil pH, nitrogen fertilizer rate and the timing of the third fertilizer application (Table 10).

For the factors explaining variability in milling recovery, model 10 provided the best fit with an AIC of 112 (Table 10). This model considers variety and soil organic carbon for explaining 20 % of the variability in the milling recovery. The expected increase in milling recovery from JT11 to ORYLUX6 was 5%. In the case of head rice yield, model 6 provided the best fit with an AIC of 139. This model considers the variety used by farmers for explaining 34 % of the variability in head rice yield. For rice chalkiness, Model 7 provided the best fit with an AIC of 129. This model considers the variety and age of seedling for explaining 78 % of the variability in the rice chalkiness. The expected increase in rice chalkiness from JT11 to WITA9 was 27 % (Table 10). In safe AWD fields, rice yield and water productivity were strongly positively correlated (Table 11). Irrigation water input in the safe AWD fields was not related to rice yield or water productivity. However, head rice yield and weed biomass and head rice yield and chalkiness were negatively correlated (Table 11).

4. Discussion

4.1. Weed biomass in response to water and crop management

There have been limited studies on the effects of AWD on weed infestation (Luo et al., 2017; Gealy et al., 2019). Luo et al. (2017) evaluated the effects of water management on weed infestation and diversity in East China and reported that AWD reduced weed density and coverage compared to CF. Gealy et al. (2019) assessed the effects of

Table 6
Most dominant (>10 % occurrence for any weeding operation) weed species and soil dryness index of three water management practices evaluated in farmers' fields located at three positions across two growing seasons. Plant family, frequency of occurrence (Freq. %) in 90 plots, weed group (B: broad-leaved; G: grasses; S: sedges), and ecological preference (Ecosystem; H: hydromorphic; L: lowland) are presented for weed species.

Species	Family	Weed group	Ecosystem	Position [a]			Water management [b]		
				Close	Middle	Far	AWD	CF	FP
Ammannia auriculata	Lythraceae	B	L	8	9	10	10	9	8
Bacopa decumbens	Scrophulariaceae	B	L	7	6	6	6	6	7
Cyperus difformis	Cyperaceae	S	L/H	14	12	10	13	12	11
Cyperus iria	Cyperaceae	S	H	2	2	2	2	2	2
Echinochloa colona	Poaceae	G	L/H	1	2	2	2	1	2
Echinochloa crus-pavonis	Poaceae	G	L/H	4	6	5	4	5	6
Fimbristylis littoralis	Cyperaceae	S	H	11	7	7	10	9	6
Heteranthera callifolia	Pontederiaceae	B	L	15	15	17	13	20	14
Leptochloa caerulescens	Poaceae	G	L/H	18	13	12	13	13	17
Lindernia crustacea	Linderniaceae	B	L/H	3	3	5	3	5	3
Ludwigia abyssinica	Onagraceae	B	L	11	12	10	9	12	12
Marsilea minuta	Marsileaceae	B	L	2	3	3	3	3	2
Nymphaea Lotus	Nymphaeaceae	B	L	2	4	4	4	3	3
Panicum laxum	Poaceae	G	H	2	3	2	2	3	2
Sphenoclea zeylanica	Sphenocleaceae	B	L	15	14	13	12	17	13
Spilanthes filicaulis	Asteraceae	B	H	3	4	4	3	4	4
Soil dryness index (P – H) [b]				0.42 ± 0.19	0.40 ± 0.21	0.37 ± 0.18	0.50 ± 0.08	0.14 ± 0.06	0.55 ± 0.05

Field positions are close, at a middle distance and far from the water source.
[a] Water management practices are safe AWD: safe alternate wetting and drying; CF: continuous flooding; FP: farmer's practice.
[b] Soil dryness index (P - H): soil dryness index measured from planting (P) to harvest (H). Mean ± standard deviation is presented.

Table 7
p-value from the analysis of variance for weed biomass (g/m^2), irrigation water input (mm), total water input (rainfall + irrigation water input) (mm), number of irrigations, rice yield (t/ha), water productivity (kg/m^3/ha), milling recovery (%), head rice yield (%) and chalkiness (%) of field position and water management evaluated at two sites and for two years.

