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Effects of drainage intensity on water and nitrogen use efficiency and rice grain yield in a semi-arid marshland in Rwanda

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ABSTRACT

Drainage management is important in intensification of irrigated paddy rice production. This study assessed the effects of drainage intensity on water and nitrogen use efficiency and rice grain yield in a field experiment conducted during three seasons in Rwanda. The experiment comprised 12 plots with four blocks and three treatments: $DS_{0.6}$ (0.6 m deep drain), $DD1_{1.2}$ (1.2 m deep drain, control structure open four times per week), and $DD2_{1.2}$ (1.2 m deep drain, control structure open two times per week). Outflow was calculated from water balance. Nitrogen (N) content in drainage water was determined weekly. Crop yield and N uptake were determined in grain and straw.

In all seasons, grain yield was 61–131% higher, crop N uptake was 24–90% higher, harvest index (HI) was 24–65% higher and water use efficiency (WUE) was 50–150% higher in treatments $DD1_{1.2}$ and $DD2_{1.2}$ than in $DS_{0.6}$. There was a decrease in soil carbon/nitrogen ratio at the end of Seasons 2 and 3. Recirculating straw to fields is thus necessary to replenish SOC for long-term soil fertility. A practical implication of the study is that managed deep drainage systems could enhance water use efficiency and rice grain yield in poorly drained paddy fields.

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Surface drainage; paddy rice; nutrient losses; rice yield; harvest index

Introduction

Paddy rice is a water-demanding crop that requires large amounts of fresh water under flooded-irrigated conditions. Water consumption by paddy rice fields accounts for 40% of all irrigation water globally, while paddy rice fields are also responsible for 10% of global methane emissions (ESG 2019). Paddy rice is grown under continuously flooded conditions, and hence most conventional water management practices aim to maintain a standing depth of water in the field throughout the season. Water productivity is generally low under continuously flooded irrigation. Moreover, decreasing water availability for agriculture threatens the productivity of irrigated agro-ecosystems, so ways must be sought to save irrigation water and maintain rice yield (Zhi 2002).

Drainage of agricultural land is a common measure to increase production, safeguard sustainable investment in irrigation and conserve land resources. In arid and semi-arid regions, drainage also critically provides leaching capability to control salinity build-up in the crop root zone and the soil profile (Ritzema et al. 2008). Field water management can create a favourable environment for crop growth and also reduce nitrogen (N) losses through leaching (Skaggs et al. 2012). Improved water management in drained paddy fields is possible through controlling drainage depth and allowing drainage during specific periods, thereby decreasing the drainage intensity and saving irrigation water (Skaggs et al. 2012).

Drainage intensity management involves the use of weirs or 'stop-log' structures to raise the water level in the drainage outlet, thereby reducing N loads in drainage effluent (Skaggs et al. 2005; Wesström et al. 2014). A previous study on paddy fields in China found that reducing drainage depth resulted in a drainage flow reduction of 50–60%, but no clear trend was observed in N concentration changes in drainage water (Luo et al. 2008). In a field study in Iran, Darzi-Naftchali and Ritzema (2018) concluded that managed drainage can reduce N losses in drainage water and improve paddy rice yields compared with conventional drainage.

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Nitrogen is the key element in production of rice. Paddy soils in irrigated and rainfed lowland rice production systems have a prolonged period of submergence (Buresh and Haefele 2010). A specific feature of submerged soils is simultaneous formation and loss of nitrate (NO_3^-) within adjoining aerobic and anaerobic soil zones. The accumulated NO_3^- in aerobic soils during the dry season is lost during the transition to anaerobic conditions, through nitrification-denitrification and leaching. Nitrogen losses in drainage water are undesirable because they represent loss of valuable nutrients, and hence an economic loss (Darzi-Naftchali et al. 2017). In addition, N losses in drainage water raise environmental concerns linked to their impact in surface water eutrophication (Kröger et al. 2012). Understanding the magnitude and pathways of N losses in paddy fields is essential for decision making to improve N use efficiency in paddy fields and avoid N pollution (Darzi-Naftchali et al. 2017).

Paddy rice production has become a significant component of the agricultural sector in Rwanda (MINAGRI 2011). The Crop Intensification Program (CIP) in Rwanda is working towards consolidation of farmland use and facilitating access to inputs, including providing improved seeds and fertilisers at subsidised rates to farmers. In general, this has resulted in increased N fertiliser use, e.g. from 4 to 32 kg ha^{-1} between 2007 and 2014. The area under irrigated rice cultivation in Rwanda increased from 3549 ha in year 2000 to around 17,000 ha in year 2014. The recommended fertiliser rate for rice in Rwanda is 80 kg N ha^{-1}, 15 kg P ha^{-1} and 28 kg K ha^{-1} (Cyamweshi et al. 2017). The average rice grain yield is 5.5 tons ha^{-1} (Ghins and Pauw 2017).

Shallow agricultural drainage systems, as used for example in most rice-producing semi-arid marshlands in Rwanda, are not sufficient to manage potential soil salinity problems. Such drainage systems are generally designed only to protect rice crops from excess soil water conditions during the seedling and maturity stages, and improve accessibility for tillage operations and harvesting. Increased use of agricultural inputs, coupled with the shallow drainage systems in paddy fields in Rwanda, has raised concerns about potential negative impacts on the environment and, in turn, potential threats to human health and biodiversity (REMA 2011).

In 2016 and 2017, a three-season field experiment was carried out to assess the effects of drainage intensity on water and N use efficiency and rice grain yield in Muvumba Marshland in Rwanda. The research hypothesis was that managed drainage intensity reduces N loads in drainage water and improves rice yield.

Materials and methods

Site description

The experimental site was in Muvumba Marshland (1° 17′33.0″S 30°18′48.2″E; 1513 m above sea level) in north-eastern Rwanda (Figure 1a). The region has a semi-arid climate, with mean annual temperature of 20°C and mean annual rainfall of 827 mm (Nyagatare station, 1984–2013). Annual potential evapotranspiration exceeds 1400 mm. Rainfall is distributed over two rainy seasons, one from mid-February to mid-June and another from September to mid-December, with precipitation peaks in April and November (Figure 2).

The marshland is divided into three areas with width varying from 200 to 800 m that extend over 27 km along the Muvumba River. Each area is sub-divided into irrigation sectors. The cropping system in the marshland generally consists of continuous rice cropping without crop rotation. Basin irrigation, a traditional method for paddy rice, is used and two rice crops are produced per year. Irrigation water comes from a dam diverted from the Muvumba River (Figure 1b). A main channel from the dam (blue line in Figure 1b) distributes water to three storage dams with distributing reservoirs. Thirty-nine secondary channels supply water to tertiary channels that irrigate the rice fields. The drainage system consists of eight collectors and secondary drains, which are mainly designed to remove excess water. The experimental site was located in the southern part of the marshland (Figure 1c).

Field plots

The field experiment was run over three seasons: March-July 2016 (Season 1), September 2016-January 2017 (Season 2) and March-July 2017 (Season 3). The experiment comprised four blocks (I, II, III and IV) each with three treatments (plots), arranged in a randomised complete block design (Figure 3a). The treatments were: $DS_{0.6}$ (0.6 m deep drain (the traditional drainage system in the study area), control structure open four times per week), $DD1_{1.2}$ (1.2 m deep drain, control structure open four times per week) and $DD2_{1.2}$ (1.2 m deep drain, control structure open two times per week). The area of individual plots was 8 m × 8 m and a 4 m wide zone separated adjacent plots and blocks (Figure 3b). Vertically positioned polythene black plastic sheeting (0.5 mm thick) was installed to 1 m depth on three sides of the plots, to prevent lateral water movement from one plot to another and to the surroundings. The fourth side of each plot was open to the drainage channel (collector) via the plot ditch (Figure 3b).

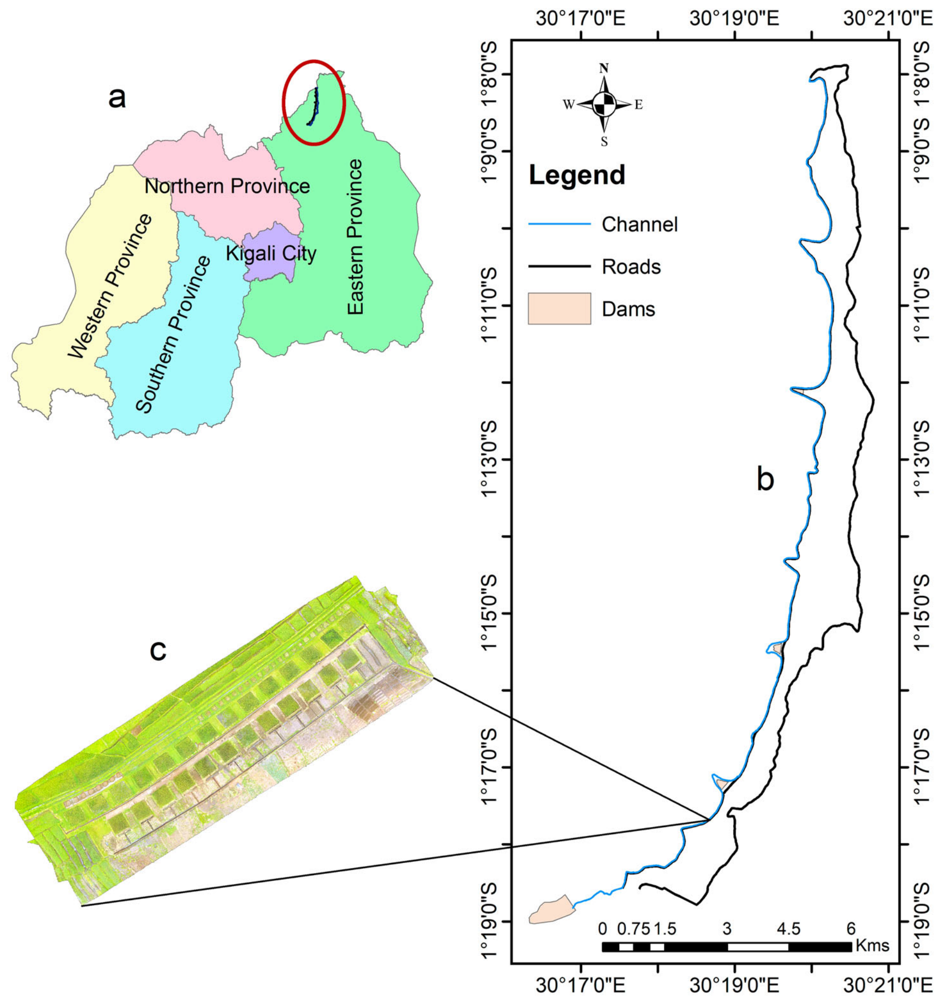

Figure 1. Map of Rwanda showing (a) location of the site in north-eastern Rwanda, (b) outline of Muvumba Marshland, and (c) position/sketch of the experiment.

