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Drainage intensity in paddy rice fields

Nitrogen flows, salinity, rice yield and greenhouse gas emissions

OLIVE TUYISHIME

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Olive Tuyishime
Faculty of Natural Resources and Agricultural Sciences
Department of Soil and Environment
Uppsala

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Cover: Aerial view of the experimental site.
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Abstract

Managing drainage intensity is important in controlling soil moisture and nutrient losses and improving crop yields. This thesis evaluated the effects of drainage intensity on nitrogen losses, salinity and rice grain yield in three cropping seasons, and on gaseous emissions of methane (CH_4) and nitrous oxide (N_2O) from rice flowering to ripening in one season, on a marshland in semi-arid region of Rwanda. Three drainage treatments were compared in a randomised complete block design: drainage to 0.6 m depth, weir open four times per week (S4); drainage to 1.2 m depth, weir open four times per week (D4); and drainage to 1.2 m, weir open twice per week (D2). In seasons 1 and 3, treatment D4 had higher drainage outflow and higher salt loads than treatments D2 and S4, but in season 2 treatment D2 had higher drainage outflow and higher salt loads than D4 and S4. Drainage water salinity (EC_{wd}) decreased by around 41-57% from season 1 to season 2, and by 29-37% from season 2 to season 3. Soil salinity decreased by one electrical conductivity (EC) unit (dS m^{-1}) from season 1 to season 2, and by a similar amount from season 2 to season 3. Nitrogen uptake and rice grain yield were significantly greater in the deep drainage treatments (D4, D2) compared with shallow drainage (S4). Deep drainage (D4, D2) reduced CH_4 emissions but had no marked effect on N_2O emissions. These findings suggest that deep drainage performs better than shallow drainage in semi-arid paddy fields, as it enables a balance between maintaining water in the soil and having sufficient drain outflow to leach salts, reduce CH_4 emissions and achieve high rice yield.

Keywords: Agricultural water management, N losses, salts, paddy fields, greenhouse gases

Author's address: Olive Tuyishime, SLU, Department of Soil and Environment, P.O. Box 7014, 75007, Uppsala, Sweden.
E-mail: olive.tuyishime@slu.se or olivetuyishime2@gmail.com

Intensité du drainage en rizières

Flux d'azote, la salinité, le rendement en riz et les émissions de gaz à effet de serre

Résumé

La gestion de l'intensité du drainage est important pour contrôler l'humidité du sol et les pertes de nutriments et améliorer les rendements des cultures. Cette thèse a évalué les effets de la variation de l'intensité du drainage (i) sur les pertes d'azote, la salinité et le rendement en grains du riz au cours de trois saisons de culture (saisons 1-3), et (ii) sur les émissions gazeuses de méthane (CH_4) et d'oxyde nitreux (N_2O) du stade de la floraison du riz au stade de la maturation en un seule saison (saison 4), au sein de marais situé en climat semi-aride au Rwanda. Trois types de drainage ont été comparés au sein d'un dispositif en blocs complet aléatoire : un drainage à 0,6 m de profondeur et un déversoir ouvert quatre fois par semaine (S4) ; un drainage à 1,2 m de profondeur et un déversoir ouvert 4 fois par semaine (D4) ; et un drainage à 1,2 m et un déversoir ouvert 2 fois par semaine (D2). Au cours des saisons 1 et 3, le traitment D4 avait un débit de drainage et des charges en sel plus élevés que les traitement D2 et S4, mais au cours de la saison 2, le traitment D2 avait à la fois un débit de drainage et des charges en sel plus élevés que les deux autres traitments (D4 et S4). La salinité du sol a diminué d'une unité de conductivité électrique (EC) (dS m^{-1}) de la saison 1 à la saison 2, puis de la saison 2 à la saison 3. La salinité des eaux de drainage (EC_{wd}) a également diminué pour l'ensemble des traitements sur un intervalle de 41 à 57 % de la saison 1 à la saison 2 et de 29 à 37 % de la saison 2 à la saison 3. Le drainage profond (D4, D2) a réduit les émissions de CH_4 sans effet notable sur les émissions de N_2O (saison 4). Dans l'ensemble, l'absorption d'azote et le rendement en grains de riz étaient plus élevés avec un drainage profond (D4, D2) par rapport à un drainage peu profond (S4). Ces résultats indiquent que le drainage profond est le système le plus adéquat pour les rizières semi-arides parce qu'il permet un équilibre entre le drainage et le maintien de l'eau dans le sol, ce qui maintient la salinité du sol à un niveau adéquat et conduisant à de bons niveaux de rendement.

Mots clés : Gestion de l'eau agricole, pertes d'azote, sels, rizières, gaz à effet de serre

Adresse de l'auteur: Olive Tuyishime, Université Suédoise des Sciences Agricoles, Département du Sol et de l'Environnement, Uppsala, Suède.
E-mail: olive.tuyishime@slu.se ou olivetuyishime2@gmail.com

Dedication

To Emmanuel, Geulah and Gavriil, for your endless love and support!
To my dear Father, always loved!

“*Nature makes blue and green water. Humans make-and have learned to reuse-grey water. But how much grey water can be there?*” ASA, CSSA and SSSA

“Life can get better. Challenges can be overcome. Hard work and determination can make a difference” Howard G. Buffet

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I. Tuyishime, O., Joel, A., Messing, I., Naramabuye, F., Sankaranarayanan, M. & Wesström, I. (2020). Effects of drainage intensity on water and nitrogen use efficiency and rice grain yield in a semi-arid marshland in Rwanda. *Acta Agriculturae Scandinavica, Section B-Soil & Plant Science* 70 (7), 578-593.

II. Tuyishime, O., Joel, A., Messing, I., Strömgren, M., Naramabuye, F.X. & Wesström, I. Effect of drainage intensity on soil salinity and rice grain yield on marshland in a semi-arid environment in Rwanda (manuscript).

III. Tuyishime, O., Strömgren, M. Joel, A., Messing, I., Naramabuye, F.X. & Wesström, I. (2022). Deep drainage lowers methane and nitrous oxide emissions from rice fields in a semi-arid environment in Rwanda. *Soil Systems* 6 (4), 84.

Papers I and III are open-access and may be distributed under the terms and conditions of CCBY 4.0.

The contribution of Olive Tuyishime to the papers included in this thesis was as follows:

I. Planned the study with the co-authors. Performed the experimental fieldwork, sample collection and laboratory analysis. Carried out data analysis, interpretation and writing, with assistance from the co-authors.

II. Planned the study with the co-authors. Performed the experimental fieldwork, sample collection and laboratory analysis. Carried out data analysis, interpretation and writing, with assistance from the co-authors.

III. Planned the study with the co-authors. Performed the experimental fieldwork and sample collection. Interpreted the results and wrote the paper, with assistance from the co-authors.

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Abbreviations

CH_4	Methane
C/N	Carbon/nitrogen ratio
dS	Deci-Siemens
D4	Drainage to 1.2 m depth, weir opened four times per week
D2	Drainage to 1.2 m depth, weir opened two times per week
EC_e	Electrical conductivity of saturated soil paste extract
EC_{wd}	Electrical conductivity of drainage water
EC_{wi}	Electrical conductivity of irrigation water
EC_{ws}	Electrical conductivity of soil water
ET_c	Crop evapotranspiration
ET_o	Reference evapotranspiration
GHG	Greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
K	Potassium
N	Nitrogen
NH_4^+-N	Ammonium-nitrogen
NO_3^--N	Nitrate-nitrogen
N_2O	Nitrous oxide
SOC	Soil organic carbon
SOM	Soil organic matter
S4	Drainage to 0.6 m depth, weir opened four times per week
TN	Total nitrogen

1. Introduction

Supplying food for an increasing population is a current and future challenge in sub-Saharan Africa. Besides existing water scarcity in the region, future agricultural production will also be impaired by climate change, which is expected to affect water availability and food security (Hunt *et al*., 2020; Sun *et al*., 2020). Therefore, there is a need for novel strategies to balance improvements in crop yield, water use efficiency and water quality, in order to achieve food security and a sustainable environment.

Rice (*Oryza sativa L.*) is an important stable food crop and a vital component in the diet of billions of people around the globe (Razzaq *et al*., 2020). Paddy rice is a water-demanding crop that needs considerable amounts of fresh water in flooded-irrigated conditions. Most traditional water management practices strive to keep a standing depth of water on the field throughout the season, which provides a sufficient water supply and also controls weed by keeping root zones in anaerobic conditions (Bwire *et al.*, 2022). Rice production in arid and semi-arid areas depends on irrigation, due to low and unpredictable rainfall. However, excessive irrigation, high groundwater levels and irrigation water salinity can lead to waterlogging and soil salinisation. In these circumstances, the main role of drainage is to prevent waterlogging and salinisation (Ritzema, 2016). On the other hand, excessive drainage can result in nutrient leaching and low irrigation water use efficiency, leading to decreased crop yield and adverse environmental effects (Crézé & Madramootoo, 2019; Jouni *et al*., 2018; Sojka *et al*., 2019).

Attempts to manage the quantity and quality of drainage outflow and ensure consistent yields have led to the development of controlled drainage approaches. Controlled drainage involves managing the groundwater level and controlling the amount of outflow by applying a structure such as a flashboard riser and adjusting the elevation of the drainage outlet (Evans *et al.*, 1995; Wesström *et al*., 2001). Unlike conventional drainage systems, which remove excess soil water to drain depth, controlled drainage systems increase water retention and storage within the soil profile (Jouni *et al*., 2018; Lalonde *et al*., 1996; Ng *et al.*, 2002; Skaggs & Youssef, 2008; Wesström & Messing, 2007). By holding water in and above the drains, controlled drainage reduces drainage volume and decreases the loads and concentrations of plant nutrients in drainage outflow. This approach can effectively improve the use efficiency of irrigation water and water productivity (Luo *et al*., 2008).

1.1 Water management in irrigated agriculture

Irrigated agriculture is one of the major users of water resources worldwide, consuming approximately 70% of total water withdrawn (FAO, 2013). Since water shortage is a harsh reality in arid and semi-arid regions, high agricultural water use efficiency is imperative to ensure global water security (Nazari *et al*., 2018). In a water management context, water use efficiency refers to crop production per unit of water used, expressed as *e.g*. kg of dry matter ha^{-1} mm^{-1} or kg m^{-3} (Sadras *et al*., 2011). Crop water use efficiency is defined as the ratio of biomass accumulation, expressed as carbon dioxide (CO_2) assimilation, total crop biomass or grain yield, to the amount of water consumed, which can be expressed as transpiration, evapotranspiration (ET) or total water input to the system (Waraich *et al*., 2011). Water use efficiency in paddy rice is generally low, because this crop requires large amounts of fresh water under flooded irrigated conditions. Most conventional water management approaches in paddy rice production aim to maintain a standing depth of water in the field throughout the season. Water consumption by paddy rice fields accounts for 40% of all irrigation water globally. Moreover, decreasing water availability for agriculture threatens the productivity of irrigated agro-ecosystems, so ways to save irrigation water, improve water use efficiency and maintain rice yield must be identified (Liang *et al*., 2016; Zhi, 2002).