Variable	Df	Weed biomass	Irrigation water	Total water	No. of irrigations	Yield	Water productivity	Milling recovery	Head rice yield	Chalkiness
Site (S)	1	0.348	0.007	0.007	0.954	<0.001	<0.001	<0.001	0.481	0.014
Year (Y)	1	0.004	<0.001	<0.001	<0.001	<0.001	<0.001	–	–	–
Position (P)	2	0.487	0.597	0.597	0.091	0.510	0.159	0.877	0.001	0.829
Water management (W)	2	<0.001	<0.001	<0.001	<0.001	0.008	<0.001	0.715	0.673	0.848
S x Y	1	0.109	<0.001	<0.001	0.503	0.002	0.007	–	–	–
S x P	2	<0.001	0.207	0.207	0.003	0.015	0.021	0.572	0.008	<0.001
Y x P	2	0.163	0.054	0.054	0.068	0.029	0.047	–	–	–
S x W	2	0.431	0.686	0.686	0.192	0.618	0.210	0.124	0.209	0.734
Y x W	2	0.055	0.886	0.887	0.070	0.668	0.339	–	–	–
P x W	4	0.289	0.842	0.842	0.820	0.634	0.659	0.535	0.363	0.893
S x Y x P	2	0.359	0.721	0.721	0.077	0.233	0.348	–	–	–
S x Y x W	2	0.537	0.083	0.083	0.107	0.969	0.610	–	–	–
S x P x W	4	0.816	0.715	0.715	0.276	0.846	0.887	0.479	0.182	0.717
Y x P x W	4	0.590	0.769	0.769	0.760	0.793	0.876	–	–	–
S x Y x P x W	4	0.939	0.997	0.997	0.856	0.985	0.986	–	–	–

Dash symbol indicates no data because rice grain quality was assessed only in Year 2.

Table 8
Weed biomass, irrigation water input, total water input (rainfall + irrigation water input), number of irrigations, rice yield, water productivity, milling recovery, head rice yield and chalkiness of field position and water management practice evaluated at two sites and for two years.

Variables	Weed biomass (g/m^2)	Irrigation water (mm)	Total water (mm)	No. of irrigations	Yield (t/ha)	Water productivity (kg/m3/ha)	Milling recovery (%)	Head rice yield (%)	Chalkiness (%)
Site (S)									
Mbe	167 a	311 a	827 a	6.0 a	5.0 a	0.63 a	62.0 a	52 a	3.1 a
Lokapkli	184 a	285 b	802 b	6.0 a	6.2 b	0.80 b	66.0 b	53 a	8.1 b
Year (Y)									
Year 1	197 a	218 a	733 a	6.0 a	6.0 a	0.82 a	–	–	–
Year 2	144 b	419 b	939 b	7.0 b	5.0 b	0.54 b	–	–	–
Position (P)									
Close	163 a	315 a	832 a	6.0 a	5.4 a	0.67 a	64 a	56 a	2.7 a
Medium	183 a	289 a	806 a	6.0 a	6.4 a	0.73 a	62 a	50 b	4.1 a
Far	179 a	293 a	809 a	6.0 a	5.7 a	0.72 a	63 a	50 b	8.0 b
Water management (W)									
Safe AWD	133 a	190 a	707 a	4.0 a	5.6 ab	0.81 a	63 a	51 a	5.5 a
CF	208 b	403 c	920 c	8.0 c	5.9 a	0.67 b	64 a	53 a	4.2 a
FP	186 b	302 b	819 b	6.0 b	5.2 b	0.66 b	63 a	52 a	3.9 a

Numbers followed by different letters in a column within a set are significantly different at $p \leq 0.05$ by the HSD test.
Dash symbol indicates no data because rice grain quality was assessed only in Year 2.