Soil

The soil at the site is a former Vertisol changed to Vertic-Fluvic Gleysol due to continuous deposition of alluvial and colluvial materials and waterlogged conditions. The problems with the soil are associated with physical rather than chemical properties. The sub-soil is very hard, with abundant cracks when dry (due to shrinkage) and very plastic and poorly drained structure when wet (due to swelling). Despite the blackish colour, the soil is relatively poor in organic matter. After water evaporation, salts accumulate on the surface in the dry season. When properly managed, however, the agricultural potential of the soil is high and it is suitable for several crops.

Before setting up the experiment, soil samples were collected in the zones between the 12 experimental plots (see Figure 3), from soil depths of 0–20, 20–40, 40–60 and 60–80 cm, using an auger. The samples were taken to the laboratory, where soil pH was determined with a pH metre at a soil water: KCl ratio of 1 : 2.5, electrical conductivity with an EC probe (EC Testrs ®11 series) in a saturated soil-paste extract, total nitrogen (TN) by the micro-Kjeldahl method (Anderson and Ingram 1994), organic carbon by the Walkley and Black method (Nelson and Sommers 1982), and particle size distribution by the hydrometer method (Bouyoucos 1962). Additional undisturbed soil cylinder core samples (5 cm diameter, 5.1 cm high, 3 replicates) were collected from the same between-plot zones at the same depths as the auger samples, for laboratory determination of dry bulk density (after drying to 105°C for 72 h) and soil water retention. Soil moisture content at 1 m tension was determined on undisturbed soil samples using a sand box apparatus (Eijkelkamp Agrisearch Equipment, Giesbeek, The Netherlands), and at 150 m tension on disturbed soil samples using pressure plate equipment (Soil Moisture Equipment Santa Barbara CA, USA).

Based on ranges reported in Landon (1991), the experimental soil had high pH (7.1–7.5), medium total

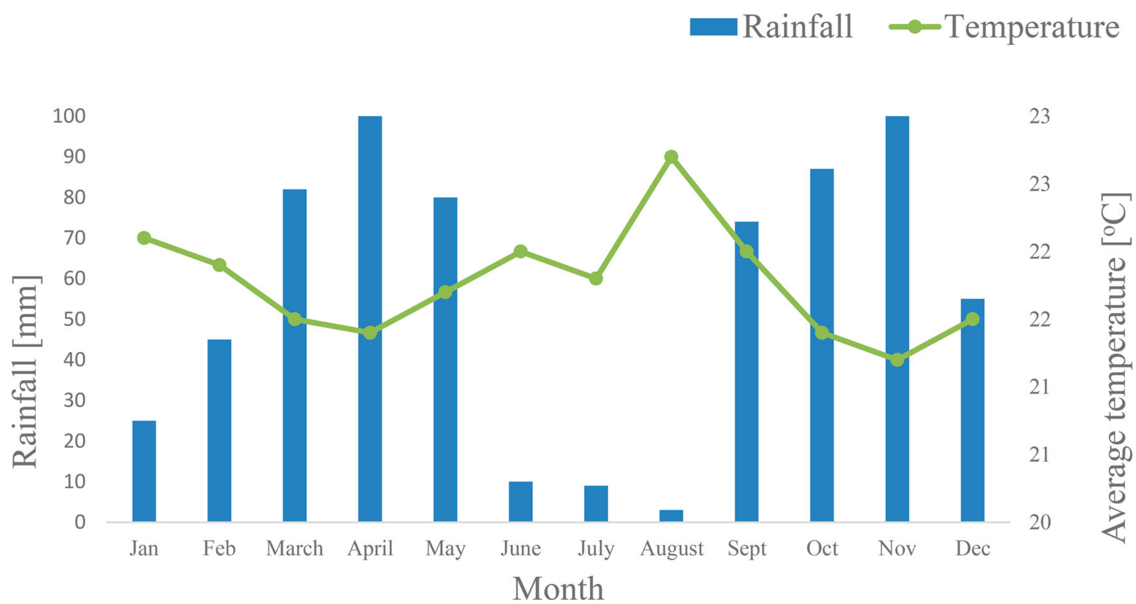

Figure 2. Mean monthly rainfall and temperature in the Muvumba Marshland area (Nyagatare station, 1984–2013).

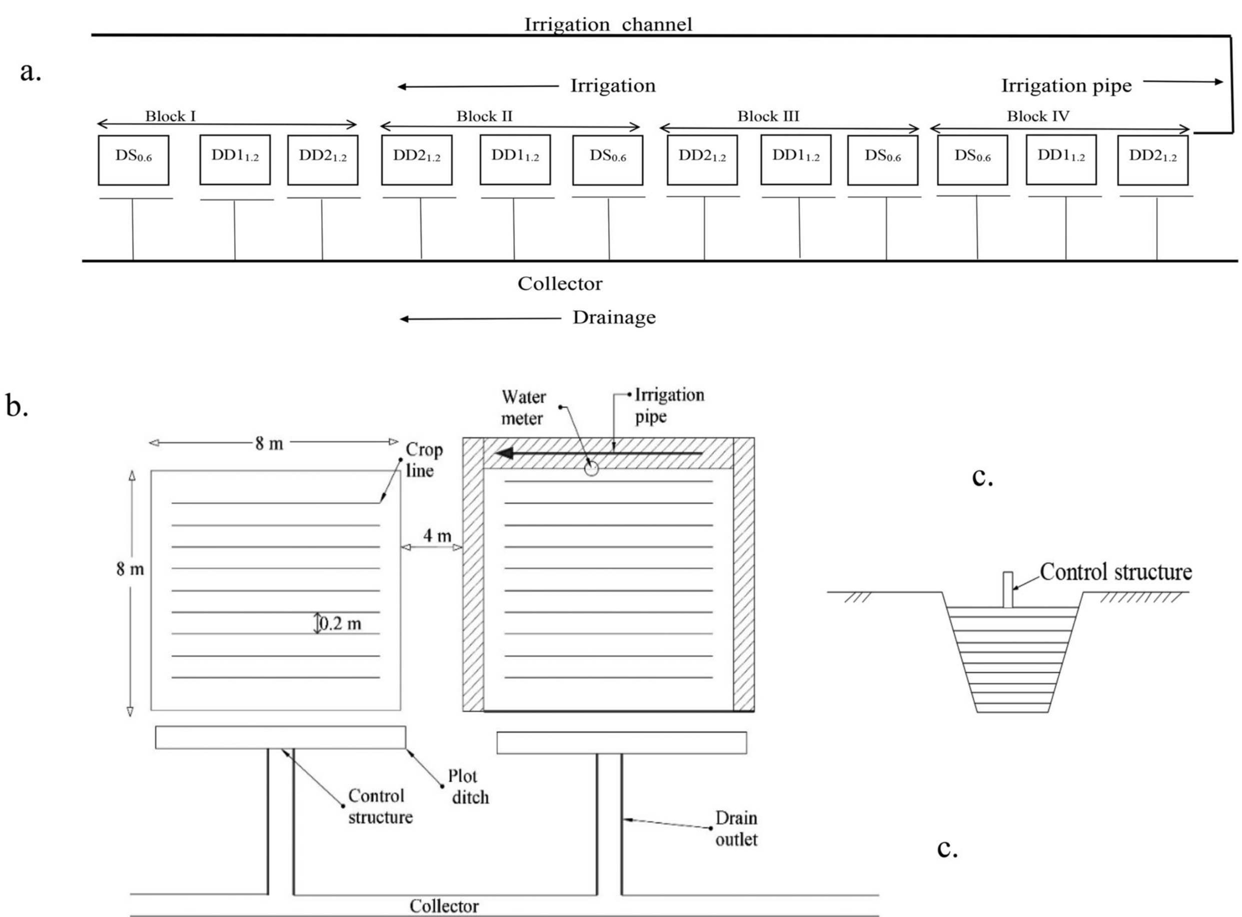

Figure 3. Sketch of a) blocks and treatments in the experimental set-up $DS_{0.6}$ (0.6 m deep drain, control structure open four times per week), $DD1_{1.2}$ (1.2 m deep drain, control structure open four times per week) and $DD2_{1.2}$ (1.2 m deep drain, control structure open two times per week), b) dimensions of experimental plots and ditches, and c) cross-section of control structure at the outlet of each plot.

N content (0.26–0.28%) and medium soil organic matter content (7.73–8.98%), and was slightly to moderately saline (EC_e = 5.0–8.2 dS m^{-1}) (Table 1). The soil had a sandy loam to sandy clay loam texture (sand 49.0–67.8%, silt 17.3–19.7%, clay 13.5–31.2%), and a dry bulk density between 1.31 and 1.43 g cm^{-3} (Table 2). Clay content and dry bulk density increased with depth.