1.2 Controlling nitrogen losses and drainage intensity

Nitrogen (N) is the key nutrient in production of rice. Paddy soils in irrigated and rainfed lowland rice production systems undergo a prolonged period of submergence (Buresh & Haefele, 2010). The main nitrogen transformation processes in submerged soils, as in aerated soils, are mineralisation, immobilisation, nitrification, denitrification, ammonia volatilisation and biological nitrogen fixation. However, soil submergence modifies these processes. A unique feature of submerged soils is the simultaneous formation and loss of nitrate (NO_3^-) occurring within adjoining aerobic and anaerobic soil zones (Buresh *et al*., 2008). The NO_3^- that accumulates in aerobic soils during the dry season is lost through nitrification-denitrification and leaching during the transition to anaerobic conditions.

Decreased NO_3^- loads in controlled drainage systems compared with conventional drainage systems have been reported in previous studies. In Italy, for example, decreases in drainage volume of up to 77% and in NO_3^- loads in drainage water of up to 70% have been observed in controlled drainage systems compared with conventional drainage systems (Bonaiti & Borin, 2010). Similar decreases in drainage volume (of 65-95%) and reductions in NO_3^- loading in the drainage outflow have been observed in a study in southern Sweden (Wesström & Messing, 2007). In addition to decreasing NO_3^- loads in drainage water, some studies have also observed decreases in drainage outflow and in NO_3^- concentrations in drainage water from controlled drainage systems compared with conventional drainage (*e.g*. Lalonde *et al*., 1996). In addition to decreased NO_3^- concentrations, *Ng et al*. (2002) observed higher cumulative drainage outflow from controlled drainage systems compared with conventional drainage.

In a review of existing studies on controlled drainage systems, Skaggs and Youssef (2008) concluded that the decrease in NO_3^- loads under controlled drainage is due to lower drainage outflow, based on the fact that the percentage decrease in flow and NO_3^- loads is generally similar. However, decreased flow rates and elevated groundwater levels also increase the likelihood of anoxia and denitrification (Singh *et al*., 2006). Denitrification results in loss of nitrogen as di-nitrogen (N_2) or nitrous oxide (N_2O). The latter is a 300 times more potent greenhouse gas (GHG) than CO_2, *i.e.* it absorbs 300 times more heat than CO_2 (Huang, 2017). Gaseous losses of nitrogen can decrease the concentration of NO_3^- in soil water.

1.3 Irrigated agriculture and soil salinity

Soil salinity, *i.e.* elevated concentrations of salts in soil, is amongst the foremost global challenges affecting agricultural production and environmental sustainability (Shahid *et al*., 2018). It has severe effects on the global economy, resulting in loss of $27.3 billion in annual income worldwide (Qadir *et al*., 2014). The global area of salinised soil is increasing at a rate of 1-2 million ha per year, and the pace is likely to continue rising during coming decades as a result of climate change (Hassani *et al*., 2021).

In efforts to feed the growing global population while combating soil salinity and its effects on agriculture, there has been an increase in research on soil salinity and on possible salinisation mitigation strategies at farm level (Shahid *et al*., 2018). Primary salinity (due to natural processes), irrigation water quality, agricultural water management (irrigation and drainage), use of fertilisers and climate change impacts, such as decreases in rainfall, increases in temperature and sea level rise, are among the key causes of soil salinisation (Haj-Amor *et al*., 2022).

Around 33% of the world's irrigated agricultural land area is affected by soil salinity (Shrivastava & Kumar, 2015), due to poor quality of irrigation water and inadequate agricultural water management. Thus, there is a need for immediate interventions to reduce the expansion of salt-affected soils, which are expected to make up around 50% of total global irrigated area by 2050 (Nachshon, 2018; Wang *et al*., 2020). Improving agricultural water management, through understanding the functioning of irrigation and drainage systems across different environmental scales, is critical in mitigating the adverse effects of soil salinity in irrigated agricultural production.

For effective salinity control, adequate drainage can be provided to prevent salt accumulation in the crop rootzone and upper soil layers (Ritzema *et al*., 2008). Most previous studies have focused on the off-site environmental impacts of using controlled drainage, mainly in humid regions, aiming at reducing drainage outflow and therefore reducing nitrate loads in drainage water (Lalonde *et al*., 1996; Ng *et al*., 2002; Wesström & Messing, 2007). However, the results are not applicable to arid and semi-arid regions, where controlled drainage has to take into account soil salinity management issues in order to avoid salt accumulation in the crop rootzone (Ayars *et al*., 2006). Studies that have been performed in arid and semi-arid areas have shown improved irrigation water use efficiency under controlled drainage systems, with no significant effects on crop yield or salinity in the root-zone compared with conventional drainage systems (Khalil *et al*., 2004). However, some studies have observed noticeable yield decreases in crop yields in saline conditions with managed drainage depth (Foda *et al*., 2020).

1.4 Rice production and soil salinity management

Rice is a high-yielding crop, although different factors such as environmental stress, inappropriate management strategies and nutrient deficiency can lower its potential yield. Soil salinity is among the main causes of low rice yield. The United Nations Food and Agriculture Organization (FAO) has categorised rice plants as highly susceptible to salinity stress, with a salinity threshold level of 3.0 dS m^{-1} (Abrol *et al*., 1988). Field studies have found that an increase in the concentration of salts in soil from around 2 to 6.1-8.0 dS m^{-1} can cause substantial reductions in seedling growth and in number of filled rice grains per panicle (Aref & Rad, 2012; Zeng & Shannon, 2000). High soil salinity generally induces changes in different components of rice which are linked to each other, and therefore affects final grain yield and composition (Razzaq *et al*., 2020). The response of rice to salinity varies with growth stage, *e.g*. young seedlings of the most commonly cultivated rice cultivars are very sensitive to salinity (Rad *et al.*, 2012). It has also been shown that salinity stress decreases rice stand density and production of seedling biomass, reflecting this crop's high sensitivity to salinity (Grattan *et al*., 2002).

Excessive irrigation without adequate drainage is a major driver of soil salinisation (Wichelns & Qadir, 2015). Various strategies have been suggested to halt salinisation of agricultural soils (Qadir *et al*., 2007). These include different agronomic techniques aimed at minimising the negative impact of salinity on crop yields, use of better-quality irrigation water, prevention of further salinisation by improved drainage and cropping with salt-tolerant plants. The best solutions to dealing with salinity are suggested to be leaching salt from the crop rootzone and controlling groundwater level (Cuevas *et al.*, 2019). Irrigation with an adequate quantity of water of good quality to promote salt leaching and installing a suitable drainage network are suggested to be the most sustainable and affordable solutions to prevent salinisation when sources of water of good quality are available (Cuevas *et al*., 2019; Kara & Willardson, 2006).

1.5 Methane and nitrous oxide emissions in paddy fields

The contribution of agriculture to global GHG emissions has been considered throughout all previous work by the Intergovernmental Panel on Climate Change (IPCC), with increased efforts more recently to estimate the impacts of increasing crop yield on GHG emissions and mitigation potential and adaptation to a changing climate (Porter *et al*., 2017). From the first IPCC Assessment Report (FAR) in 1990 to the latest (AR6) in 2021, agriculture has featured in several regards. Agriculture and food production are primarily related to three main GHG, *i.e.* CO_2, methane (CH_4) and N_2O (Lynch *et al*., 2021). Agricultural intensification using conventional cropland management practices such as intensive tillage, excessive use of nitrogen fertiliser and conventional water management create environmental problems, such as global warming, as a result of increased soil organic carbon decomposition and N_2O and CH_4 emissions (Shang *et al*., 2021). In recent decades, various smart cropland management approaches, such as conservation agriculture, straw management and partial replacement of synthetic fertiliser, have been recommended to ensure food security and reduce GHG emissions (Shang *et al*., 2021).

Rice paddies are responsible for approximately 11% of global anthropogenic CH_4 emissions, and rice has the highest GHG emissions of the main food crops (Carlson *et al*., 2017; Linquist *et al*., 2012). In previous field studies, use of different rice varieties has been found to affect the rate of GHG emissions, especially CH_4 emissions (Zheng *et al*., 2014). For example, emissions of CH_4 have been shown to be lower for high-yielding improved rice varieties compared with traditional varieties (Gogoi *et al*., 2008).

Controlled drainage could be a feasible mitigation strategy to reduce CH_4 emissions from paddy fields, because of its effect in regulating groundwater level (Liu *et al*., 2010; Peng *et al*., 2011; Yang *et al*., 2014), considering that rice growers prefer flooded conditions to counteract weeds and increase productivity. Methane is produced in flooded soils by anaerobic bacteria, so reducing the water cover on the surface of paddy fields, thereby enhancing soil aeration, inhibits the activity of methanogens and decreases CH_4 emissions (Ball, 2013; Canadell & Schulze, 2014; Smith *et al*., 2008). Periods of higher soil water content can also lead to potential release of N_2O through denitrification (Jiang *et al*., 2019). Controlled drainage has been found to have inconsistent effects on GHG emissions, including possibly N_2O release through denitrification due to periods with higher soil water content (Jiang *et al*., 2019). In paddy rice, the effect of crop management practices varies with soil moisture due to flooding conditions. Draining the soil is one of the key strategies to reduce CH_4 emissions from paddy fields (Yan *et al*., 2005). However, a clear understanding of factors driving CH_4 and N_2O emissions in paddy fields is needed before different methods for rice production can be advocated on the grounds of climate change mitigation.

1.6 Irrigated areas and rice production in Rwanda

The territory of Rwanda comprises 26,338 km^2 including water bodies (REMA, 2017). Agricultural land comprises around 1,475,385 ha (NISR, 2020), with an irrigation potential of 600,000 ha (Malesu, 2010). The population is currently around 12.7 million and 64% of the population work in agriculture and related sectors. In Rwanda, agriculture contributes around 24% of national gross domestic product (GDP) (MINAGRI, 2020). Rwandan agriculture is generally rainfed, which means low productivity and high vulnerability to climate shocks (FAO, 2023). Through the Ministry of Agriculture (MINAGRI), the government of Rwanda has developed strategies to increase agriculture production by reducing dependency on rainfed agriculture and has initiated marshland, hillside and small-scale irrigation projects to achieve the target of 102,284 ha of agricultural land set by the National Strategy for Transformation (NST1) by the year 2024. The total land under irrigation is now about 68,126 ha including 37,273 ha of marshlands, 8,780 ha of hillside and 22,073 ha of small-scale irrigation technology (SSIT) (MINAGRI, 2022). Marshland and hillside irrigation are 100% funded by the government, but the budget for SSIT is decentralised by MINAGRI to the districts, for 50% subsidy provision to farmers.

Rice (*Oryza sativa* L.) was introduced in Rwanda in the 1960s, but mass cultivation only began recently as the Government of Rwanda sought to diversify food production, as well as providing employment in rural areas (MINAGRI, 2021). Rwanda is endowed with extensive marshlands with high potential for rice production, which allows better use of existing marshlands and reduces pressure on land located on hillsides. The area under irrigated rice cultivation in Rwanda has increased from 3,549 ha in 2000 to 17,000 ha today. Rice production is considered to be one of the most profitable cropping enterprises as regards utilisation of the hydro-agricultural investments made to date. Rice is produced in the Western, Southern and Eastern provinces of Rwanda, predominantly by smallholder farmers who grow the crop under farmer-cooperative schemes set up by the government. About 62,000 farmers operate within 122 rice growing cooperatives, with an average of 0.2 ha rice crop per household (MINAGRI, 2021).