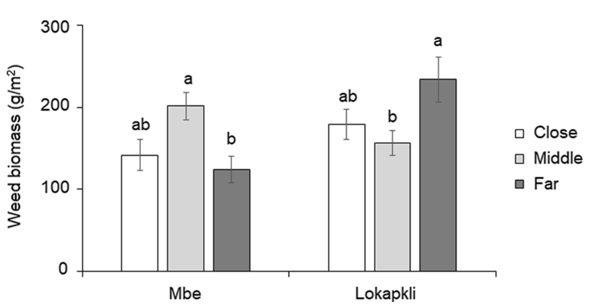

Fig. 3. Weed biomass in the irrigation schemes of Mbe and Lokapkli in fields located close, at a middle distance, and far from the water source. Means with different lower-case letters across positions within each scheme are significantly different at $p \leq 0.05$. The error bars represent the standard error.

water management on the weed biomass of *Echinochloa crus-galli* in USA and showed that the dry biomass of *Echinochloa crus-galli* was lower under AWD than CF. The results of our study substantiated these earlier findings. Lower weed biomass under safe AWD than CF in our study was attributed to two reasons. First, the fact that safe AWD fields were maintained flooded during the first 10 days after transplanting might have limited the establishment of weeds as many weed species will not germinate under anaerobic conditions (Rodenburg and Johnson, 2009). Second, the higher soil dryness index during the growing season in safe AWD fields reduced the growth of lowland and broad-leaved weeds particularly of *Heteranthera callifolia* and *Sphenoclea zeylanica* (Table 6). Further reduction in weed biomass in the safe AWD fields was associated

Table 9
Model parameters explaining variability in weed biomass (g/m^2) in fields with continuous flooding and alternate wetting and drying method of irrigation.

Variable	Estimate	95 % confidence interval		P-value
		Lower	Upper	
Weed biomass (n = 100) – Model 5				
Intercept	234.370	198.971	269.763	<0.001
Soil dryness index (P - H) [a]	−199.730	−294.671	−104.795	<0.001

[a] Soil dryness index (P - H): soil dryness index measured from planting (P) to harvest (H).

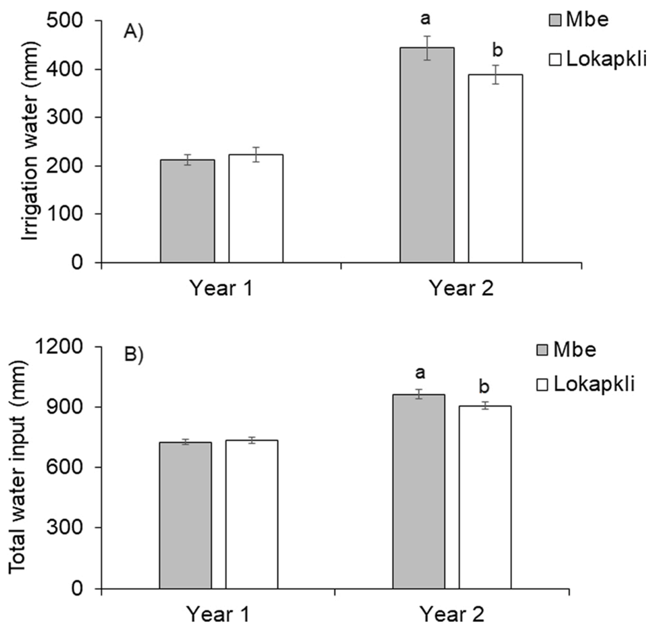

Fig. 4. Irrigation water input in the irrigation schemes of Mbe and Lokapkli in two experimental years (Year 1 and Year 2) (A), total water input (irrigation + rainfall) in the irrigation schemes of Mbe and Lokapkli in two experimental years (Year 1 and Year 2) (B). Means with different lower-case letters across sites within each year are significantly different at $p \leq 0.05$. The error bars represent the standard error.

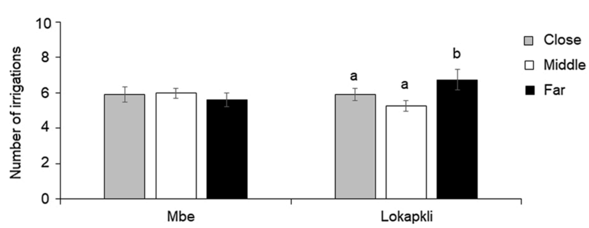

Fig. 5. Number of irrigations in the schemes of Mbe and Lokapkli in the fields located close, at a middle distance and far from the water source. Means with different lower-case letters across locations within each scheme are significantly different at $p \leq 0.05$. The error bars represent the standard error.