Soil and crop management

Rice (*Oryza sativa L.* var. 'Nemeyubutaka', WAB-880-1-38-20-28-P1-HB) was used as a test crop. Seedlings were grown in a nursery for three weeks before transplanting to the experimental plots. Prior to transplanting, the plots were irrigated and prepared by manual hoeing in primary tillage (to break and invert the soil), secondary tillage (to level the soil) and puddling (to churn the soil with water). In Season 1, a hard pan was observed at 50 cm depth in some experimental plots. Before Season 2, these plots were prepared by removing the topsoil, tilling with a hoe to 50 cm depth, and returning the topsoil to the plots. The other plots were prepared by manual hoeing of the upper topsoil. In Season 3, the only soil preparation performed was manual hoeing of the upper topsoil. After puddling, the rice seedlings were transplanted at a rate of two seedlings per planting spot on 19 March 2016 (Season 1), 6 October 2016 (Season 2) and 31 March 2017 (Season 3), with a spacing of 0.2 m between rows and 0.2 m between plants (Figure 3b).

During each season, two types of granular fertiliser were applied: (i) NPK (17-17-17) at a rate of 200 kg ha^{-1} and (ii) urea (46% N) at a rate of 100 kg ha^{-1}, as adapted from the Rwandan fertilisation regime for irrigated rice (Cyamweshi et al. 2017). In total, 80 kg N ha^{-1}, 15 kg P ha^{-1} and 28 kg K ha^{-1} were applied to each plot, in split doses given on three occasions. On the first occasion, in early vegetative stage, 10 kg N ha^{-1}, 4 kg P ha^{-1} and 8 kg K ha^{-1} were applied as NPK (17-17-17). On the second occasion, at panicle initiation, 24 N ha^{-1}, 11 kg P ha^{-1} and 20 kg K ha^{-1} were applied as NPK (17-17-17). On the third occasion, at flowering stage, 46 kg N ha^{-1} were applied as urea. Pests were controlled by spraying with chemicals according to recommendations by MINAGRI (2011) and weeds were controlled manually by hoeing. Aboveground crop residues were not returned to the plots, following common practice in the study area.

Table 1. Soil chemical properties at different depths at the experimental site, based on samples collected before the first season: EC_e = electrical conductivity, TN = total nitrogen, SOM = soil organic matter (mean ± standard deviation; n = 11).

Depth cm	pH	EC_e dS m^{-1}	TN %	SOM %
0–20	7.1 ± 0.6	8.2 ± 2.5	0.27 ± 0.08	8.98 ± 2.05
20–40	7.6 ± 0.5	6.0 ± 1.9	0.28 ± 0.08	8.69 ± 2.76
40–60	7.5 ± 0.3	5.6 ± 1.5	0.26 ± 0.07	7.84 ± 1.02
60–80	7.5 ± 0.4	5.0 ± 1.1	0.28 ± 0.06	7.73 ± 2.59

Water flow parameters

Precipitation and temperature data for the area were obtained from Rwanda Meteorology Agency (Nyagatare weather station, located 2.7 km from the experimental site). Throughout Seasons 1–3, water from the Muvumba River was used for irrigation. The water from this river is generally suitable for irrigation (EC_w < 0.3 dS m^{-1}). The irrigation system consisted of a main pipeline, which conducted water from an existing irrigation channel (Figure 3a). Laterals connected to the main pipeline supplied water to each plot. Irrigation water use was recorded using water metres (AO Tong Biao Ye, China) (Figure 3b). Before planting, all plots were uniformly irrigated with 100 mm, in order to establish equivalent antecedent soil moisture conditions. Irrigation scheduling was planned so that the plots would be irrigated three times per week to keep a 3-cm water layer standing on the soil surface during the cropping season. In the study area, irrigation water is distributed to irrigation channels for a time period specified by the local irrigation water management association and rice fields are irrigated on a rotational basis. The present study was conducted under these 'local allocation management' conditions. The drainage system consisted of a main collector and sub-drainage channels for each plot (Figure 3b). Control structures made of wood were installed in the sub-drains to regulate drainage depth (Figure 3c).

Table 2. Soil physical properties at different depths, based on auger samples (texture) and on core samples (water retention and dry bulk density), all collected in the area between plots. Mean ±standard deviation (n = 11).

Depth cm	Sand weight%	Silt weight %	Clay weight %	Dry bulk density Field capacity (1 m tension) volume%	Dry bulk density Wilting point (150 m tension) volume%	Dry bulk density g cm^{-3}
0–20	67.8 ± 4.4	18.6 ± 2.1	13.5 ± 2.9	50.6 ± 4.9	10.4 ± 3.2	1.31 ± 0.12
20–40	61.4 ± 6.1	17.3 ± 4.4	20.4 ± 6.8	49.3 ± 3.7	12.4 ± 7.8	1.33 ± 0.16
40–60	56.6 ± 4.6	19.4 ± 3.2	23.9 ± 6.5	37.1 ± 3.7	22.4 ± 7.7	1.43 ± 0.13
60–80	49.0 ± 6.1	19.7 ± 4.1	31.2 ± 6.8	40.1 ± 1.8	22.9 ± 8.0	1.43 ± 0.13

During the rice cropping seasons, the control structures were open or closed depending on drainage treatments, as described in section 2.2.

Drainage outflow was determined from water balance calculated for each plot as:

$$Dr_i = Dr_{i-1} + Ir_i + P_i - ET_{c,i} \quad (1)$$

where Dr_i is drainage outflow (mm) when the control structure is open on day *i* (i.e. accumulated water between two drainage events), Dr_{i-1} is soil water excess (i.e. beyond water content at field capacity) at the end of the previous day (mm), Ir_i is irrigation water applied on day *i* (mm), P_i is rainfall on day *i* (mm) and $ET_{c,i}$ is crop evapotranspiration on day *i*.

Daily reference evapotranspiration was calculated by the Blaney-Criddle formula (Allen and Pruitt 1986) as:

$$ET_{o,i} = p\ (0.46\ T_{mean} + 8) \quad (2)$$

where $ET_{o,i}$ is the reference crop evapotranspiration (mm) on day *i*, p is the mean daily percentage of annual daytime hours and T_{mean} is mean daily temperature (°C).

Daily crop evapotranspiration ($ET_{c,i}$) was calculated using the FAO-56 approach (Allen 1998) as:

$$ET_{c,i} = ET_{o,i} * K_{c,i} \quad (3)$$

where $ET_{c,i}$ is daily crop evapotranspiration (mm), $ET_{o,i}$ is reference evapotranspiration on day *i* (mm) and $K_{c,i}$ is crop coefficient on day *i*.

Crop coefficient was determined for initial (K_c ini), mid-season (K_c mid) and late season (K_c end) stages (Table 3) as:

$$K_{c\,i} = K_{c\,pre} + \left[\frac{i - \Sigma(L\,\text{prev})}{L_{\text{stage}}}\right](K_{c\,\text{next}} - K_{c\,\text{prev}}) \quad (4)$$

where *i* is day number within the growing season, $K_{c,i}$ is crop coefficient on day *i*, L_{stage} is length of the stage under consideration [days] and Σ (L_{prev}) is the sum of lengths of all previous stages [days], $K_{c\ prev}$ is crop coefficient at the end of the previous stage, and $K_{c\ next}$ is crop coefficient at the beginning of the next stage.

Nitrogen in water, soil and plant material, grain yield, nitrogen balance and water use efficiency

Samples of drainage water were collected weekly for analysis of N content. These samples were analysed for nitrate-N (NO_3^--N) by the cadmium reduction colorimetric method and for ammonium-N (NH_4^+-N) by the dichloroisocyanurate-salicylate method (APHA, 1992). Daily N loss in drainage water from each plot was calculated by multiplying the N concentration in each sample by the daily drain outflow values.

Table 3. Length of rice development stages and crop coefficient (K_c) in the initial (K_c ini), mid-season (K_c mid) and late season (K_c end) stages.

Rice development stage	Initial	Development	Mid-season	Late season	Total
Stage length (days)	30	28	56	30	144
K_c	1.05		1.27	0.91	

Organic carbon and total N were determined on soil samples from 0–20, 20–40, 40–60 to 60–80 cm depth, collected before Season 1 and at the end of each season. Total N (TN) was determined by the micro-Kjeldahl method (Anderson and Ingram 1994) and organic carbon by the Walkley and Black method (Nelson and Sommers 1982). Mineral N concentrations (NO_3^--N and NH_4^+-N) were determined in fresh soil samples collected from the same depths as listed above before Season 1 and at the end of each season, using the colorimetric method (Okalebo et al. 2002). The values obtained were converted to kg per hectare using the values obtained for dry bulk density.

Plant sampling was carried out at harvest by cutting the aboveground biomass on a 4 m^2 area representative of the average crop cover in each plot. The grains were separated from the straw and both fractions were oven-dried at 70°C for 72 h, milled and analysed for N content by the colorimetric method (Okalebo et al. 2002). Rice grain and straw yield were determined on a dry matter basis. Harvest index (HI) was calculated as the ratio of grain yield to total aboveground biomass.

Nitrogen balance was estimated for each treatment as the difference between inputs and outputs (Oenema et al. 2003; Pinitpaitoon et al. 2011; Zhang et al. 2013):

$$\text{N balance} = \text{Total N input - Total N output} \quad (5)$$

where N balance is expressed in kg ha^{-1}, Total N input (kg ha^{-1}) is N from mineral fertiliser (kg ha^{-1}) + soil mineral N before sowing (kg ha^{-1}), and Total N output (kg ha^{-1}) is crop N uptake (kg ha^{-1}) + N in drainage water (kg ha^{-1}) + ΔN [soil mineral N before sowing (kg ha^{-1}) – soil mineral N after harvesting (kg ha^{-1})].

The full 0–80 cm soil profile was used for inorganic N in the N budget calculations, because most crop roots are distributed in the 0–80 cm layer under the experimental conditions (Tian et al. 2007).

Water use efficiency (WUE) was calculated as (Condon and Hall 1997):

$$WUE = \frac{GY}{Ir + P} \quad (6)$$

where WUE is expressed in kg m^{-3}, GY is grain yield (kg ha^{-1}), Ir is the amount of irrigation water (mm) applied per season, and P is the amount of rainfall (mm) per season.