Equitable distribution of water is a major constraint for rice growers in Rwanda, particularly during the dry season and for farmers whose fields are located at the lower end of marshland, or at the tail end of the irrigation canal (MINAGRI, 2021). The major causes are inadequate infrastructure, inefficient water management and use, water shortages and floods. In new marshlands, water is sufficient but often not distributed equitably, due to inappropriate design of the irrigation scheme, uneven levelling and inadequate management of water distribution. Irrigation infrastructure is usually maintained by a local water users' organisation (WUO), and supervised by the Rwanda Agricultural Board (RAB). The activities of WUO are funded through water fees agreed upon and paid by members of cooperatives. Cooperatives usually oversee farmers' responsibility in maintaining plots. However, WUO is responsible for operation and maintenance of irrigation infrastructure. Water user fees are often inadequate to cover the maintenance cost, leading to deterioration of irrigation infrastructure. Inadequate involvement and limited finances of smallholder farmers, as well as limited technical capacities of WUO, remain serious challenges to management, operation and maintenance of irrigation infrastructure in some marshlands (MINAGRI, 2021).

Despite considerable investments in irrigated agriculture in Rwanda, so far no sound investments have been made in drainage infrastructure. In rice-producing marshlands in semi-arid regions of Rwanda, shallow agricultural drainage systems are mainly used. These drainage systems are generally designed to protect rice crops from excess soil water conditions during the seedling and maturity stages, and to improve accessibility for tillage operations and harvesting, and are not sufficient to manage potential water-logging and soil salinity problems. Increased use of agricultural inputs, coupled with the shallow drainage systems in paddy fields in Rwanda, have raised concerns about potential negative impacts on the environment and potential threats to human health and biodiversity (REMA, 2011).

Against this background, this thesis investigated the effects of drainage intensity on nitrogen losses, salinity, rice grain yield and GHG emissions in field studies on a marshland in a semi-arid region of Rwanda.

2. Objectives

The overall aim of the work performed in this thesis was to improve understanding of how different drainage strategies affect nitrogen losses, soil salinity, rice yields and GHG emissions in irrigated rice production on marshland in a semi-arid region (Rwanda). Specific objectives were to determine the effects of drainage intensity (depth and frequency) on:

- Drainage outflow, nitrogen dynamics and rice grain yield (Paper I)
- Soil salinity and rice grain yield (Paper II)
- Soil-surface fluxes of CH_4 and N_2O in paddy rice production (Paper III).

The main hypotheses tested in this thesis were:

1. Deep drains with less frequently opened weirs reduce drainage outflow and nitrogen losses compared with deep or shallow (traditional) drains with more frequently opened weirs.
2. Deep drains with less frequently opened weirs extend water residence time in soil while still achieving sufficient outflow to leach salts, and improve rice yields compared with deep drains with more frequently opened weirs.
3. Deep drains with more frequently opened weirs lower the groundwater level, and therefore reduce CH_4 and N_2O emissions, compared with deep drains with less frequently opened weirs and shallow drains with more frequently opened weirs.

3. Materials and Methods

3.1 Thesis framework

In field studies in Rwanda (Papers I-III), the effects of drainage intensity management (through varying drainage depth and frequency) on drainage outflow, nitrogen loads in drainage water, rice nitrogen uptake, rice grain yield, soil salt leaching, and soil surface CH_4 and N_2O emissions in different parts of the soil-plant-atmosphere system were determined. The links between the work in Papers I-III are shown in Figure 1.

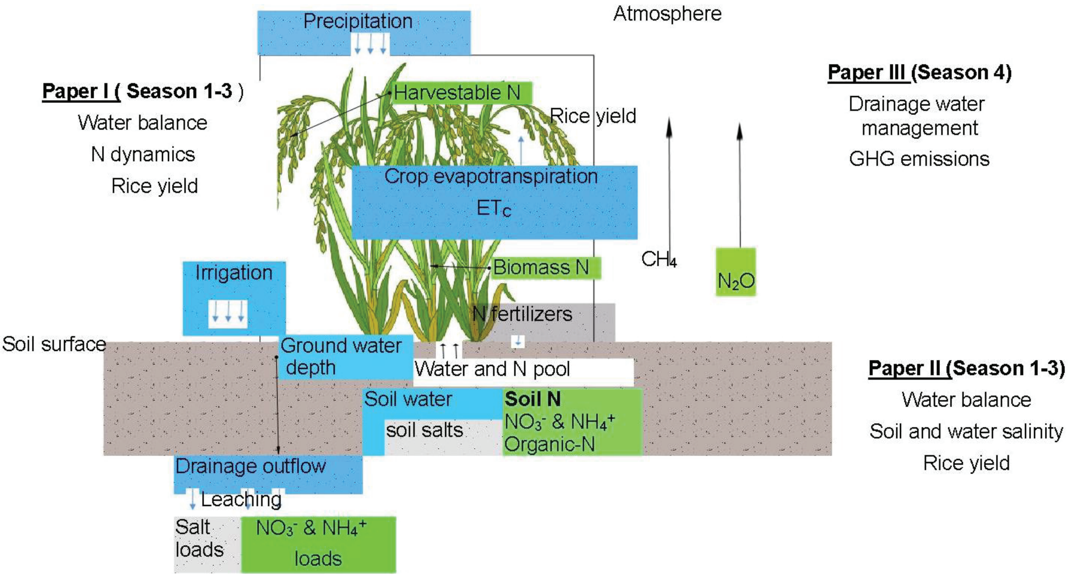


Figure 1. Diagram summarising the links between the work in Papers I-III and the different parameters measured, such as water and nitrogen (N) flows, salt dynamics, rice yield and greenhouse gas emissions, in different time periods during four cropping seasons (seasons 1-4).

3.2 Study area, site and experimental design

The field studies were carried out from 2016 to 2018 in Muvumba marshland (1°17'33.0"S, 30°18'48.2"E) in north-eastern Rwanda (Figure 2). The region has a semi-arid climate, with mean annual temperature of 20 °C and mean annual rainfall of 827 mm (data from Nyagatare station, 1984-2013). Mean annual potential evapotranspiration exceeds 1400 mm (Abimbola *et al*., 2017; RIWSP, 2012). Rainfall is distributed over two rainy seasons, February-May (long rainy season) and September-December (short rainy season), with precipitation peaks in April and November.

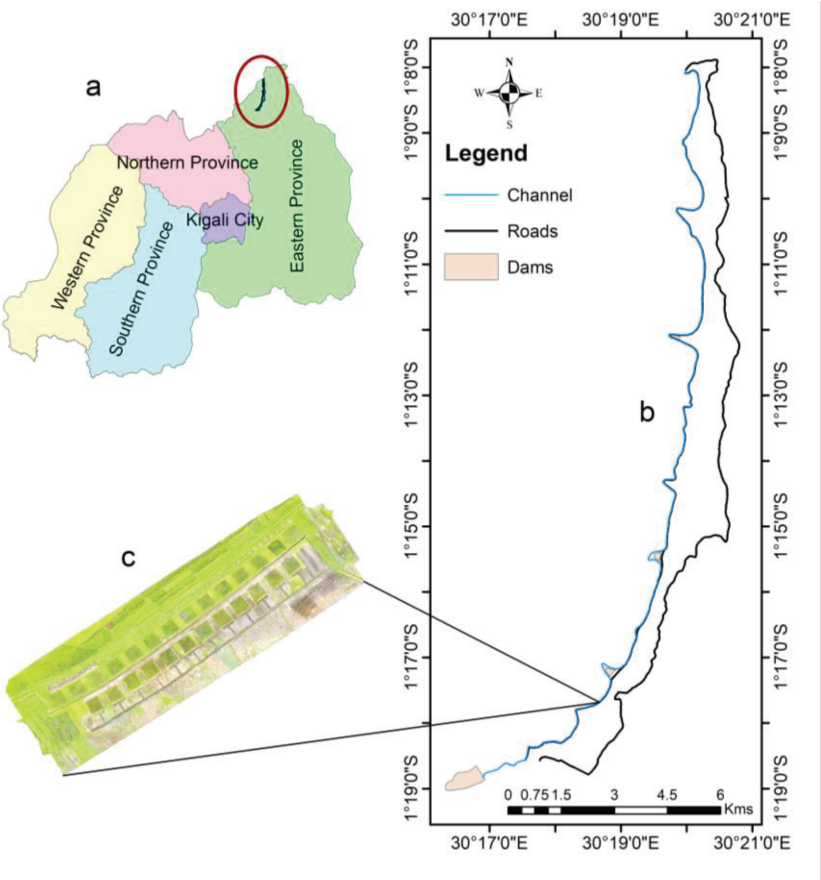


Figure 2. Map of Rwanda showing (a) location of the study site in the north-east (red circle), (b) outline of Muvumba marshland, and (c) position/sketch of the field experiment (source: Paper I).

The soil in the area is a former Vertisol changed into Vertic-Fluvic-Gleysol (FAO/IUSS, 2015) due to continuous deposition of alluvial and colluvial material and waterlogged conditions. When dry, the soil develops cracks observable at the soil surface due to shrinking of the 2:1 clay minerals that dominate the subsoil. Owing to infilling of surface material from the surface and the presence of clay materials in the subsoil, soil compaction is common in the periods between rainy seasons. In fact, most soils develop a hard pan from around 30 cm depth. Prior to establishment of the first field experiment in 2016, the soil at the study site had been abandoned for at least two years due to soil salinity. Before the start of the experiment, composite soil samples were collected from the 0-20, 20-40, 40-60, 60-80 cm soil layers in the zones between the experimental plots and analysed for chemical and physical properties, as baseline soil data (Table 1).

The topsoil at the site has a sandy loam texture, with increasing clay content with depth changing the texture to sandy clay loam in the subsoil, and has neutral pH. Before the experiment began, the soil was strongly saline (Omuto *et al*., 2020) and, based on the Landon (1991) classification, had medium total nitrogen (TN) content and medium soil organic matter (SOM) content (Table 1). Mean moisture content at field capacity ranged between 37.1 and 50.6 % and wilting point between 10.4 and 22.9 %. Porosity decreased with depth, while dry bulk density increased with depth from 1.31 to 1.43 g cm^{-3} (Table 1).