with the timing of the first weeding operation (Table 10). In this study, the average date of the first weeding operation is 24 days after transplanting (DAT). Weed biomass was lower in the safe AWD fields in which the first weeding operation was made earlier possibly because the fields were maintained flooded until the first 10 DAT and a weeding operation before 24 DAT might reduce weed establishment and persistence. Previous studies emphasized the need for early post-emergence weed control to reduce weed infestation and rice – weed competitiveness in irrigated rice system (Johnson et al., 2004; Singh et al., 2005; Rao et al., 2007). The timing of the second weeding operation was not determinant in reducing the weed biomass in safe AWD fields because it did not have large variation in farmers' fields. Most farmers weed their field between 51 and 60 days after transplanting. This period corresponds to the panicle initiation phase when farmers want to have their fields free of weeds to avoid yield reduction due to weeds.

4.2. Irrigation water input, rice yield and water productivity in response to water and crop management

Across years, schemes, and field positions, safe AWD implementation decreased the irrigation water input by 53 % and the number of irrigations by 50 % compared to CF (Table 8). These results are consistent

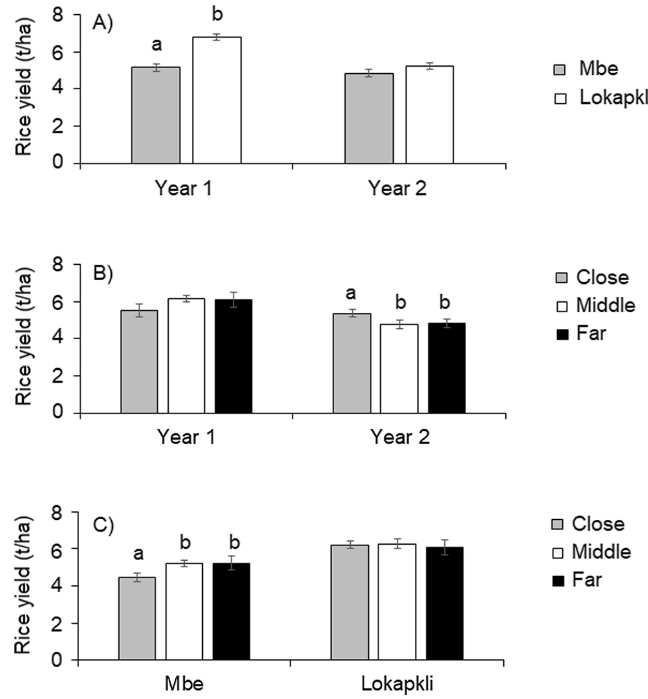

Fig. 6. Rice yield in the irrigation schemes of Mbe and Lokapkli in the experimental years 1 and 2 (A), in the fields located close, at a middle distance and far from the water source in the experimental years 1 and 2 (B) and in the irrigation schemes of Mbe and Lokapkli in the fields located close, at a middle distance, and far from the water source (C). Means with different lower-case letters within each year (A and B) or within each scheme (C) are significantly different at $p \leq 0.05$. The error bars represent the standard error.

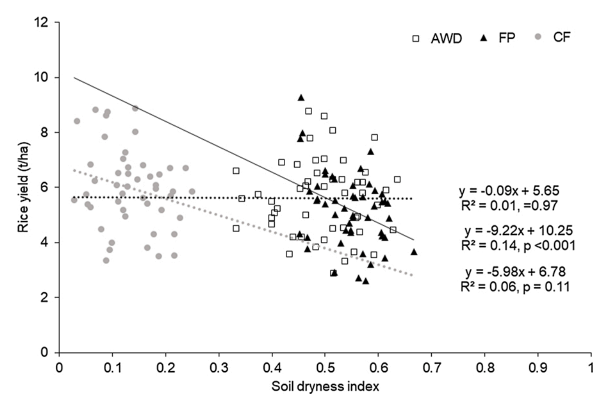

Fig. 7. Relationship between soil dryness index during the growing season and rice yield in fields with the safe alternate wetting and drying (safe AWD), continuous flooding (CF) and farmer's practice of irrigation (FP). The discontinuous black, discontinuous grey and continuous black lines represent the linear relationships between soil dryness index and rice yield for fields with safe AWD, CF and FP, respectively. Model performance metrics (R^2 and p-value) are presented for AWD, FP and CF (top, middle, bottom).