Statistical analysis

All data were statistically analysed using JMP Pro 14 software (JMP ®14.0.0, SAS Institute Inc., Cary, NC, USA). Comparison of treatment means was done using Tukey honest significant difference test ($p < 0.05$). Block and treatment effects were assessed separately for each season by a randomised complete block design model:

$$Y_{ij} = \mu + T_i + B_j + \text{random error} \qquad (7)$$

where $Y_{ij\text{-}}$ is any observation for which i is the treatment factor and j is the block factor, μ is the mean, T_i is treatment effect of treatment I, and B_j is block effect.

Results

Water flow parameters

Season 1 and Season 3 were characterised by lower rainfall amounts than Season 2 (Figure 4 and Table 4). The period June-July (Season 1 and Season 3) was very dry, with little or no rain (Figure 4). The highest rainfall amount (169 mm) was observed in November 2016 (Season 2). Monthly rainfall deficit was observed in all months except November 2016 (Season 2), which had a rainfall surplus. Total ET_c during the cropping season was 630 mm (Season 1), 668 mm (Season 2) and 653 mm (Season 3) (Table 4). Mean irrigation amount per season ranged between 622 and 651 mm (Season 1), 568 and 703 mm (Season 2), and 708 and 820 mm (Season 3). A significant difference in drainage outflow was observed between treatments in Season 3 ($p = 0.0025$), but not in Season 1 ($p = 0.0915$) or Season 2 ($p = 0.1930$). In Season 1, mean drainage outflow from $DD1_{1.2}$ tended to be larger than from $DS_{0.6}$ ($\boldsymbol{p} = 0.0700$), but more or less similar to that from $DD2_{1.2}$. In Season 3, $DD1_{1.2}$ had significantly larger drainage outflow than $DS_{0.6}$ ($p = 0.0044$) and $DD2_{1.2}$ ($p = 0.0041$), with the latter two not differing from each other.

Nitrogen concentrations and nitrogen loads in drainage water

Weekly measured N concentrations for the three treatments in Seasons 1, 2 and 3 are plotted in Figure 5. The NO_3^--N and NH_4^+-N concentrations were low in all seasons. The highest weekly NO_3^--N concentration (4.52 mg L^{-1}) was observed in November 2016 (Season 2) in the $DD1_{1.2}$ treatment and the lowest (0.01 mg L^{-1}) was observed in June 2017 (Season 3) in the $DS_{0.6}$ treatment. Generally, no major differences in NO_3^--N and NH_4^+-N concentrations between treatments were observed. However, Season 2 was characterised by a distinctly different distribution pattern of NO_3^--N concentration, with relatively higher NO_3^--N concentrations than in Seasons 1 and 3. For NH_4^+-N concentration, the distribution pattern was more or less similar in all three seasons.

Overall, no significant differences in either NO_3^--N or NH_4^+-N loads in drainage water were observed between treatments ($p > 0.05$) in any season. In Season 1, $DS_{0.6}$ and $DD2_{1.2}$ had lower mean NO_3^--N loads (3.8 and 3.2 kg ha^{-1}) than $DD1_{1.2}$ (6.6 kg ha^{-1}) (Table 5). A similar trend was observed in Season 3, but not in

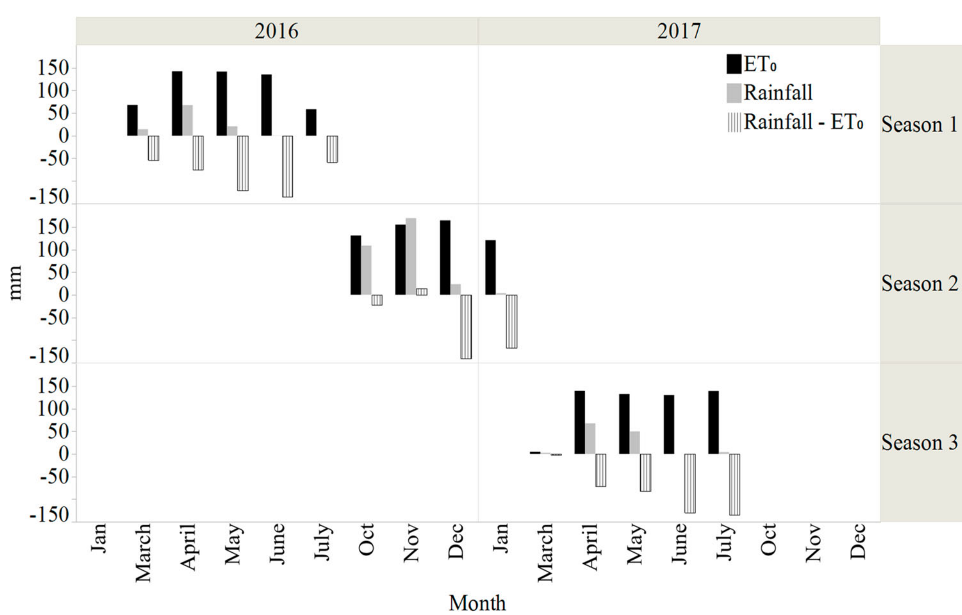

Figure 4. Reference evapotranspiration (ET_o), rainfall, and rainfall-ET_o during the study period, in Season 1, Season 2 and Season 3.

Table 4. Actual crop evapotranspiration (ET_c), rainfall, irrigation amount (mean ± standard deviation, $n = 4$) and drainage outflow (mean ± standard deviation, $n = 4$) for each treatment/season.

Season	Treatment	ET_c mm	Rainfall mm	Irrigation mm[†]	Drainage outflow mm[†]
1	$DS_{0.6}$	630	103	622 ± 4^a	168 ± 7^a
	$DD1_{1.2}$	630	103	651 ± 19^a	201 ± 22^a
	$DD2_{1.2}$	630	103	646 ± 20^a	187 ± 12^a
2	$DS_{0.6}$	668	305	568 ± 68^a	311 ± 28^a
	$DD1_{1.2}$	668	305	677 ± 112^a	408 ± 133^a
	$DD2_{1.2}$	668	305	703 ± 54^a	432 ± 27^a
3	$DS_{0.6}$	653	124	708 ± 16^b	329 ± 14^b
	$DD1_{1.2}$	653	124	820 ± 22^a	430 ± 44^a
	$DD2_{1.2}$	653	124	717 ± 10^b	328 ± 14^b

[†]Different letters (a, b) indicate significant differences ($p < 0.05$) between treatments within each season.

Season 2. Larger mean NH_4^+-N load (8 kg ha^{-1}) was observed for $DD1_{1.2}$ in Season 3 compared with Season 1 and Season 2. Observations on total N (sum of NO_3^--N and NH_4^+-N) showed that $DD1_{1.2}$ tended to have higher N loads than $DS_{0.6}$ and $DD2_{1.2}$, with 34% (Season 1), 47% (Season 2) and 34% (Season 3) lower mean total N values observed in $DD2_{1.2}$ than in $DD1_{1.2}$. Lower mean total N values were also observed in $DS_{0.6}$ than in $DD1_{1.2}$ (31% lower in Season 1, 14% in Season 2, and 34% in Season 3).

Grain and straw yield and nitrogen content, crop nitrogen uptake and harvest index

Grain yield, grain N uptake and total N uptake were significantly affected by treatments in all seasons, while for HI a significant treatment effect was observed only in Seasons 1 and 3 (Table 6). A block effect was observed for straw yield, straw N uptake and total N uptake in Season 1, and for straw yield, total N uptake and HI in Season 3. Compared with $DS_{0.6}$, deep drainage treatments ($DD1_{1.2}$ and $DD2_{1.2}$) had significant positive effects on rice grain yield and grain N uptake in all seasons (Table 6). No treatment effect was observed on straw yield in any season, but straw N content and straw N uptake were higher in deep drainage treatments ($DD1_{1.2}$ and $DD2_{1.2}$) than in $DS_{0.6}$ in Season 2, whereas $DD2_{1.2}$ had higher straw N uptake than $DD1_{1.2}$ and $DS_{0.6}$ in Season 1. In Season 1, Season 2 and Season 3, grain yield in $DD1_{1.2}$ was 106, 63 and 100% higher, respectively, than in $DS_{0.6}$, while grain yield in $DD2_{1.2}$ was 131, 61, and 106% higher, respectively, than in $DS_{0.6}$. Similarly, in Season 1, Season 2 and Season 3, grain N uptake in $DD1_{1.2}$ was 119, 83, and 70% higher, respectively, than in $DS_{0.6}$, while grain N uptake in $DD2_{1.2}$ was 151, 92 and 85% higher, respectively, than in $DS_{0.6}$. Treatment effects on HI were observed in

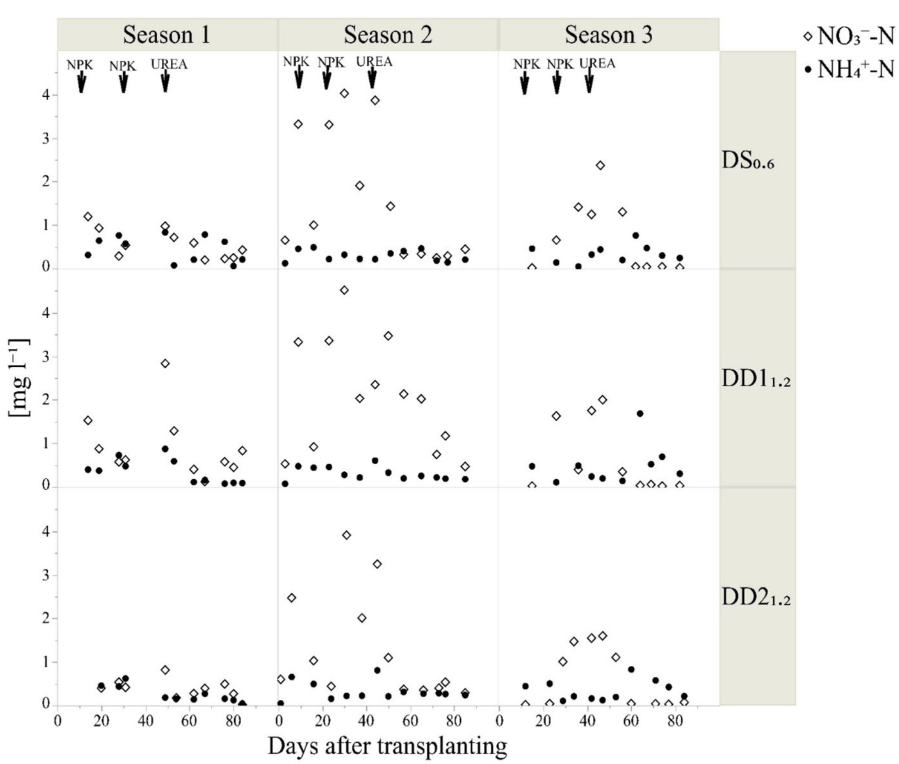

Figure 5. Measured nitrate-nitrogen (NO_3^--N) and ammonium-N (NH_4^+-N) concentrations in drainage water in treatments $DS_{0.6}$, $DD1_{1.2}$ and $DD2_{1.2}$ in Season 1, 2 and 3. $DS_{0.6}$ = 0.6 m deep drain, control structure open 4 times/week, $DD1_{1.2}$ = 1.2 m deep drain, control structure open 4 times/week, $DD2_{1.2}$ = 1.2 m deep drain, control structure open 2 times/week.