Table 1. *Soil chemical and physical properties (mean ± standard deviation, n=11) at the experimental site based on samples collected in the zones between the 12 experimental plots before establishment of the experiment: pH, electrical conductivity of saturated soil paste extract (*EC_e*, dS m*$^{-1}$*), total nitrogen (TN, %), soil organic matter content (SOM, %), content of sand (%), silt (%) and clay (%), water retention (%) and dry bulk density (g cm*$^{-3}$*)*

Chemical properties

Soil layer	pH	EC_e	TN	SOM
cm		dS m^{-1}	%	%
0-20	7.1 ± 0.6	8.2 ± 2.5	0.27 ± 0.08	9.0 ± 2.1
20-40	7.6 ± 0.5	6.0 ± 1.9	0.28 ± 0.08	8.7 ± 2.8
40-60	7.5 ± 0.3	5.6 ± 1.5	0.26 ± 0.07	7.8 ± 1.0
60-80	7.5 ± 0.4	5.0 ± 1.1	0.28 ± 0.06	7.7 ± 2.6

Physical properties

	Sand	Silt	Clay	Water retention		Porosity	Dry bulk density
				Field capacity	Wilting point		
	weight%	weight %	weight %	volume%	volume%	%	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	60.0 ± 2.5	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	59.7 ± 3.6	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	46.0 ± 3.5	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	45.9 ± 3.5	1.43 ± 0.13

Field measurements were performed in four cropping seasons (2016-2018). Season 1 ran from March to July 2016, season 2 from October 2016 to January 2017, season 3 from March to July 2017, and season 4 from March to July 2018. Data on water flow parameters, nitrogen flows, salinity and rice grain yield were collected in seasons 1-3 (Papers I and II). Fluxes of CH_4 and N_2O from soil, groundwater level and soil temperature (10 cm depth) were measured from rice flowering stage to ripening stage in season 4 (Paper III). The experiment comprised four blocks (I-IV), each with three drainage treatments arranged in a randomised complete block design. These treatments were: i) shallow drainage (to 0.6 m depth), weir opened four times per week (S4); ii) deep drainage (to 1.2 m depth), weir opened four times per week (D4); and iii) deep drainage (to 1.2 m depth), weir opened twice per week (D2). Mineral fertiliser application was based on the Rwandan fertilisation regime for irrigated rice (Cyamweshi *et al*., 2017), for an expected yield of 5.5 tons ha^{-1} (Ghins & Pauw, 2017). The regime consisted of two types of granular fertiliser applied at a rate of 200 kg NPK ha^{-1} (17% N, 7.5% P, 14% K) and 100 kg ha^{-1} of urea (46% N), *i.e.* 80 kg N ha^{-1}, 15 kg P ha^{-1} and 28 kg K ha^{-1}.

Water from the nearby Muvumba river was used for irrigation. 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 scheduling was planned so that the plots were irrigated three times per week, to keep the soil saturated during the cropping season.

The drainage system consisted of a plot ditch in each experimental plot, an outlet and a main collector (Figure 3b). To prevent lateral water flow from plot to plot and from the surroundings, black polythene sheeting (0.5 mm thick) was vertically installed to 1 m depth on the three sides of the plot. Wood weirs were installed in drain outlets to regulate drainage depth (Figure 3b). During the cropping season, the weirs were opened four times per week (treatments S4 and D4) or two times per week (treatment D2).

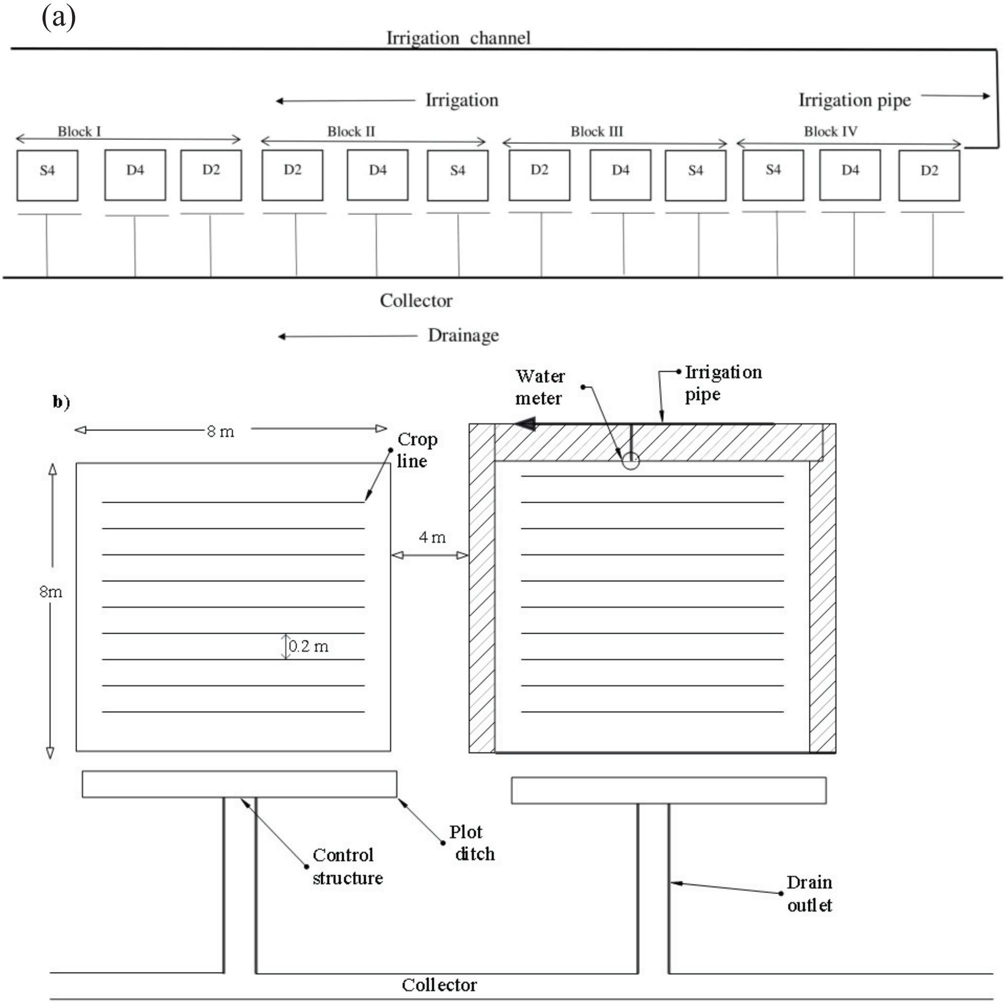


Figure 3. (a) Blocks and treatments in the experimental set-up and (b) dimensions of experimental plots and ditches (image source: modified from Figure 2 in Paper I).

3.3 Measurements and analysis

3.3.1 Climate and hydrological measurements

Water balance components (Papers I and II) were either measured directly or estimated indirectly from measured parameters (Table 2). Precipitation data for the area were obtained from the Rwandan Meteorology Agency (Nyagatare weather station, located 2.7 km from the experimental site). Climate data used to estimate reference evapotranspiration (ET_o) were also obtained from the Rwandan Meteorology Agency. ET_o was calculated using the Blaney-Criddle formula (Allen & Pruit, 1986):

$$ET_{o,i} = p\,(0.46\,T_{mean}+8) \qquad \text{(Eq. 1)}$$

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

Actual crop evapotranspiration (ET_c) was calculated using the FAO-56 approach (Allen *et al.*, 1998):

$$ET_{c,i} = ET_{o,i} * K_{c,i} \qquad \text{(Eq. 2)}$$

where $ET_{c,i}$ is ET_c on day i and $K_{c,i}$ is crop coefficient on day i (dimensionless).

Crop coefficient (K_c) was estimated using the FAO-56 approach (Allen *et al.*, 1998) and was adjusted to the study conditions, *i.e.* three rice growth stages (initial stage (K_c ini), mid-season stage (K_c mid) and late-season stage (K_c end)) and considering the length of each stage:

$$K_{c,i} = K_{c,prev} + \left[\frac{i\text{-}\Sigma\left(L_{prev}\right)}{L_{stage}}\right](K_{c,next}\text{-}K_{c,prev}) \qquad \text{(Eq. 3)}$$

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

The actual amount of irrigation water applied was recorded with water meters installed in each experimental plot (Figure 3b). Drainage outflow was measured with flumes and Solinst level-loggers (Model 3001), two times per week for treatment D2 and four times per week for treatments S4 and D4. The drains were opened for one hour during the drainage outflow measurement events, and then kept closed until the next scheduled opening time. For drainage outflow calculations, values of soil water content corresponding to drainage equilibrium at a groundwater level of 20 cm below the soil surface were used, *i.e.* soil water content near saturation in the top 20 cm and water content at saturation below 20 cm depth. Daily drainage outflow was calculated through the soil water balance approach (Allen *et al*., 1998):

$$Dr_i = Ir_i + P_i - ET_{c,i} - Dr_{i-1} \qquad \text{(Eq. 4)}$$

where Dr_i is drainage outflow (mm) on day i (*i.e.* accumulated water amount between two drainage events), Ir_i is irrigation water applied on day i (mm), P_i is rainfall on day i (mm), $ET_{c,i}$ is ET_c on day i (mm), and Dr_{i-1} is the change in soil water storage (mm).

Groundwater levels were monitored in seasons 2, 3 and 4 using a perforated 60 cm deep pipe installed at the centre of each experimental plot.

Table 2. *Measured and estimated water balance parameters for the experimental site, 2016-2017(seasons 1-3)*

Water balance parameter	Measurement/calculation	Time interval
Rainfall (P)	Data obtained from Rwanda Meteorology Agency	Daily readings
Actual crop evapotranspiration (ET_c)	Calculated from reference crop evapotranspiration and crop coefficient (Eqs. 1-3) (FAO-56 approach, Allen *et al*., 1998)	Calculated daily
Irrigation (I)	Measured with water meters	2-3 times per week
Drainage outflow (Dr)	Calculated using a soil water balance approach (Eq.4) (Allen *et al*., 1998) Measured with level loggers	2-4 times per week
Depth to groundwater	Perforated pipe	2-4 times per week

3.3.2 Nitrogen balance (Paper I)

Nitrogen balance (kg ha^{-1}) was estimated as the difference between nitrogen inputs and nitrogen outputs (Oenema *et al*., 2003; Pinitpaitoon *et al*., 2011; Zhang *et al*., 2013) (equation 5). The inputs consisted of nitrogen from mineral (min.) fertiliser plus soil mineral nitrogen (N min.) before sowing, while the outputs consisted of nitrogen losses in drainage water and crop nitrogen uptake, all expressed in kg ha^{-1}.

$$\text{N balance} = (N_{\text{min. fertiliser}} + N_{\text{min. before sowing}}) - (N_{\text{drain. water}} + N_{\text{crop uptake}}) \quad \text{(Eq. 5)}$$

Nitrate-nitrogen (NO_3-N) and ammonium-nitrogen (NH_4^+-N) were determined in fresh soil samples (collected at 0-20, 20-40 and 40-60 cm soil depth), using the colorimetric method (Okalebo *et al*., 2002). The values obtained were converted to kg per hectare using dry bulk density values (see Table 1), soil layer thickness and soil nitrogen concentration. Nitrogen in drainage water was determined from weekly drainage water samples, *i.e.* samples collected on different days of the week and mixed to give a weekly composite sample. Daily nitrogen loss in drainage water was calculated by multiplying the nitrogen concentration by daily drain outflow (calculated from the water balance). After harvest of the rice, grain was separated from the straw fraction and both fractions were oven-dried at 70 °C for 72 hours, milled and analysed for nitrogen content by the colorimetric method (Okalebo *et al*., 2002). It should be noted that the continuous supply of mineral nitrogen from mineralisation of soil organic matter and possible alternative pathways of nitrogen losses, such as ammonia volatilisation, were not determined in this thesis.

3.3.3 Soil and drainage water salinity (Paper II)

Soil salinity was determined in the laboratory (baseline) and in the field during cropping seasons 1-3 (Paper II). In the laboratory, the electrical conductivity of a saturated soil paste extract (EC_e) was determined from composite soil samples collected from 0-20, 20-40, 40-60, 60-80 cm depth in the zones between the 12 experimental plots. During cropping seasons 1-3, the electrical conductivity of soil water (EC_{ws}), irrigation water (EC_{wi}) and drainage water (EC_{wd}) was measured directly at the experimental site, using a calibrated EC probe (Testrs $^{®}$11 series). EC_{ws} was measured at three depths (10, 30 and 50 cm, *i.e.* within rice rooting depth) in each experimental plot directly after irrigation, *i.e.* when salinity was at its highest. EC_{wd} was measured two to three times per week, while EC_{wi} was measured every four weeks. EC_{wi} was generally low in all seasons (below the FAO EC_{wi} limit of 0.7 dS m^{-1}).