with previous findings from Senegal, China, Philippines, and Bangladesh (Zhang et al., 2008; de Vries et al., 2010; Lampayan et al., 2015; Liang et al., 2016; Yang et al., 2017; Djaman et al., 2018). Lower irrigation water input and number of irrigations under safe AWD compared to CF could be explained by reduced loss of non-productive water through evaporation, seepage, and percolation which could represent 15–48% of the total water input (Sharma et al., 2002; Cabangon et al., 2004). Across site, field position and water management, the average total water input (irrigation + rainfall) was 733 mm in Year 1 and 939 mm in Year 2. Mean values of total water input observed in this study were

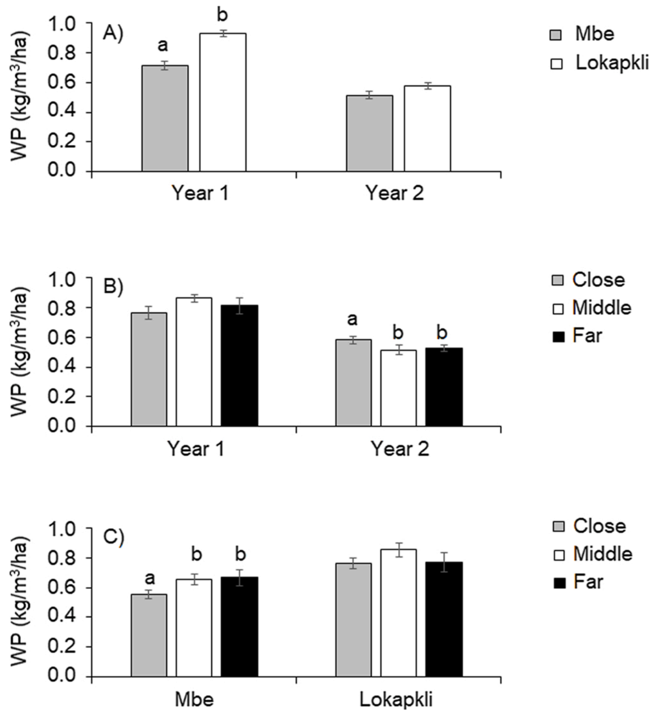

Fig. 8. Water productivity (WP) in the irrigation schemes of Mbe and Lokapkli in the experimental years 1 and 2 (A), in the fields located close, at a middle distance and far from the water source in the experimental years 1 and 2 (B) and in the irrigation schemes of Mbe and Lokapkli in the fields located close, at a middle distance, and far from the water source (C). Means with different lower-case letters across scheme within each year (A), across location within each year (B) or across location within each scheme (C) are significantly different at $p \leq 0.05$. The error bars represent the standard error.

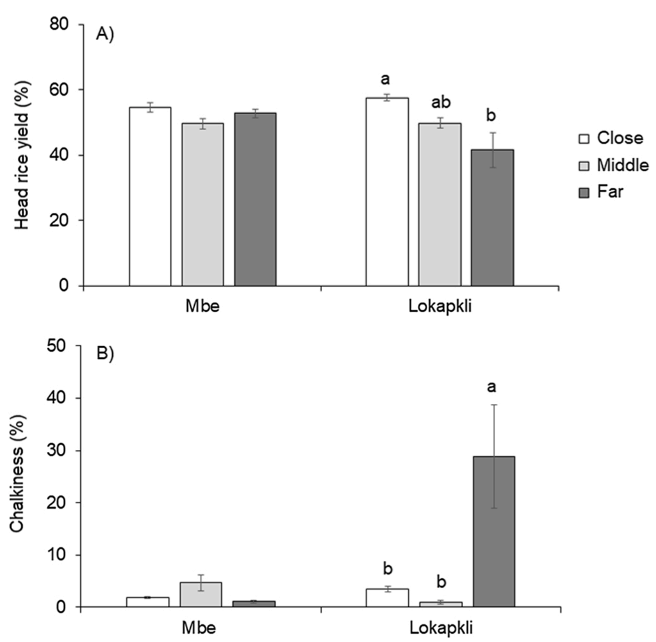

Fig. 9. Head rice yield (A) and chalkiness (B) in the irrigation schemes of Mbe and Lokapkli in the fields located close, at a middle distance, and far from the water source. Means with different lower-case letters across position within each scheme are significantly different at $p \leq 0.05$. The error bars represent the standard error.