Table 5. Nitrate-N (NO_3^--N) and ammonium-N (NH_4^+-N) loads (mean ± standard deviation, $n = 4$) in drainage water and their sum (Total N) in Season 1, 2 and 3 in treatments $DS_{0.6}$ (0.6 m deep drain, control structure open 4 times/week), $DD1_{1.2}$ (1.2 m deep drain, control structure open 4 times/week) and $DD2_{1.2}$ (1.2 m deep drain, control structure open 2 times/week).

Season	Treatment	NO_3^--N kg N ha^{-1}	NH_4^+-N kg N ha^{-1}	Total N kg N ha^{-1}
1	$DS_{0.6}$	3.8 ± 1.6	2.4 ± 0.6	6.3 ± 2.2
	$DD1_{1.2}$	6.6 ± 2.6	2.4 ± 0.3	9.0 ± 2.9
	$DD2_{1.2}$	3.2 ± 1.4	2.7 ± 1.1	5.9 ± 1.2
2	$DS_{0.6}$	10.9 ± 3.7	1.3 ± 0.2	12.2 ± 3.7
	$DD1_{1.2}$	12.0 ± 4.0	2.2 ± 1.5	14.2 ± 5.5
	$DD2_{1.2}$	5.7 ± 1.7	1.8 ± 0.7	7.5 ± 2.0
3	$DS_{0.6}$	5.2 ± 2.9	5.0 ± 3.1	10.3 ± 3.8
	$DD1_{1.2}$	7.5 ± 3.7	8.0 ± 2.5	15.5 ± 2.3
	$DD2_{1.2}$	6.2 ± 4.0	4.0 ± 2.1	10.2 ± 4.9

Seasons 1 and 3, with significantly larger HI values in $DD1_{1.2}$ and $DD2_{1.2}$ than in $DS_{0.6}$. Mean HI ranged between 0.17 and 0.36 over the three seasons.

Water use efficiency

Grain yield and WUE were significantly affected by the treatments in all seasons (Figure 6). Significant differences between treatments in terms of irrigation water and total water input were observed in Season 3. Mean WUE ranged between 0.2 and 0.8 kg m^{-3} over the three seasons (Figure 6). Significantly higher WUE and grain yield were observed for deep drainage treatments ($DD1_{1.2}$ and $DD2_{1.2}$) in all seasons compared with the shallow drainage treatment ($DS_{0.6}$).

Soil organic carbon, total nitrogen, C/N ratio and mineral nitrogen

Generally, soil organic carbon (SOC), soil TN, C/N ratio and soil mineral N content decreased during the experimental period (Table 7). Relatively higher SOC and TN contents were observed in the topsoil (0–20 cm) and no treatment effect on SOC, TN or C/N ratio was observed in any season ($p > 0.05$). However, $DD2_{1.2}$ showed a smaller decrease in SOC compared with $DD1_{1.2}$ at the end of all seasons. Soil mineral N concentrations (NO_3^--N and NH_4^+-N) are shown in Figure 7. At the end of Season 3, SOC, TN and soil mineral N ranged, respectively, from 0.8–1.9%, 0.05–0.1%, to 8.1–8.3 kg ha^{-1} compared with before Season 1, where the SOC, TN and soil mineral N range was 3.7–5.7%, 0.2–0.3% and 158.6–172.2 kg ha^{-1}, respectively (Table 7, Figure 7). The C/N ratio ranged between 7.8 and 28.3 over the three seasons. At the end of Season 1, high C/N ratio was observed because of a decrease in TN with only a slight change in SOC.

Nitrogen balance

In the N balance, soil mineral N was the largest component of TN input in Season 1 and 2, but in Season 3 mineral N fertiliser was the largest N input (Figure 8). Crop (grain + straw) N uptake ranged from 92.5 to 167.4 kg ha^{-1} and showed much larger N output values compared with N in drainage water, which was an order of magnitude lower (range 5.9–15.5 kg ha^{-1}). The value of ΔN (N_{min} before sowing − N_{min} residual)

Table 6. Grain and straw yield (dry matter basis), nitrogen (N) content and N uptake, and total crop N uptake (grain N uptake + straw N uptake) and harvest index, in Season 1, 2 and 3 in treatments $DS_{0.6}$ (0.6 m deep drain, control structure open 4 times/week), $DD1_{1.2}$ (1.2 m deep drain, control structure open 4 times/week) and $DD2_{1.2}$ (1.2 m deep drain, control structure open 2 times/week). Mean ± standard deviation ($n = 4$). The last six lines show the results of pairwise comparisons.

Season	Treatment	Grain yield† ton ha^{-1}	Straw yield ton ha^{-1}	Grain N content %	Straw N content† %	Grain N uptake† kg N ha^{-1}	Straw N uptake† kg N ha^{-1}	Total Crop N uptake† kg N ha^{-1}	Harvest index†
1	$DS_{0.6}$	1.6 ± 0.3^b	8.0 ± 1.7	1.2 ± 0.1	0.9 ± 0.1	19.6 ± 2.7^b	72.9 ± 11.8b	92.5 ± 12.4^a	0.17 ± 0.0^b
	$DD1_{1.2}$	3.3 ± 0.6^a	8.8 ± 1.9	1.3 ± 0.1	0.8 ± 0.1	43.0 ±7.5^a	71.8 ± 21.8b	114.9 ± 19.9^b	0.28± 0.03^a
	$DD2_{1.2}$	3.7 ± 0.8^a	10.2± 1.4	1.3 ± 0.1	0.9 ± 0.1	49.3 ± 9.9^a	91.1 ± 10.2a	140.4 ± 14.3^c	0.26 ± 0.02^a
2	$DS_{0.6}$	3.8 ± 1.1^b	9.2 ± 2.2	1.1 ± 0.1	0.5 ± 0.1^b	43.3 ± 11.0^b	44.8 ± 9.8^b	88.1 ± 18.7^b	0.29 ± 0.03
	$DD1_{1.2}$	6.2 ± 0.6^a	11.5 ± 1.4	1.3 ± 0.3	0.8 ± 0.1^a	79.4 ± 19.0^a	87.4 ± 10.7^a	166.8 ± 26.5^a	0.36 ± 0.03
	$DD2_{1.2}$	6.1 ± 0.6^a	10.9 ± 2.4	1.4 ± 0.2	0.8 ± 0.1^a	83.0 ± 13.8^a	84.3 ± 29.4^a	167.4 ± 28.7^a	0.36 ± 0.04
3	$DS_{0.6}$	3.2 ± 0.6^b	11.7 ± 4.5	1.3 ± 0.2	0.7 ± 0.2	43.5 ± 11.0^b	70.6 ± 8.6	114.1 ± 18.5^b	0.22 ± 0.02^b
	$DD1_{1.2}$	6.4 ± 0.3^a	14.7 ± 1.7	1.2 ± 0.1	0.5 ± 0.1	74.1 ± 7.3^a	81.9 ± 16.5	156.0 ± 17.7^a	0.30 ± 0.01^a
	$DD2_{1.2}$	6.6 ±0.5^a	14.4 ± 2.0	1.2 ± 0.1	0.5 ± 0.1	80.5 ±11.0^a	77.4 ± 31.4	157.9 ± 35.2^a	0.31 ± 0.02^a
1	Treatment	0.0031**	0.0668	0.3316	0.2396	0.0013**	0.0179*	0.0012**	0.0192*
	Block	0.2357	0.0339*	0.4585	0.9067	0.2106	0.0073**	0.0279*	0.2173
2	Treatment	0.0042**	0.1452	0.4360	0.0025**	0.0088**	0.0119*	0.0008***	0.0951
	Block	0.2091	0.0662	0.5391	0.1673	0.2113	0.1282	0.0506	0.5443
3	Treatment	< 0.001***	0.1106	0.1295	0.5064	<0.001***	0.6322	0.0124*	0.0043**
	Block	0.2139	0.0295*	0.2695	0.7293	0.0762	0.1111	0.0342*	0.0773*

†Different letters (a,b) indicate significant difference ($p < 0.05$) between treatments within each season.
Significance levels: ***$p < 0.001$; **$p < 0.01$; *$p < 0.05$.