Total dissolved salt (TDS) content in drainage water (mg L^{-1}) was calculated using the FAO-57 approach (Rhoades *et al.*, 1999):

$$TDS = EC_{wd} * 640 \qquad \text{(Eq. 6)}$$

Salt load in drainage water was calculated for each plot as (Ayars & Tanji, 1999):

$$S_d = \frac{Dr * TDS}{A} * 10^{-2} \qquad \text{(Eq. 7)}$$

where S_d is the salt load in drainage water (kg ha^{-1}), Dr is drainage water amount (L), TDS (mg L^{-1}) is total dissolved salts and A is plot area (m^2), the factor 10^{-2} was used to convert mg m^{-2} to kg ha^{-1}.

3.3.4 Soil organic carbon and total nitrogen (Paper I)

Soil organic carbon (SOC) and total nitrogen (TN) concentrations were determined in auger samples collected in zones between the plots (baseline) and in samples collected in each plot after harvesting (seasons 1-3). Concentration of

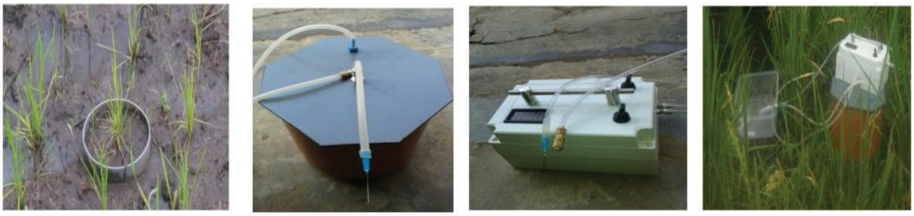
SOC was determined in the laboratory by the Walkley-Black method (Nelson, 1982) and TN was determined using the micro-Kjeldahl method (Anderson & Ingram, 1994).

3.3.5 Grain yield, water productivity and harvest index

At maturity of the rice crop, all aboveground biomass within a 4 m^2 area representative of the crop stand in each plot was harvested. The grain and straw fractions were separated and oven-dried for 72 hours. Yield of rice grain and yield of straw were then calculated on a dry matter basis and converted to yield per hectare (Papers I and II). Water productivity was calculated as rice grain yield over total water input (irrigation + rainfall). Harvest index (HI) was calculated as grain yield (ton ha^{-1}) over total aboveground biomass (ton ha^{-1}).

3.3.6 Greenhouse gas flux measurements and calculations (Paper III)

Fluxes of CH_4 and N_2O from the soil surface were measured at one point in the middle of each plot in season 4, using a closed chamber method (Pumpanen *et al.*, 2010). Emissions of CH_4 and N_2O were measured on nine occasions during rice flowering and ripening stages (from 24 May to 8 July 2018). For each measurement, a dark PVC chamber (diameter 18.7 cm, height 16 cm) was attached to a pre-installed collar (diameter 18.7 cm), which was equipped with a rubber gasket to keep the joint air-tight. Collar height varied from 24 to 67 cm depending on crop height, with collars of greater height used at the end of the study. One chamber was deployed in each rice plot (Figure 4), and six plots (*i.e.* two blocks) were measured at the same time (Paper III). After chamber closure, a pump with ~0.5 L min^{-1} capacity was used to circulate the air between the chamber and the vial for 60 seconds and then an air sample was taken in a 20-mL glass vial. Three more air samples were taken in the same way over a 24-minute interval.



a. A pre-installed collar

b. A PVC chamber

c. A pump

d. A deployed chamber during GHG measurement

Figure 4. (a) Pre-installed collar, (b) PVC chamber, (c) pump and (d) chamber deployed during greenhouse gas (GHG) measurement (Photos: Olive Tuyishime).

The CH_4 and N_2O concentrations in the air samples were analysed in the laboratory at the Swedish University of Agricultural Sciences using a gas chromatograph (Clarus 500, PerkinElmer Inc., USA), equipped with an automatic head-space injector (TurboMatrix 110, PerkinElmer Inc., USA) together with a flame ion detector (FID) for CH_4 and an electron capture device (ECD) for N_2O.

Fluxes of the monitored gases were calculated using the following equation:

$$F=\frac{pVM}{RTA}\cdot\frac{\Delta c}{\Delta t} \qquad \text{Eq. 8}$$

where F is the flux to the atmosphere ($\mu g\ m^{-2}\ h^{-1}$), p is atmospheric pressure (Pa), V is air volume of headspace including tubings, pump and glass vial (m^3), M is molar mass of the monitored gas ($g\ mol^{-1}$), A is collar base area (m^2), R is the ideal gas constant (8.314 J/ mol·K), T is absolute air temperature (K), and $\Delta c / \Delta t$ (ppm h^{-1}), is the increase rate in gas concentration in the chamber during measurement. The increase rate was derived from linear slope between gas concentration in the chamber over time and based on all collected gas samples.

3.4 Statistical analyses

One-way analysis of variance (ANOVA) was used to assess the effects of treatment on drainage outflow, nitrogen losses, soil and drainage water salinity and rice yield (Papers I and II). Block and season effects on soil salinity were determined using a mixed model (Paper II). Drainage treatment effects on CH_4 and N_2O fluxes were tested by mixed model ANOVA. Measurement date of

CH_4 and N_2O fluxes was used as a repeated measure, since they were assumed not to be independent of time considering that the measurements were made in the same plots on every occasion. Tukey’s honestly significant difference (HSD) test was applied for pair-wise comparisons of means, with the significance level set at $p \leq 0.05$ (Papers I-III). All statistical analyses were performed using JMP Pro 14 software (JMP ®14.0.0, SAS Institute Inc., Cary, NC, USA) (Papers I and II) and SAS Statistical software (v9.4, SAS Institute, Cary, NC, USA) (Paper III).

4. Results

4.1 Water parameters

4.1.1 Water balance

In Papers I and II, three cropping seasons in the period 2016-2017 (seasons 1-3) were studied and water balance variables were determined (Table 3). Mean irrigation amount per treatment in the different seasons ranged between 622 and 651 mm in season 1, 568 and 703 mm in season 2, and 708 and 820 mm in season 3. Seasons 1 and 3 were characterised by lower rainfall amount (103 mm and 124 mm, respectively) compared with season 2 (305 mm). Total ET_c was 630 mm, 668 mm and 653 mm in season 1, 2 and 3, respectively. Calculated drainage outflow (Dr_{calc}, based on water balance) was 167-205 mm in season 1, 306-425 mm in season 2 and 332-425 mm in season 3 (Table 3).

Table 3. *Irrigation (mm), precipitation (mm), crop evapotranspiration (ETc, mm), calculated drainage outflow (Dr_{calc}, mm) (mean ± standard deviation, n=4) in seasons 1-3 in the different drainage treatments: shallow drainage to 0.6 m depth, weir opened four times per week (S4), deep drainage to 1.2 m depth, weir opened four times per week (D4) and deep drainage to 1.2 m depth, weir opened two times per week (D2). Different letters (a,b) within lines indicate significant differences ($p<0.05$) between treatments*

Cropping season	Water parameter	Drainage treatment		
		S4	D4	D2
Season 1	Irrigation	622 ± 4	651 ± 19	646 ± 20
	Precipitation	103	103	103
	ET_c	630	630	630
	Dr_{calc}	167 ± 5^{b}	205 ± 24^{a}	173 ± 22^{ab}
Season 2	Irrigation	568 ± 68	677 ± 112	703 ± 54
	Precipitation	305	305	305
	ET_c	668	668	668
	Dr_{calc}	306 ± 32	396 ± 124	425 ± 17
Season 3	Irrigation	708 ± 16^{b}	820 ± 22^{a}	717 ± 10^{b}
	Precipitation	124	124	124
	ET_c	653	653	653
	Dr_{calc}	333 ± 12^{b}	425 ± 44^{a}	332 ± 17^{b}

4.1.2 Groundwater level

Depth to groundwater was monitored in different periods during three cropping seasons (seasons 2-4). During seasons 2 and 3, it was measured from vegetative to ripening growth stage of the rice crop (Figure 5), while in season 4 it was measured before each GHG measurement event. In general, the shallow drainage treatment (S4) had a shorter depth to groundwater (higher groundwater level) than the deep drainage systems (D2 and D4). Mean depth to groundwater ranged from 1.7 to 12.4 cm in season 2, from 2 to 10.7 cm in season 3 (Figure 5) and from 0 to around 35 cm in season 4 (Figure 6).

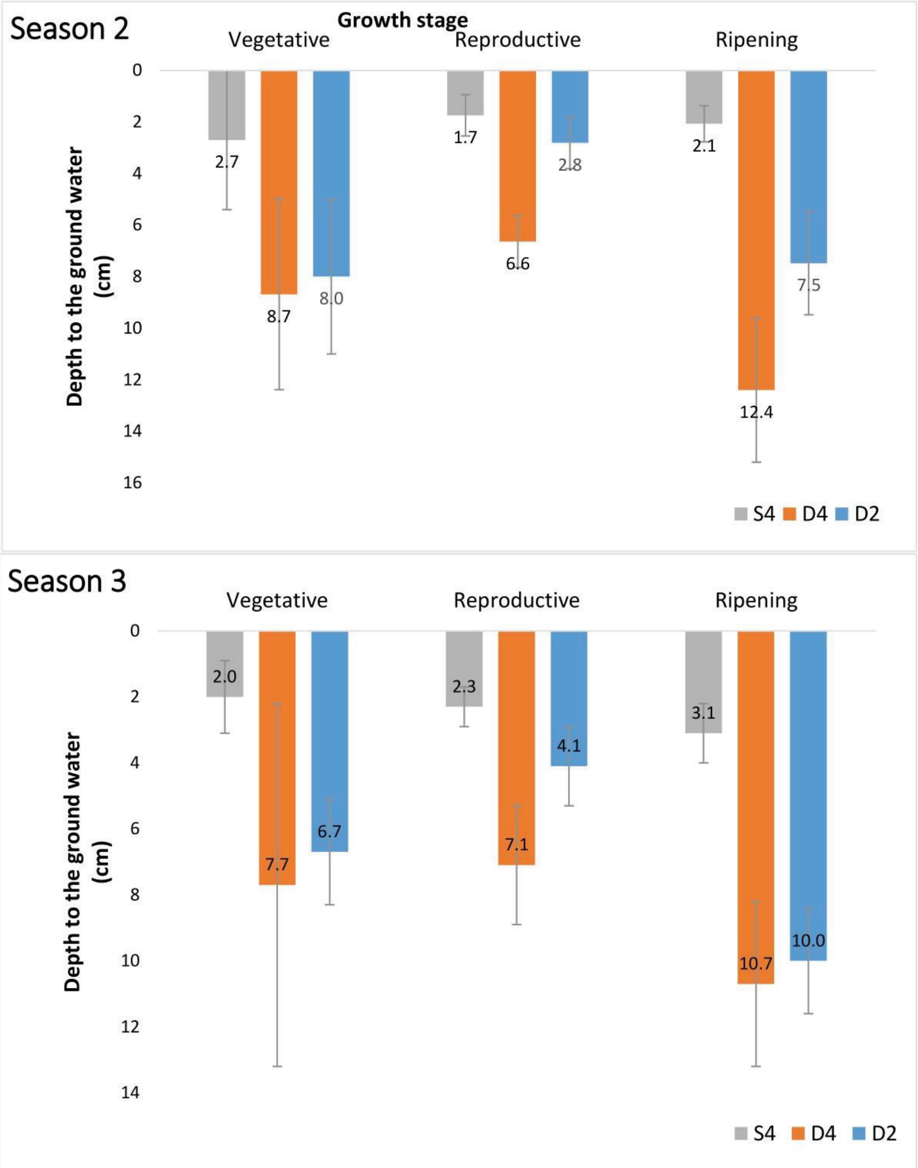


Figure 5. Depth to groundwater from vegetative to ripening stage of the rice crop in seasons 2 and 3 in the different drainage treatments: shallow drainage to 0.6 m depth, weir opened four times per week (S4), deep drainage to 1.2 m depth, weir opened four times per week (D4) and deep drainage to 1.2 m depth, weir opened two times per week (D2). Error bars indicate one standard deviation (n=4)