Table 10
Model parameters explaining variabilities in weed biomass (g/m^2), rice yield (t/ha), water productivity ($kg/m^3/ha$), milling recovery (%), head rice yield (%) and chalkiness (%) in the rice fields with the safe alternate wetting and drying method of irrigation.

Variable	Estimate	95 % confidence interval		P-value
		Lower	Upper	
Weed biomass (n = 50) – Model 8				
Intercept	−172.510	−300.950	−44.070	0.010
Timing of the first weeding operation	13.680	8.214	19.146	<0.001
Variety				
ORYLUX6	−31.602	−102.354	39.150	0.373
WITA9	−21.400	−60.047	17.247	0.271
Yield (n = 50) – Model 18				
Intercept	−13.694	−25.052	−2.336	0.019
Soil pH	2.731	0.818	4.644	0.006
Soil organic carbon	0.457	−0.136	1.049	0.127
Nitrogen fertilizer input	0.019	0.005	0.033	0.011
Timing of the third fertilizer application	0.056	0.002	0.110	0.041
Date of transplanting	−0.025	−0.053	0.003	0.084
Water productivity – Model 12				
Intercept	−2.158	−3.647	−0.670	0.005
Soil pH	0.318	0.060	0.577	0.017
Nitrogen fertilizer input	0.006	0.004	0.008	<0.001
Timing of the third fertilizer application	0.011	0.004	0.019	0.003
Milling recovery (n = 25) – Model 10				
Intercept	57.885	50.610	65.161	<0.001
Variety				
ORYLUX6	4.827	0.144	9.509	0.044
WITA9	3.678	−1.074	8.431	0.120
Soil organic carbon	1.594	−0.801	3.988	0.177
Head rice yield (n = 25) – Model 6				
Intercept	52.758	48.854	56.662	<0.001
Variety				
ORYLUX6	4.869	−4.424	14.162	0.284
WITA9	−13.128	−22.421	−3.835	0.008
Chalkiness (n = 25) – Model 7				
Intercept	−18.181	−40.420	4.058	0.102
Variety				
ORYLUX6	−1.776	−9.378	5.827	0.627
WITA9	27.133	19.895	34.371	<0.001
Age of seedling	0.884	−0.065	1.833	0.066

within the range (635–1563 mm) of previous studies in West Africa (de Vries et al., 2010; Krupnik et al., 2012; Djaman et al., 2018). A portion of the total water supplied to the plants through irrigation and rainfall is lost through seepage, percolation, and evapotranspiration. However, the capillary rise of groundwater, which supplements irrigation and rainfall to meet water needs for rice and compensate for water loss through seepage, percolation, and evaporation, is another source of water for rice plants in irrigated systems. Total water inputs in lowland rice in Asia have been reported to range from 400 mm in heavy clay soils with shallow groundwater to over 2000 mm in coarse-textured soils with deep groundwater (Bouman and Tuong, 2001; Tuong et al., 2005). The total water input (irrigation + rainfall) values found in our study are within the range of 400 and 2000 mm.

Rice yield was not significantly different in safe AWD and CF fields. Owing to the significant reduction in irrigation water input without yield penalty, safe AWD increased water productivity by 21 % compared to CF. These results are in good agreement with previous findings (Lampayan et al., 2015; Liang et al., 2016; Yang et al., 2017; Carrijo et al., 2017). Rice yield and water productivity were higher in Year 1 than in Year 2 (Table 8), which could be attributed to the higher rate of nitrogen fertilizer used by farmers in Year 1 than in Year 2 (Table 3). Compared to safe AWD and CF, rice yield was lower with FP practice of

Table 11
Correlations between rice yield (t/ha), irrigation water input (mm), water productivity ($kg/m^3/ha$), weed biomass (g/m^2), milling recovery (%), head yield (%) and chalkiness (%) in the fields with the safe alternate wetting and drying method of irrigation.