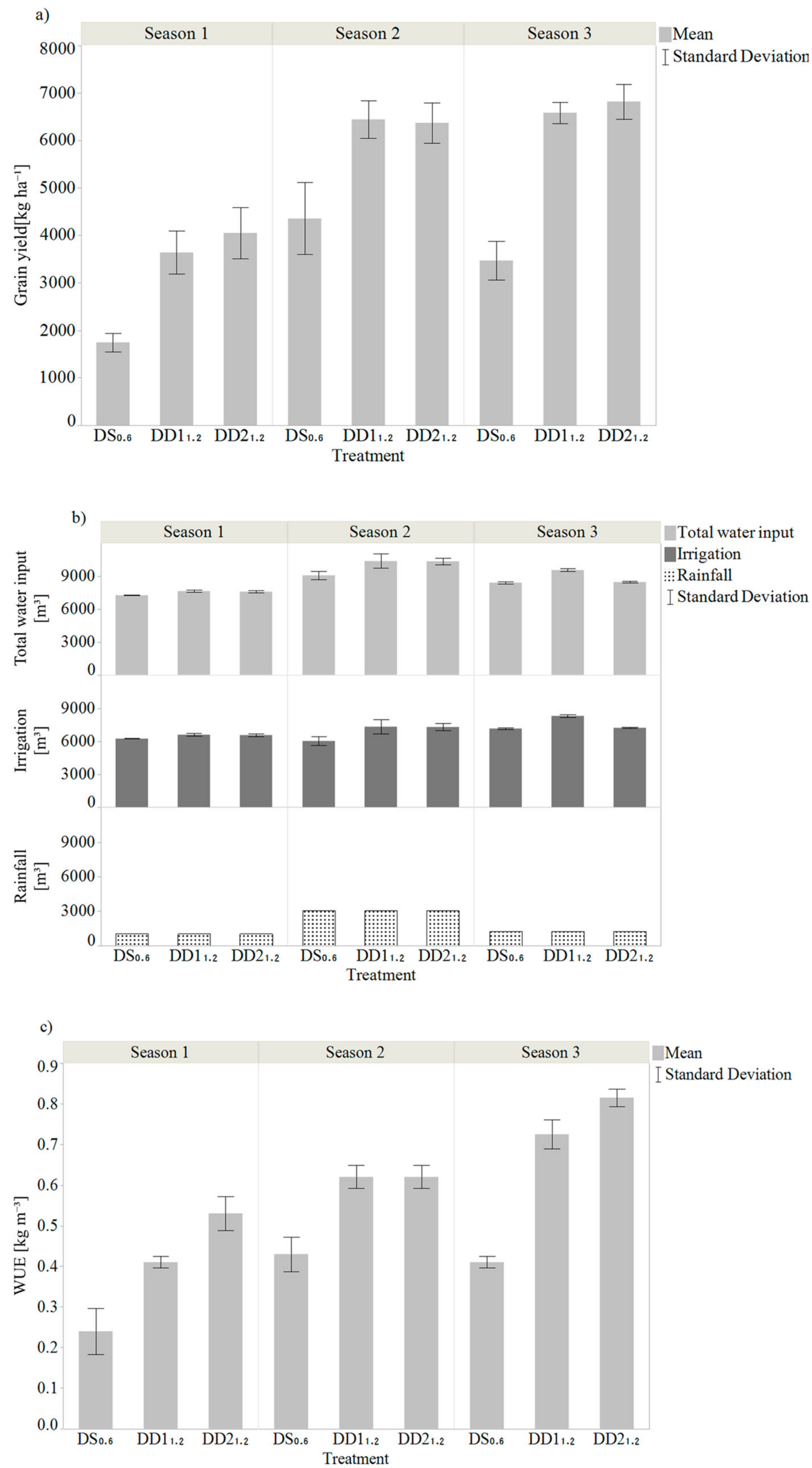

Figure 6. Mean and standard deviation ($n = 4$) of a) grain yield, b) total water input, irrigation and rainfall amount, and c) water use efficiency (WUE) in Seasons 1, 2 and 3 in treatments $DS_{0.6}$ (0.6 m deep drain, control structure open 4 times/week), $DD1_{1.2}$ (1.2 m deep drain, control structure open 4 times/week) and $DD2_{1.2}$ (1.2 m deep drain, control structure open 2 times/week).

Table 7. Soil organic carbon (SOC), soil total nitrogen (TN) and C/N ratio, based on soil samples collected at depths 0–20, 20–40, 40–60 and 60–80 cm before Season 1 and at the end of Season 1, 2 and 3. Mean ± standard deviation ($n = 4$).

Season	Treatment	Soil depth cm	SOC %	TN %	C/N ratio
Before Season 1	$DS_{0.6}$	0–20	4.9 ± 1.1	0.28 ± 0.09	17.5
		20–40	4.6 ± 0.3	0.28 ± 0.08	16.4
		40–60	4.0 ± 1.4	0.27 ± 0.09	14.8
		60–80	3.7 ± 0.9	0.25 ± 0.10	14.8
	$DD1_{1.2}$	0–20	5.0 ± 1.3	0.30 ± 0.07	17.0
		20–40	4.7 ± 1.6	0.30 ± 0.13	15.7
		40–60	4.2 ± 0.4	0.27 ± 0.10	15.5
		60–80	4.0 ± 0.4	0.25 ± 0.09	16.0
	$DD2_{1.2}$	0–20	5.7 ± 1.0	0.24 ± 0.06	23.7
		20–40	5.2 ± 1.4	0.25 ± 0.08	23.7
		40–60	4.7 ± 0.8	0.23 ± 0.11	20.4
		60–80	4.2 ± 1.0	0.20 ± 0.07	21.0
End Season 1	$DS_{0.6}$	0–20	5.1 ± 1.5	0.18 ± 0.07	28.3
		20–40	4.7 ± 1.3	0.20 ± 0.02	23.5
		40–60	3.5 ± 1.5	0.18 ± 0.01	19.4
		60–80	3.3 ± 1.6	0.16 ± 0.02	20.6
	$DD1_{1.2}$	0–20	4.4 ± 2.4	0.20 ± 0.07	22.0
		20–40	4.1 ± 1.6	0.16 ± 0.04	20.5
		40–60	2.9 ± 1.5	0.15 ± 0.02	19.3
		60–80	2.7 ± 0.9	0.15 ± 0.03	18.0
	$DD2_{1.2}$	0–20	5.2 ± 2.7	0.20 ± 0.06	26.0
		20–40	5.0 ± 2.0	0.20 ± 0.09	25.0
		40–60	3.8 ± 1.8	0.18 ± 0.01	21.1
		60–80	3.5 ± 1.5	0.16 ± 0.01	21.9
End Season 2	$DS_{0.6}$	0–20	2.3 ± 0.5	0.21 ± 0.05	10.9
		20–40	2.3 ± 0.3	0.16 ± 0.02	14.4
		40–60	1.5 ± 0.1	0.14 ± 0.01	10.7
		60–80	1.2 ± 0.2	0.14 ± 0.01	8.6
	$DD1_{1.2}$	0–20	2.4 ± 0.4	0.19 ± 0.04	12.6
		20–40	2.1 ± 0.1	0.15 ± 0.03	14
		40–60	1.5 ± 0.2	0.14 ± 0.03	10.7
		60–80	1.2 ± 0.1	0.13 ± 0.02	9.2
	$DD2_{1.2}$	0–20	3.0 ± 0.6	0.20 ± 0.02	15.0
		20–40	2.4 ± 0.2	0.16 ± 0.01	15.0
		40–60	1.3 ± 0.2	0.15 ± 0.02	8.6
		60–80	1.1 ± 0.2	0.14 ± 0.01	7.8
End Season 3	$DS_{0.6}$	0–20	1.4 ± 0.8	0.10 ± 0.07	14.0
		20–40	1.3 ± 0.7	0.09 ± 0.03	14.4
		40–60	1.1 ± 0.2	0.07 ± 0.03	15.7
		60–80	0.8 ± 0.2	0.05 ± 0.02	16.0
	$DD1_{1.2}$	0–20	1.3 ± 0.6	0.09 ± 0.04	14.4
		20–40	1.3 ± 0.8	0.09 ± 0.02	14.4
		40–60	1.0 ± 0.5	0.08 ± 0.04	12.5
		60–80	0.9 ± 0.3	0.06 ± 0.03	15.0
	$DD2_{1.2}$	0–20	1.9 ± 0.8	0.11 ± 0.03	17.3
		20–40	1.7 ± 0.9	0.08 ± 0.03	21.2
		40–60	1.5 ± 0.5	0.08 ± 0.01	18.7
		60–80	1.2 ± 0.3	0.05 ± 0.02	24.0

ranged between 39.1 and 68.6 kg ha^{-1} over the three seasons. In Season 1, a positive N balance was observed for all treatments, whereas in Season 2 only $DS_{0.6}$ had a positive N balance and $DD2_{1.2}$ and $DD1_{1.2}$ had a negative balance. All treatments had a negative N balance in Season 3.

Discussion

This study showed that higher drainage intensity (deeper drains, coupled with drainage depth control structures), had positive effects in all seasons. Rice grain yield, crop N uptake, HI, and WUE were higher with the deep drainage treatments ($DD1_{1.2}$ and $DD2_{1.2}$) than with the shallow drainage treatment ($DS_{0.6}$). However, N concentrations in drain outflow water did not show consistent differences between treatments.