4.2 Nitrogen flows

4.2.1 Nitrate-N, ammonium-N and nitrite-N concentrations in drainage water (Paper I)

Based on the FAO acceptable ranges of nitrogen concentrations in drainage water (Ayers & Westcot, 1985), nitrate-N (NO_3^--N) concentrations in drainage water were generally low (below 5 mg L^{-1}) in all drainage treatments (Paper I). In addition, ammonium-N (NH_4^+-N) and nitrite (NO_2^--N) concentrations in drainage water were also low (below 5 mg L^{-1}) throughout the study period. The highest concentration of NO_3^--N (4.5 mg L^{-1}) was observed in November 2016 (season 2) and the lowest (0.01 mg L^{-1}) was recorded in June 2017 (season 3) (Paper I). November 2016 and June 2017 were also characterised by the highest and lowest amount of rainfall, respectively, during the study period (Paper I). Overall, no significant differences in NO_3^--N, NH_4^+-N or NO_2^--N loads in drainage water were observed between the treatments (*p*>0.05) (Table 4).

Table 4. *Nitrate-nitrogen (NO_3^--N),ammonium-N (NH_4^+-N) and nitrite-N (NO_2^--N) loads (mean ± standard deviation, n=4) in drainage water and their sum (total N loss in drainage water) in season 1, 2 and 3 in the different treatments: shallow drainage to 0.6 m depth, weir opened four times per week (S4), deep drainage to 1.2 m depth, weir opened four times per week (D4) and deep drainage to 1.2 m depth, weir opened two times per week (D2)*

Season	Treatment	NO_3^--N	NH_4^+-N	NO_2^--N	Total N loss in drainage water
		kg N ha^{-1}	kg N ha^{-1}	kg N ha^{-1}	kg N ha^{-1}
1	S4	5.4 ± 2.5	4.0 ± 2.0	1.0 ± 0.7	10.4 ± 2.9
	D4	8.5 ± 4.5	3.4 ± 1.5	0.3 ± 0.2	12.2 ± 5.3
	D2	3.7 ± 1.3	3.0 ± 1.4	1.0 ± 1.2	7.7 ± 2.9
2	S4	10.9 ± 3.7	1.3 ± 0.2	0.7 ± 0.7	12.9 ± 3.9
	D4	12.0 ± 4.0	2.2 ± 1.5	0.4 ± 0.5	14.6 ± 5.3
	D2	5.7 ± 1.7	1.8 ± 0.7	0.3 ± 0.3	7.8 ± 2.2
3	S4	5.2 ± 2.9	5.0 ± 3.1	1.6 ± 2.5	11.8 ± 6.2
	D4	7.5 ± 3.7	8.0 ± 2.5	0.8 ± 0.5	16.3 ± 2.2
	D2	6.2 ± 4.0	4.0 ± 2.1	1.3 ± 2.3	11.6 ± 2.7
		p-value			
1		0.14	0.68	0.41	0.42
2		0.05	0.47	0.70	0.09
3		0.68	0.14	0.87	0.24

4.2.2 Nitrogen balance (Paper I)

Soil mineral nitrogen stock ranged between 134.3 and 154.3 kg ha^{-1} in season 1 and between 82.4 and 96.0 kg ha^{-1} in season 2, while the mineral nitrogen fertiliser input was 80 kg ha^{-1}. In season 3, however, mineral nitrogen fertiliser (80 kg ha^{-1}) was the largest nitrogen input, with the soil mineral nitrogen contribution ranging between 41.7 and 45.8 kg ha^{-1}. Throughout the three seasons, nitrogen losses in drainage water (range 7.7-16.3 kg N ha^{-1}) represented a relatively small contribution to nitrogen outputs compared with crop uptake (range 92.5-167.5 kg N ha^{-1}) which was the largest single nitrogen output in seasons 1-3 (Table 5). A positive nitrogen balance was observed for all treatments in season 1, whereas in season 2 only treatment S4 had a positive nitrogen balance and in season 3 all treatments had a negative balance.

Table 5. *Nitrogen (N) balance: N inputs (N from mineral fertiliser, initial soil mineral N (N_{min}) before sowing), N outputs (crop N uptake, N in drainage water) and N balance during seasons 1, 2 and 3 in the different drainage treatments: shallow drainage to 0.6 m depth, weir opened four times per week (S4), deep drainage to 1.2 m depth, weir opened four times per week (D4) and deep drainage to 1.2 m depth, weir opened two times per week (D2)*

Season	Nitrogen balance component	S4	Treatment D4	D2
			kg N ha^{-1}	
Season 1	i. N fertiliser	80.0	80.0	80.0
	ii. N_{min} before sowing	143.9	154.3	134.3
	iii. Total crop uptake (grain + straw)	92.5	114.9	140.4
	Grain N uptake	19.6	43.0	49.3
	Straw N uptake	72.9	71.9	91.1
	iv. N in drainage water	10.4	12.2	7.7
	N balance = (i + ii) - (iii + iv)	121.0	107.2	66.2
Season 2	i. N fertiliser	80.0	80.0	80.0
	ii. N_{min} before sowing	96.0	82.4	89.7
	iii. Total crop uptake (grain + straw)	88.1	166.8	167.4
	Grain N uptake	43.3	79.4	83.0
	Straw N uptake	44.8	87.4	84.3
	iv. N in drainage water	12.9	14.6	7.8
	N balance = (i + ii) - (iii + iv)	75.0	-19.0	-5.5
Season 3	i. N fertiliser	80.0	80.0	80.0
	ii. N_{min} before sowing	45.8	44.3	41.7
	iii. Total crop uptake (grain+ straw)	114.1	156.0	157.9
	Grain N uptake	43.5	74.1	80.5
	Straw N uptake	70.6	81.9	77.4
	vi. N in drainage water	11.8	16.3	11.6
	N balance = (i + ii) - (iii + iv)	-0.1	-48	-47.8

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

Throughout seasons 1-3, soil organic carbon (SOC) and soil total nitrogen (TN) content and C/N ratio generally declined (Paper I and Table 6). Relatively higher SOC and TN concentrations were observed in the topsoil (0-20 cm) and there was no treatment effect on SOC, TN or C/N ratio in any season (p>0.05). At the end of each season (1-3), however, treatment D2 showed a smaller decrease in SOC compared with D4. The SOC concentration range was 0.8-1.9% and that of TN was 0.05-0.1% at the end of season 3, compared with 3.7-5.7% and 0.2-0.3%, respectively, before season 1 (Paper I and Table 6). Over the three seasons, the C/N ratio ranged between 7.8 and 28.3. High C/N ratio was observed at the end of season 1 due to a decrease in TN with only a slight change in SOC.

Table 6. Soil organic carbon (SOC), soil total nitrogen (TN) and C/N ratio, based on soil samples collected at 0-20, 20-40, 40-60, and 60-80 cm depth before season 1 and at the end of seasons 1, 2 and 3. Mean ± standard deviation (n=4)

Season	Treatment	Soil layer (cm)	SOC (%)	TN (%)	C/N ratio
Before season 1	S4	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
	D4	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
	D2	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	S4	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
	D4	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
	D2	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	S4	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
	D4	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
	D2	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	S4	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
	D4	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
	D2	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

4.4 Water and soil salinity

4.4.1 Drainage water salinity (Paper II)

Overall, there was no clear effect of drainage treatment on electrical conductivity in drainage water (EC_{wd}) (p>0.05). However, the results in Paper II revealed a significant decrease in EC_{wd} from season to season. EC_{wd} was high in season 1 (10.4-15.5 dS m^{-1}) compared with season 2 (6.0-7.0 dS m^{-1}) and season 3 (3.8-4.2 dS m^{-1}) (Table 7). As observed for calculated drainage outflow (Dr_{calc}, Table 3), total salt loads in drainage water were within the same range in all treatments in season 1 (Table 8). However, there were variations in the loads between the treatments in seasons 2 and 3 (Paper II). Corresponding variations in drainage outflow between treatments were observed in season 2 and season 3 (see Table 3). In all three seasons, the vegetative growth stage of the rice crop was generally characterised by higher salt load than the reproductive and ripening growth stages.

Table 7. *Electrical conductivity in drainage water (EC_{wd}, $dS\ m^{-1}$) in the different drainage treatments: shallow drainage to 0.6 m depth, weir opened four times per week (S4), deep drainage to 1.2 m depth, weir opened four times per week (D4) and deep drainage to 1.2 m depth, weir opened two times per week (D2) during three growth stages of the rice crop (vegetative, reproductive, ripening) in seasons 1-3 (mean ± standard deviation, n= 4), data from Paper II*

	Season 1			Season 2			Season 3		
	Growth								
	Vegetative[†]	Reproductive[†]	Ripening	Vegetative[†]	Reproductive[†]	Ripening	Vegetative	Reproductive	Ripening
Treatment									
S4	12.5 ± 2.2^{a}	15.5 ± 2.7^{a}	13.6 ± 3.2	6.9 ± 1.0	6.4 ± 1.1	7.0 ± 1.1	4.4 ± 0.4^{a}	5.1 ± 1.2^{a}	4.5 ± 1.1
D4	10.7 ± 0.6^{b}	12.4 ± 0.6^{b}	12.1 ± 0.9	7.0 ± 0.4	7.0 ± 0.5	6.6 ± 2.4	4.2 ± 0.4^{ab}	4.8 ± 0.3^{ab}	4.7 ± 0.8
D2	10.4 ± 1.8^{b}	11.9 ± 2.7^{b}	11.3 ± 2.4	6.5 ± 0.8	6.1 ± 0.6	6.0 ± 2.3	3.8 ± 0.4^{b}	4.2 ± 1.0^{b}	3.8 ± 1.4
p-value	***	**	0.17	0.51	0.36	0.07	**	*	0.30

[†] Significant differences between treatments are indicated by different letters (a,b): ***$p<0.001$; **$p<0.01$; *$p<0.05$.