	Rice yield	Irrigation water	Water productivity	Weed biomass	Milling recovery	Head yield	Chalkiness
Rice yield	1	−0.33	0.94***	0.01	−0.04	0.24	−0.38
Irrigation water		1	−0.28	0.05	−0.19	−0.26	0.05
Water productivity			1	−0.06	0.09	0.36	−0.39
Weed biomass				1	−0.32	−0.49*	0.05
Milling recovery					1	0.27	0.28
Head yield						1	−0.65**
Chalkiness							1

* Significant at $p < 0.05$.
** Significant at $p < 0.01$.
*** Significant at $p < 0.001$.

water management, possibly due to prolonged soil drying in the fields located at a higher altitude with FP (Table 5), which negatively affected rice yield (Fig. 7). Fields located at a higher altitude might have a deeper groundwater table as previously reported by Condon and Maxwell (2015) in the USA. Unlike rice yield with FP, rice yield with safe AWD was not dependent on the soil dryness index during the growing season (Table 10), indicating that safe AWD can avoid prolonged soil drying in drought-prone areas due to the use of the field water tube to monitor soil water status. Large variabilities observed in soil properties and agricultural practices in experimental fields (Table 3) could be reflected in the significant site by year, position by year and site by position interaction effects on rice yield and water productivity (Table 7).

In the fields with safe AWD water management, increases in rice yield and water productivity were associated with an increase in soil pH, the timing of the third fertilizer application, and nitrogen fertilizer rate (Table 10). The average soil pH in the safe AWD fields in this study was 5.8, while the optimum soil pH for rice in West Africa is 6.6 (Narteh and Sahrawat, 1999). Higher rice yield with an increase in soil pH in the safe AWD fields might be attributed to higher availability of nutrients such as nitrogen, phosphorus, potassium, sulfur, calcium, magnesium, and molybdenum to rice plants (Kashem and Singh, 2001; Fageria et al., 2011). We found that safe AWD fields that received the third split of fertilizer application late had greater yields (Table 10). The average timing for the third split of fertilizer application in this study was 44 DAT (Table 3), which corresponded to the pre-panicle initiation stage. There might be a lower loss of nitrogen through N_2O emission and ammonia volatilization when the third split of fertilizer was applied later because the safe AWD fields were flooded from panicle initiation to flowering stage (50–70 DAT) and a nitrogen application after 44 DAT might have enhanced the efficiency of the applied nitrogen. Previous studies reported the effects of field water status on N_2O emission and ammonia volatilization (Bouwmeester et al., 1985; Johnson-Beebout et al., 2009; Lagomarsino et al., 2016; Sibayan et al., 2018). Besides, applying the third split of fertilizer at the panicle initiation stage when crop demand in nitrogen is higher than at a pre-panicle initiation stage enhances nutrient uptake by rice plants and yield (Fageria, 2004). The variation in rice yield with the timing of the third split fertilizer application in safe AWD fields suggests the need to increase the congruence between crop N demand and N supply. In agreement with previous studies, rice yield in safe AWD fields increased with an increase in nitrogen fertilizer rate (de Vries et al., 2010; Liu et al., 2013; Wang et al., 2016; Islam et al., 2018). Similarly, to rice yield, increases in water productivity in safe AWD fields were associated with an increase in soil pH, timing of the third fertilizer application, and nitrogen fertilizer rate (Table 10).

4.3. Grain quality independent of water management, but strongly affected by choice of rice variety

Milling recovery, head rice yield and chalkiness were independent of water management (Table 7). It is plausible that under safe AWD and FP, the decrease in soil moisture did not reach the level that affects the grain quality parameters evaluated. In this study, fields were irrigated to 5 cm depth from 10 days after transplanting to the panicle initiation stage and after the flowering stage until seven days before harvest whenever soil water reaches – 15 cm in safe AWD fields. In fields with FP water management, fields were intentionally kept wet by the farmers during most of the growing season. An earlier study indicated that the effect of safe AWD on grain quality depends on the threshold at which the soil is re-watered (Yang et al., 2017). No decrease in grain quality was reported in the field re-watered to 5 cm depth whenever soil water potential reaches – 25 kPa at 15–20 cm below the soil surface. However, a decrease in grain quality by 7.5–7.8% was reported in the field re-watered to 5 cm depth whenever soil water potential reaches – 50 kPa (Zhang et al., 2008). Increases in milling recovery, head rice yield, and chalkiness in the safe AWD fields were strongly dependent on the choice of rice variety in agreement with previous findings (Zhou et al., 2015; Jabran et al., 2017; Zhang et al., 2008). Among the three rice varieties used by farmers, ORYLUX6 had a higher milling recovery compared to JT11 and WITA9 (Table 10) while WITA 9 had a lower head rice yield and a higher chalkiness compared to JT11 and ORYLUX6 (Table 10).