In general, NO_3^--N concentrations in drainage water were low (below 5 mg L^{-1}) in all seasons. Tentatively, this resulted from high crop N uptake (Table 6), leaving less N available for leaching. By controlling drainage depth, it is possible to increase N uptake by plants, potentially reducing the amount of N available for leaching (Darzi-Naftchali et al. 2014). In paddy fields, abundant NO_3^--N losses only occur during heavy rain or ponding prior to transplanting (Zhang et al. 2013). During the seasons covered by the present study, the highest NO_3^--N concentration (4.52 mg L^{-1}) was recorded in

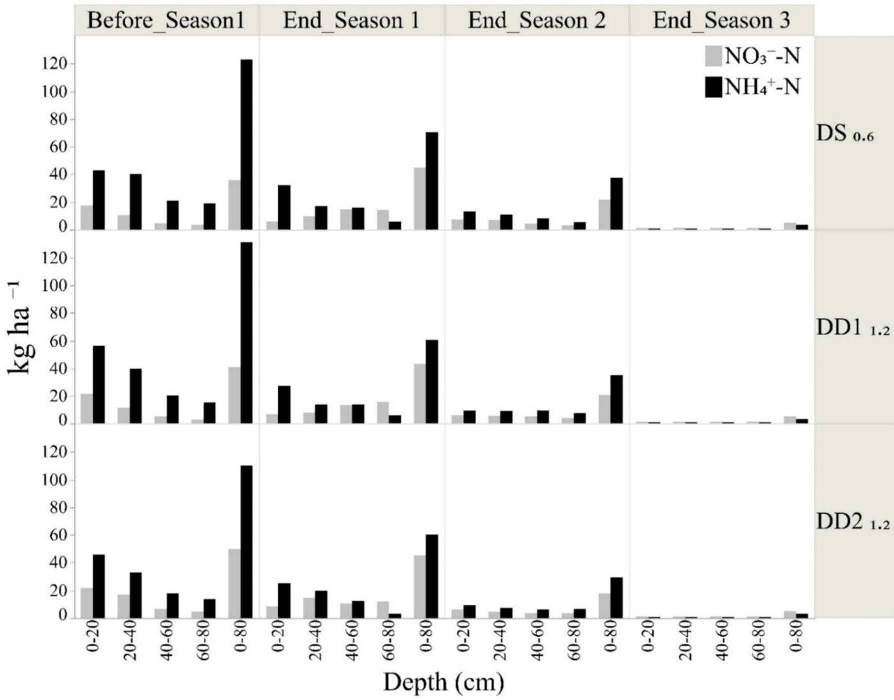

Figure 7. Nitrate-nitrogen (NO_3^--N) and ammonium-N (NH_4^+-N) concentrations in soil in treatment $DS_{0.6}$ (0.6 m deep drain, control structure open 4 times/week), $DD1_{1.2}$ (1.2 m deep drain, control structure open 4 times/week) and $DD2_{1.2}$ (1.2 m deep drain, control structure open 2 times/week) before Season 1 and at the end of Season 1, 2 and 3.

November 2016 (Season 2) (Figure 5). That month was characterised by the highest rainfall amount (169 mm) of all months (Figure 4). In general, peaks in NO_3^--N concentrations were observed after fertiliser application (Figure 5). The data did not show a clear relationship between drainage outflow and NO_3^--N concentrations in drainage water. Similar results were obtained in a previous field study in China, which found no clear trend of either an increase or decrease in NO_3^--N in drainage water as a result of controlled drainage in paddy fields (Luo et al. 2008). Peng et al. (2012) concluded that it is difficult to predict whether controlled drainage will increase or decrease N concentrations in drainage water from paddy fields, because this is influenced by multiple factors, such as rainfall, fertilisation, irrigation and drainage. However, in another field study in China, controlled drainage resulted in lower NO_3^--N losses in drainage water from paddy fields compared with the conventional drainage system (Peng et al. 2015). In the present study, $DD2_{1.2}$ (control structure less frequently opened) tended to have lower N loads in drainage water than $DD1_{1.2}$ (control structure more frequently opened) (Table 5). This might have resulted from the combination of drainage depth and opening frequency, resulting in lower drain outflow and lower N concentrations. The N fertiliser rates used in the present study were relatively low (80 kg N ha^{-1}) compared with those in other rice production systems, for example in China the recommended rate is 300 kg N ha^{-1} (Jiao et al. 2018). The observed low N losses in drainage water in the present study are probably due to most of the N fertiliser applied being taken up by the rice crop (Figure 8).

The NH_4^+-N concentrations and loads in drainage water were generally low (Figure 5). However, a slight increase was observed after urea fertilisation in Seasons 2 and 3. In general, NH_4^+-N is the stable component of N in paddy and its migration distance is very short, because it is adsorbed to negatively charged soil particles (Xiao et al. 2015). Ammonia volatilisation might lead to significant urea fertiliser loss in the study area, since the conditions are favourable for volatilisation, i.e. high soil pH (Table 1), high temperature (Figure 2) and moist conditions.

Deep drainage treatments ($DD1_{1.2}$ and $DD2_{1.2}$) had a positive effect on rice grain yield and N uptake compared with shallow drainage ($DS_{0.6}$) (Table 6). In paddy fields, rice yield response to drainage is associated with improved root conditions and increased translocation of stored reserves, which contribute to better grain filling (Ramasamy et al. 1997). In Seasons 2 and 3, the $DD1_{1.2}$ and $DD2_{1.2}$ treatments had higher rice grain yields (up to 6.6 tons ha^{-1}) than the average in Rwanda (5.5 tons ha^{-1}) (Ghins and Pauw 2017). Similar results have been observed in field studies on poorly drained

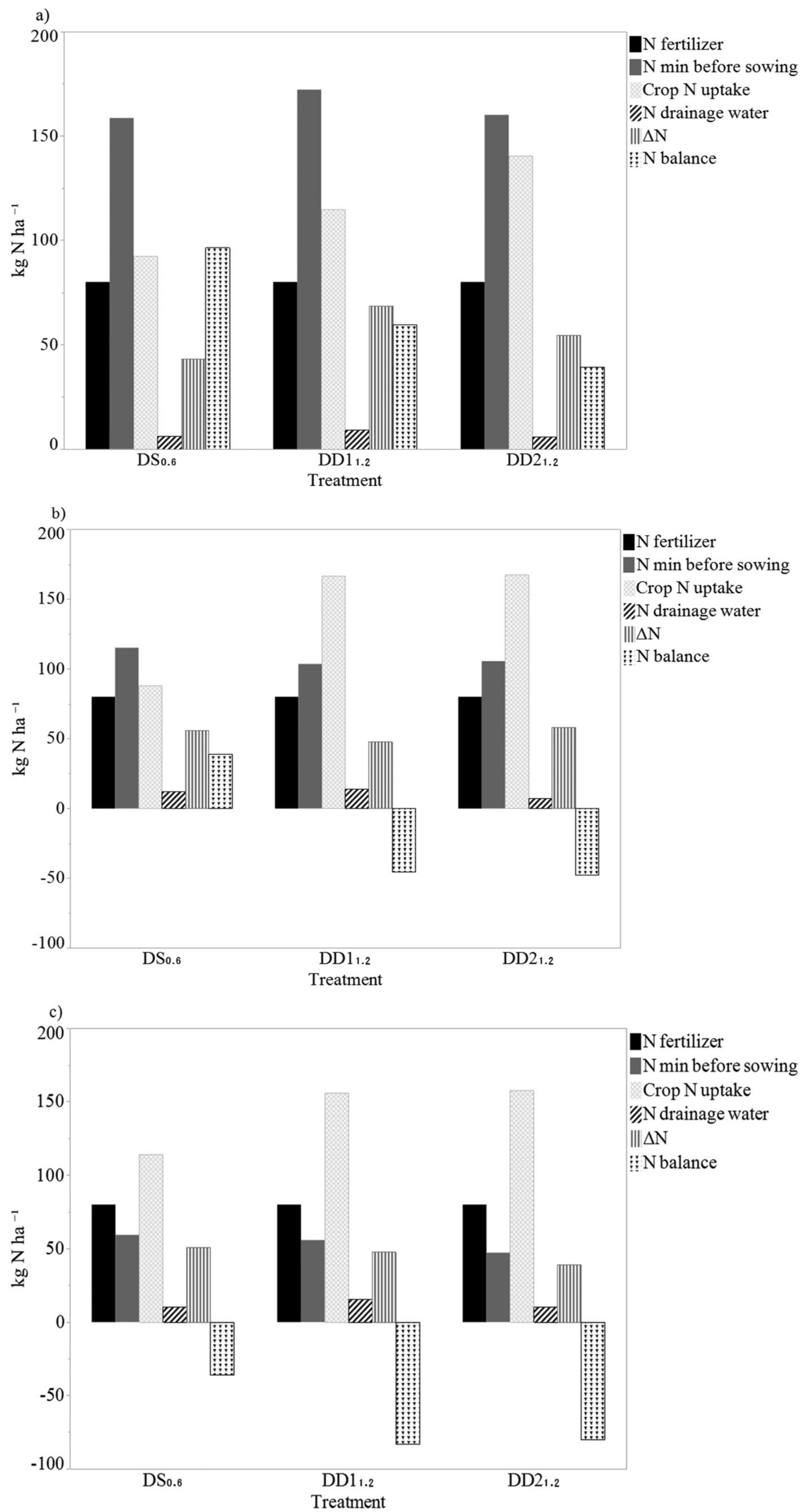

Figure 8. Nitrogen (N) budget, including N fertiliser and soil mineral N (N_{min} before sowing) as input and crop N uptake, N loads in drainage water, and ΔN (N_{min} before sowing – N_{min} residual) as output in kg N ha^{-1}, and N balance calculated as the difference between total input and total output for the three treatments ($DS_{0.6}$, $DD1_{1.2}$ and $DD2_{1.2}$) in a) Season 1, b) Season 2 and c) Season 3.

soils in India, which showed 69% higher rice yield under deep drainage than under shallow drainage (Ritzema et al. 2008). In a field study in China, Shao et al. (2014) concluded that controlled drainage could enhance root growth, facilitate remobilisation of reserve carbon to grain, accelerate grain filling and improve rice grain yield.

Harvest index (HI) as a variable in crop production is closely associated with water use efficiency (WUE) and rice grain yield (Zhang et al. 2008). In the present study, HI varied between 0.17 and 0.36 (Table 6) and the highest HI was observed in the highest-yielding treatments (i.e. $DD2_{1.2}$ and $DD1_{1.2}$). This agrees with results from a paddy rice field study in India, which showed higher HI in well-drained plots than in poorly drained plots (Ramasamy et al. 1997). The HI of many rice cultivars grown in lowlands is about 0.35 (Steduto et al. 2012). As grain yield is the product of HI and total aboveground biomass, water productivity in rice production can be improved by increasing HI (Yang and Zhang 2010). Variations in HI are mainly attributable to differences in crop management (Yang et al. 2000). In irrigated lowland rice systems, the technique of alternating wetting and moderate soil drying irrigation procedures during the grain-filling period substantially enhances WUE and maintains or even increases the grain yield of rice (Yang and Zhang 2010). This is mainly due to enhanced remobilisation of pre-stored carbon reserves from vegetative tissues to grains and improved HI (Yang and Zhang 2010). Compared with unregulated drainage systems, a combination of controlled irrigation and drainage has been found to improve WUE in paddy fields (Peng et al. 2012; Shao et al. 2014; Gao et al. 2018). In the present study, significantly higher grain yields in the $DD1_{1.2}$ and $DD2_{1.2}$ treatments resulted in higher WUE compared with $DS_{0.6}$ (Figure 6).