Table 8. *Salt load (ton ha^{-1}) in drainage water from the different drainage treatments: drainage to 0.6 m depth, weir opened four times per week (S4), drainage to 1.2 m depth, weir opened four times per week (D4) and drainage to 1.2 m depth, weir open twice per week (D2) at three rice growth stages (vegetative, reproductive, ripening) in seasons 1-3 (mean ± standard deviation, n=4)*

Season	Treatment	Salt load in drainage water			
		Growth stage			
		Vegetative†	Reproductive†	Ripening†	Total
1	S4	8.6 ± 1.9	1.1 ± 0.7	0.6 ± 0.5	10.3 ± 2.8
	D4	7.6 ± 1.7	0.8 ± 0.6	2.3 ± 0.6	10.7 ± 1.9
	D2	9.0 ± 3.3	1.0 ± 0.4	1.2 ± 0.1	11.3 ± 3.6
2	S4	3.5 ± 0.7	2.7 ± 0.6	0.5 ± 0.6	6.7 ± 4.2^{b}
	D4	4.1 ± 1.7	3.1 ± 1.3	1.6 ± 0.8	8.8 ± 1.8^{ab}
	D2	7.7 ± 3.4	3.5 ± 1.7	1.7 ± 1.7	12.9 ± 1.5^{a}
3	S4	5.5 ± 1.1^{ab}	1.5 ± 0.6	0.6 ± 0.7	7.6 ± 0.9^{b}
	D4	6.8 ± 3.0^{a}	2.4 ± 1.0	1.7 ± 1.3	10.9 ± 1.8^{a}
	D2	2.8 ± 0.7^{b}	1.2 ± 0.7	2.3 ± 1.5	6.3 ± 1.9^{b}
		p-value			
1		0.70	0.83	*	0.92
2		0.05	0.67	0.30	*
3		*	0.56	0.27	*

†Significant differences between treatments are indicated by different letters: *$p<0.05$.

4.4.2 Soil salinity (Paper II)

Soil salinity was monitored in three consecutive seasons (1-3). Throughout the three seasons, soil water electrical conductivity (EC_{ws}) ranged between 2.1 and 4.7 dS m^{-1} in treatment S4, 1.9 and 4.5 dS m^{-1} in D4, and 2.0 and 4.9 dS m^{-1} in D2 (Table 9). No clear drainage treatment effect on soil salinity was observed within the growing seasons. However, a highly significant effect of season ($p<0.001$) on soil salinity was observed for all drainage treatments, with soil salinity gradually decreasing by 1 dS m^{-1} from season 1 to season 2, and from season 2 to season 3, in all treatments (Paper II). These findings show that the experimental soil was subjected to leaching in the period between seasons, which was attributable to a combination of amount of water applied before the season and free drainage, *i.e.* weirs open in all plots before the season.

Table 9. *Soil water electrical conductivity (EC$_{ws,}$ dS m^{-1}) at three depths (10, 30, 50 cm) and at three rice growth stages (vegetative, reproductive, ripening) in the different drainage treatments: drainage to 0.6 m depth, weir opened four times per week (S4), drainage to 1.2 m depth, weir opened four times per week (D4) and drainage to 1.2 m depth, weir opened twice per week (D2) in seasons 1-3 (mean ± standard deviation, n= 4).* p-*values from one-way analysis of variance are shown in the last three rows of the table*

Measure-ment depth [cm]		Season 1			Season 2			Season 3		
		Growth stage			Growth stage			Growth stage		
	Treatment	Vegetative	Reproductive†	Ripening†	Vegetative†	Reproductive†	Ripening	Vegetative†	Reproductive†	Ripening†
10	S4	4.4 ± 1.2	4.5 ± 1.4	4.7 ± 1.5a	3.4 ± 0.7a	3.5 ± 1.0	3.7 ± 1.1	2.5 ± 0.4a	2.7 ± 0.6a	2.7 ± 0.6a
	D4	4.2 ± 0.5	4.1 ± 0.6	4.2 ± 0.6b	3.0 ± 0.5b	3.2 ± 0.5	3.3 ± 0.5	1.9 ± 0.1b	1.9 ± 0.3b	2.1 ± 0.5b
	D2	4.6 ± 0.9	4.5 ± 1.0	4.7 ± 1.0a	3.1 ± 0.4b	3.4 ± 0.5	3.5 ± 0.8	2.0 ± 0.3b	2.0 ± 0.3b	2.3 ± 0.4b
30	S4	4.2 ± 0.9	4.1 ± 0.9b	4.5 ± 1.1a	3.0 ± 0.4b	3.2 ± 0.6	3.5 ± 0.7	2.1 ± 0.2	2.3 ± 0.3a	2.4 ± 0.3a
	D4	4.0 ± 0.4	4.2 ± 0.6ab	4.1 ± 0.6b	3.0 ± 0.4b	3.3 ± 0.5	3.3 ± 0.5	2.1 ± 0.1	2.3 ± 0.2a	2.2 ± 0.3b
	D2	4.2 ± 0.6	4.4 ± 0.7a	4.6 ± 0.7a	3.2 ± 0.4a	3.4 ± 0.5	3.5 ± 0.6	2.1 ± 0.2	2.1 ± 0.2b	2.3 ± 0.2ab
50	S4	4.5 ± 0.5a	4.5 ± 0.4	4.7 ± 0.6ab	3.3 ± 0.2	3.5 ± 0.5b	3.7 ± 0.6	2.5 ± 0.1b	2.7 ± 0.2b	2.8 ± 0.2
	D4	4.3 ± 0.1b	4.5 ± 0.3	4.5 ± 0.3b	3.4 ± 0.1	3.6 ± 0.3ab	3.6 ± 0.3	2.6 ± 0.1a	2.8 ± 0.1a	2.9 ± 0.2
	D2	4.5 ± 0.4a	4.7 ± 0.5	4.9 ± 0.5a	3.4 ± 0.2	3.7 ± 0.4a	3.7 ± 0.4	2.6 ± 0.0a	2.7 ± 0.1b	2.9 ± 0.2
p-value										
10	Treatment	0.06	0.07	*	***	0.18	0.21	***	***	***
30	Treatment	0.16	*	***	*	0.19	0.54	0.44	***	***
50	Treatment	*	0.11	**	0.53	**	0.63	**	***	0.39

†Significant differences between treatments are indicated by different letters: ***$p<0.001$; **$p<0.01$; *$p<0.05$.

4.5 Grain yield, water productivity and harvest index (Papers I and II)

Rice grain yield was significantly affected by drainage treatment (Table 10). Both deep drainage systems (D4, D2) had higher grain yield, higher water productivity and higher harvest index (HI) than the shallow drainage treatment (S4). However, no differences in grain yield were observed between the D2 and D4 treatments.

Table 10. *Grain and straw yields, total water input, water productivity and harvest index (HI) in the different drainage treatments: drainage to 0.6 m depth, weir opened four times per week (S4), drainage to 1.2 m depth, weir opened four times per week (D4) and drainage to 1.2 m depth, weir opened twice per week (D2) in seasons 1-3. Mean ± standard deviation (n=4). The last three rows in the table show the results of pairwise comparison (data source: Papers I & II)*

Season	Treatment	Grain yield[†]	Straw yield[†]	Total water input	Water productivity	HI
		kg ha^{-1}	kg ha^{-1}	m^3	kg m^{-3}	
1	S4	$1.61.10^3 \pm 0.28.10^{3b}$	$8.02.10^3 \pm 1.67.10^{3a}$	7.25 ± 0.04	0.22 ± 0.08^b	0.17 ± 0.0^b
	D4	$3.32.10^3 \pm 0.64.10^{3a}$	$8.81.10^3 \pm 1.94.10^{3a}$	7.54 ± 0.19	0.44 ± 0.02^a	0.28 ± 0.03^a
	D2	$3.67.10^3 \pm 0.76.10^{3a}$	$10.20.10^3 \pm 1.44.10^{3a}$	7.49 ± 0.21	0.49 ± 0.06^a	0.26 ± 0.02^a
2	S4	$3.82.10^3 \pm 1.07.10^{3b}$	$9.20.10^3 \pm 2.23.10^{3a}$	8.73 ± 0.68	0.43 ± 0.06^b	0.29 ± 0.03^a
	D4	$6.16.10^3 \pm 0.57.10^{3a}$	$11.48.10^3 \pm 1.38.10^{3a}$	9.82 ± 1.12	0.63 ± 0.04^a	0.36 ± 0.03^a
	D2	$6.07.10^3 \pm 0.60.10^{3a}$	$10.86.10^3 \pm 2.41.10^{3a}$	10.08± 0.54	0.60 ± 0.04^a	0.36 ± 0.04^a
3	S4	$3.18.10^3 \pm 0.58.10^{3b}$	$11.73.10^3 \pm 4.52.10^{3a}$	8.32 ± 0.16^b	0.38 ± 0.02^c	0.22 ± 0.02^b
	D4	$6.42.10^3 \pm 0.32.10^{3a}$	$14.74.10^3 \pm 1.74.10^{3a}$	9.44 ± 0.22^a	0.68 ± 0.05^b	0.30 ± 0.01^a
	D2	$6.56.10^3 \pm 0.52.10^{3a}$	$14.44.10^3 \pm 2.01.10^{3a}$	8.41 ± 0.10^b	0.77 ± 0.03^a	0.31 ± 0.02^a
1	Treatment	**	0.07	0.16	**	*
2	Treatment	**	0.14	0.21	*	0.09
3	Treatment	***	0.11	***	***	**

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

4.6 Methane and nitrous oxide fluxes (Paper III)

4.6.1 Groundwater level and soil temperature

Depth to groundwater was monitored on all GHG measurement occasions and ranged between 0 and 35 cm throughout the study period in season 4 (Paper III). A significant difference (p=0.03) was observed between the shallow (S4) and deep drainage treatments (D4 and D2), with S4 displaying shallower groundwater levels compared with D4 and D2 (Figure 6). The two deep drainage treatments (D4 and D2) did not differ in terms of groundwater level.

There were no major variations in mean soil temperature between the drainage treatments, or between GHG measurement events. During the study period, mean soil temperature (at 10 cm soil depth) varied between 20.9 °C and 25.8 °C (Figure 6). Soil temperatures were somewhat higher during the first part of season 4 (May to mid-June) than during the latter part (mid-June to mid-July) (Paper III).

4.6.2 Methane and nitrous oxide fluxes

Methane and N_2O fluxes were monitored on nine occasions during the rice flowering and ripening growth stages in season 4. Differences in CH_4 fluxes were observed between the three drainage treatments (Figure 6). The two deep drainage treatments (D4 and D2) gave lower CH_4 emissions than shallow drainage (S4). The N_2O fluxes were generally low and there were no differences in N_2O emissions between the drainage treatments (Paper III).

4.6.3 Diurnal pattern in methane and nitrous oxide emissions

Diurnal patterns in CH_4 and N_2O fluxes were assessed on one occasion (30 June 2018) in season 4 (Paper III). The results revealed no effect of time of day on either CH_4 or N_2O flux (Figure 7). However, CH_4 flux tended to be higher in the afternoon than at other times of day.