4.4. Relationship between weed biomass, rice yield, irrigation water input, water productivity and grain quality in the safe AWD fields

A strong positive correlation was observed between rice yield and water productivity in the fields with safe AWD (Table 9), suggesting that an increase in rice yield is of paramount importance to improve water productivity in safe AWD fields. However, rice yield and water productivity in the safe AWD fields were independent of the weed biomass (Table 9). According to Rodenburg et al. (2009), the relationship between rice yield and weed biomass depends on the weed management. In weed-free fields (fields kept free of weeds through regular weeding operations), rice yield is independent on weed biomass. However, in weedy fields (fields weeded only once), a negative relationship between rice yield and weed biomass was reported (Rodenburg et al., 2009). In this study, the AWD fields were flooded during the first 10 days after transplanting, and afterward, farmers weeded their fields twice. Such management practices might have limited the establishment and growth of weeds in safe AWD fields, which might not reach the level that would induce a yield reduction. There was no correlation between irrigation water input and rice yield or irrigation water input and water productivity in the safe AWD fields. These results indicated synergies between yield and water productivity, and no trade-off between weeds, irrigation water input, yield and water productivity in safe AWD fields. However, weed biomass was negatively correlated with head rice yield, indicating an increase in head rice yield with lower weed biomass. Similar results were reported by Tindall et al. (2005) and Rao et al. (2007) who attributed a higher grain quality with a decrease in weed biomass to a higher percentage of whole grain. There was a negative relationship between head rice yield and chalkiness in this study (Table 11), in line with a previous report (Zhou et al., 2015).

5. Conclusions

This study analyzed data from on-farm multi-location trials, field observations and interviews with farmers to assess the effects of water management on weed biomass, irrigation water input, number of irrigations, rice yield, water productivity, milling recovery, head rice yield, chalkiness, and to identity the factors affecting their variability in the fields with safe AWD method of irrigation. The findings indicated that safe AWD decreased weed biomass, irrigation water input, the number of irrigations, and increased water productivity while maintaining rice yield, milling recovery, head yield, and chalkiness compared to CF. The lower weed biomass in safe AWD fields compared to CF was attributed to the fact that the safe AWD fields were kept flooded for the first 10 days after transplanting, suppressing weeds, and had a higher soil dryness index, reducing lowland and broad-leaved weeds. Higher rice yield and water productivity in the AWD fields were associated with higher soil pH and nitrogen fertilizer rate and better congruence between nitrogen fertilizer application and crop nitrogen demand. Milling recovery, head yield, and chalkiness in the AWD fields were strongly affected by the choice of rice variety. Combination of AWD with varieties having good grain quality characteristics and improved nutrient management practices could be recommended to the smallholder rice farmers to improve rice yield, water productivity, and grain quality and reduce labour requirement for irrigation and weeding particularly in schemes where lowland weeds are dominant.

Author statement

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Declaration of Competing Interest

The authors report no declarations of interest.

Acknowledgements

This study was financially supported by the European Union and International Fund for Agricultural Development (IFAD) under the project “Sustainable and Diversified Rice-based Farming Systems [DCI-FOOD/ 2015/360-968]” under the program “Putting Research into Use for Nutrition, Sustainable Agriculture and Resilience (PRUNSAR).” We thank Mr. Kouakou Brou, Mr. Nestor N’goran Kouame, and Mr. François Konan, technicians at AfricaRice for their support in the data collection. We thank Dr. Sali Atanga Ndindeng for the support in the rice grain quality analysis.

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