Relatively high values of SOC were observed before Season 1, which was related to build-up of organic matter during the fallow period prior to the experiment, compared with at the end of Season 3 (Table 7). At the end of Season 1, high C/N ratio (18.0–28.3) was observed, indicating low SOC mineralisation during the rice-growing season. SOC mineralisation is generally low under submerged conditions, due to inhibited microbial activity compared with aerobic conditions (Drenovsky et al. 2004). The observed decreases in C/N ratio at the end of Seasons 2 and 3 might be associated with SOC mineralisation taking place in aerobic conditions during the transition period between the seasons, combined with the fact that the organic matter stock was not replenished between seasons. The practice of not returning plant residues to the soil after harvesting might have caused depletion of SOC and TN. Wang et al. (2014) reported, when rice plant residues are removed after each harvest, there is little input of organic matter from the previous crop to soil, leading to SOC depletion in paddy fields. Proper management of the straw on the farm after harvesting, such as returning it to the fields, can be adopted to replenish SOC and enhance nutrient inputs for long-term soil fertility in the marshland study area. Soil mineral N depletion could be associated with different observed N pathways and unobserved pathways (ammonia volatilisation, denitrification, assimilation by microorganisms and roots etc.), if mineral fertilisation rate is not sufficient to enrich the soil.

In conclusion, this study showed that deep drainage systems can enhance water use efficiency and rice grain yield in poorly drained paddy fields. However, long-term field studies in similar environments are needed to confirm the interaction of drainage intensity and other processes affecting N losses in drainage water, such as N loss pathways in paddy fields. During the experimental period, a decrease in C/N ratio was observed. Therefore straw should be returned to the soil after harvesting in order to maintain soil organic matter and long-term soil fertility in paddy rice cropping systems.

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References

Allen RG. 1998. Crop evapotranspiration: guidelines for computing crop requirements. Irrigation and Drainage Paper No. 56. FAO. Rome, Italy.

Allen RG, Pruitt WO. 1986. Rational use of the FAO Blaney-Criddle formula. J Irr Drain. 112:139–155.

Anderson JM, Ingram JSI. 1994. Tropical soil biology and fertility: a handbook of methods. Wallingford, UK: CAB International.

APHA. 1992. Standard methods for the examination of water and waste water. Maryland: American Public Health Association.

Bouyoucos GJ. 1962. Hydrometer method improved for making particle size analyses of soils. Agron J. 54:464–465.

Buresh RJ, Haefele SM. 2010. Changes in paddy soils under transition to water-saving and diversified cropping systems. In World congress of soil science; Brisbane, Australia.

Condon AG, Hall AE. 1997. Adaptation to diverse environments: variation in water use efficiency within crop species. In: Jackson LE, editor. Agricultural ecology. San Diego, USA: Academic Press. p. 79–116.

Cyamweshi AR, Kayumba J, Nabahungu NL. 2017. Optimizing fertilizer use within the context of integrated soil fertility management in Rwanda. In: Wortmann CS, Sones K, editor. Wallingford, UK: CAB International. p. 165–175.

Darzi-Naftchali A, Mirlatifi SM, Asgari A. 2014. Comparison of steady and unsteady state drainage equations for determination of subsurface drain spacing in paddy fields: a case study in Northern Iran. Paddy Water Environ. 12:103–111.

Darzi-Naftchali A, Ritzema H. 2018. Integrating irrigation and drainage management to sustain agriculture in northern Iran. Sustainability. 10:1–17.

Darzi-Naftchali A, Shahnazari A, Karandish F. 2017. Nitrogen loss and its health risk in paddy fields under different drainage managements. Paddy Water Environ. 15:145–157.

Drenovsky RE, Vo D, Graham KJ, Scow KM. 2004. Soil water content and organic carbon availability are major determinants of soil microbial community composition. Microb Ecol. 48:424–430.

ESG. 2019. Financing sustainable rice for a secure future. London: Earth Security Group.

Gao S, Yu S, Wang M, Meng J, Tang S, Ding J, Li S, Miao Z. 2018. Effect of different controlled irrigation and drainage regimes on crop growth and water use in paddy rice. Int J Agric Biol. 20:486–492.

Ghins L, Pauw K. 2017. The impact of policy and the market environment on production and wholesale trade incentives for rice in Rwanda. Agricultural Development Economics Working Paper 18-02. Rome.

Jiao J, Shi K, Li P, Sun Z, Chang D, Shen X, Wu D, Song X, Liu M, Li H, et al. 2018. Assessing of an irrigation and fertilization practice for improving rice production in the Taihu Lake region (China). Agric Water Manage. 201:91–98.

Kröger R, Pierce SC, Littlejohn KA, Moore MT, Farris JL. 2012. Decreasing nitrate-N loads to coastal ecosystems with innovative drainage management strategies in agricultural landscapes: an experimental approach. Agric Water Manage. 103:162–166.

Landon JR. 1991. Booker tropical soil manual: a handbook for soil survey and agricultural land evaluation in the tropics and subtropics. New York: Longman Scientific and Technical Group Ltd..

Luo W, Jia Z, Fang S, Wang N, Liu J, Wang L, Tian S, Zhang Y. 2008. Outflow reduction and salt and nitrogen dynamics at controlled drainage in the YinNan irrigation District, China. Agric Water Manage. 95:809–816.

MINAGRI. 2011. National rice development strategy. Kigali, Rwanda: Ministry of Agriculture and Animal Resources.

Nelson DW, Sommers LE. 1982. Total carbon, organic carbon and organic matter. In: Page AL, Miller RH, Keeney DR, editor. Methods of soil analysis. Part II. Chemical and microbiological properties. Madison, WI, USA: ASA, SSSA. p. 539–579.

Oenema O, Kros H, de Vries W. 2003. Approaches and uncertainties in nutrient budgets: implications for nutrient management and environmental policies. Eur J Agron. 20:3–16.

Okalebo JR, Gathua KW, Woomer PL. 2002. Laboratory methods of soil and plant analysis: a working manual. Nairobi, Kenya: TSBF Programme.

Peng S, He Y, Yang S, Xu J. 2015. Effect of controlled irrigation and drainage on nitrogen leaching losses from paddy fields. Paddy Water Environ. 13:303–312.

Peng S, Luo Y, Xu J, Khan S, Jiao X, Wang W. 2012. Integrated irrigation and drainage practices to enhance water productivity and reduce pollution in a rice production system. Irrig Drain. 61:285–293.

Pinitpaitoon S, Bell RW, Suwanarit A. 2011. The significance of available nutrient fluxes in N and P budgets for maize cropping on a Rhodic Kandiustox: a study with compost, NP fertilizer and stubble removal. Nutr Cycl Agroecosys. 89:199–217.

Ramasamy S, Ten Berge HFM, Purushothaman S. 1997. Yield formation in rice in response to drainage and nitrogen application. Field Crops Res. 51:65–82.

REMA. 2011. Atlas of Rwanda's changing environment – implications for climate change resilience. Kigali, Rwanda: Rwanda Environment Management Authority.

Ritzema HP, Satyanarayana TV, Raman S, Boonstra J. 2008. Subsurface drainage to combat waterlogging and salinity in irrigated lands in India: lessons learned in farmers' fields. Agric Water Manage. 95:179–189.

Shao GC, Deng S, Liu N, Yu SE, Wang MH, She DL. 2014. Effects of controlled irrigation and drainage on growth, grain yield and water use in paddy rice. Eur J Agron. 53:1–9.

Skaggs R, Youssef MA, Chescheir GM, Gilliam JW. 2005. Effect of drainage intensity on nitrogen losses from drained lands. Trans ASAE. 48:2169–2177.

Skaggs RW, Fausey NR, Evans RO. 2012. Drainage water management. J Soil Water Conserv. 67:167A–172A.

Steduto P, Hsiao TC, Fereres E, Raes D. 2012. Crop yield response to water. Rome: FAO.

Tian YH, Yin B, Yang LZ, Yin SX, Zhu ZL. 2007. Nitrogen runoff and leaching losses during rice-wheat rotations in Taihu Lake Region, China. Pedosphere. 17:445–456.

Wang W, Sardans J, Zeng C, Zhong C, Li Y, Peñuela J. 2014. Responses of soil nutrient concentrations and stoichiometry to different human land uses in a subtropical tidal wetland. Geoderma. 232-234:459–470.

Wesström I, Messing I, Joel A. 2014. Controlled drainage and subirrigation. A water management option to reduce non point source pollution from agricultural land. Agr Ecosyst Environ. 198:74–82.

Xiao MH, Yu SE, She D, Hu XJ, Chu LL. 2015. Nitrogen and phosphorus loss and optimal drainage time of paddy field under controlled drainage condition. Arab J Geosci. 8:4411–4420.

Yang J, Zhang J. 2010. Crop management techniques to enhance harvest index in rice. J Exp Bot. 61:3177–3189.

Yang J, Zhang J, Huang Z, Zhu Q, Wang L. 2000. Remobilization of carbon reserves is improved by controlled soil-drying during grain filling of wheat. Crop Sci. 40:1645–1655.

Zhang JH, Liu JL, Zhang JB, Cheng YN, Wang WP. 2013. Nitrate-nitrogen dynamics and nitrogen budgets in rice-wheat rotations in Taihu Lake Region, China. Pedosphere. 23:59–69.

Zhang Z, Zhang S, Yang J, Zhang J. 2008. Yield, grain quality and water use efficiency of rice under non-flooded mulching cultivation. Field Crops Res. 108:71–81.

Zhi M. 2002. Water efficient irrigation and environmentally sustainable irrigated rice production in China. International Commission on Irrigation and Drainage. http://www.icid.org/wat_mao.pdf.