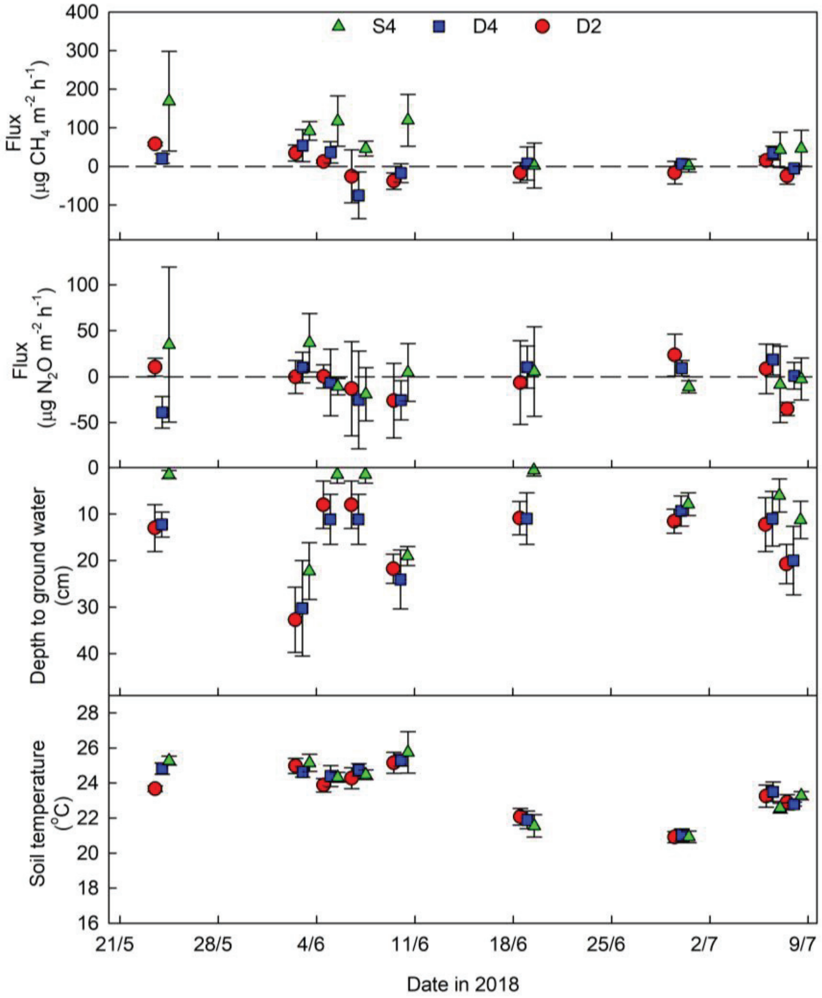


Figure 6. Fluxes of methane (CH_4) and nitrous oxide (N_2O), depth to groundwater and soil temperature during season 4 (2018) in the different drainage treatments: drainage to 0.6 m depth, weir opened four times per week (S4, green triangles), drainage to 1.2 m depth, weir opened four times per week (D4, blue squares) and drainage to 1.2 m depth, weir opened twice per week (D2, red circles). Error bars indicate one standard error (n≤4) (source: Figure 1 in Paper III).

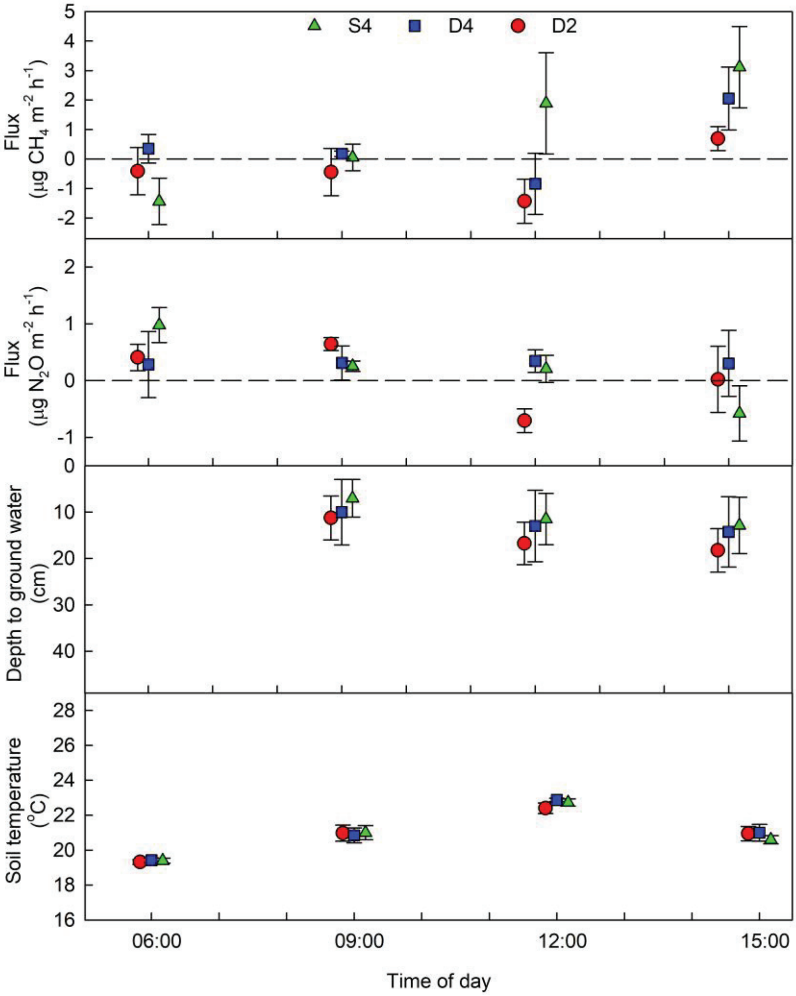


Figure 7. Diurnal pattern (30 June 2018) in methane (CH_4) and nitrous oxide (N_2O) fluxes, groundwater level and soil temperature at different times of day in the different drainage treatments: drainage to 0.6 m depth, weir opened four times per week (S4, green triangles), drainage to 1.2 m depth, weir opened four times per week (D4, blue squares) and drainage to 1.2 m depth, weir opened twice per week (D2, red circles). Error bars indicate one standard error (n≤4). Flux values represent flux from the soil surface including vegetation, with negative values indicating uptake of CH_4 or N_2O (source: Figure 2 in Paper III).

4.7 Summary of results

The research aims and the main findings obtained in Papers I-III are summarised in Table 11.

Table 11. *Main aim and summary of results in Papers I-III*

Aim	Summary of results	Paper
To assess the effect of drainage intensity on drainage outflow, nitrogen (N) dynamics and rice grain yield	Installation of deep drainage systems in poorly drained paddy fields enhanced: • water productivity • N crop uptake • rice grain yield	I
To determine the effect of drainage intensity on soil salinity and rice grain yield	• The different drainage treatments had a minor effect on soil salinity during the cropping seasons • For all drainage systems, soil salinity decreased from season to season • Both deep drainage treatments enhanced rice grain yield compared with shallow drainage.	II
To assess the effect of varying drainage depth and frequency on soil surface fluxes of methane (CH_4) and nitrous oxide (N_2O) in paddy rice cultivation in a marshland area in Rwanda.	• Shallow drainage gave greater CH_4 emissions than the two deep drainage systems, but no differences in N_2O emissions were observed between the three treatments.	III

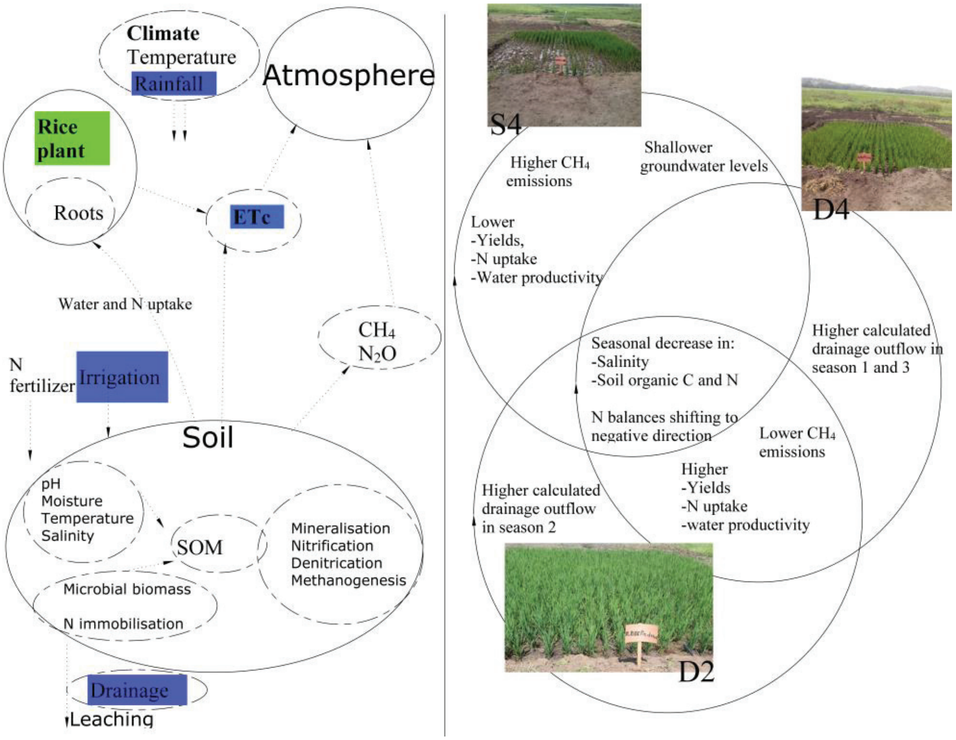


Figure 8. Schematic depiction of processes, driving factors (left) and major findings (right) for the different drainage treatments: drainage to 0.6 m depth, weir opened four times per week (S4), drainage to 1.2 m depth, weir opened four times per week (D4) and drainage to 1.2 m depth, weir opened twice per week (D2).

5. Discussion

5.1 Water balance and groundwater levels (Papers I and II)

Different soil water balance components, *i.e.* water inputs (irrigation and rainfall) and water outputs (drainage outflow and crop evapotranspiration (ET_c)) were assessed in this thesis. Seasons 1 and 3 were generally characterised by lower rainfall amount than season 2. A monthly rainfall deficit was observed in all months except November 2016 (season 1), which had a rainfall surplus (Paper I). Because of limited precipitation in the study region, irrigation was the main water input, while ET_c was the main water output (Papers I and II).

The first main hypothesis tested in this thesis was that a drainage system with deep and less frequently opened drains (D2) reduces drainage outflow compared with systems with more frequently opened deep drains (D4) or shallow drains (S4). The findings in Papers I and III did not fully support this hypothesis. In seasons 1 and 3, treatment D4 had higher values of calculated drainage outflow than D2, while S4 and D2 differed only marginally in terms of calculated drainage outflow (see Table 3) (Papers I & II). This trend was not observed in season 2, where treatment D2 had higher calculated drainage outflow than D4 and S4. However, the results regarding the effect of drainage treatment on drainage outflow could have been affected by variations in irrigation amount between treatments (Table 3). Moreover, during the drainage outflow measurement, the weirs were opened for a short period (one hour) and then remained closed until the next scheduled opening time. Through this, drainage outflow was regulated to some extent in all experimental treatments. This was also evident in the observed groundwater levels, which were generally high (above 12 cm in seasons 2 and 3 and above 35 cm depth in season 4) in all experimental plots during the study period (see Figure 5). Following a review of studies on controlled drainage in different countries, Salo *et al*. (2021) concluded that the results can be ambiguous and that challenges may arise in isolating the effects of controlled drainage from other effects. Therefore other contributing factors such as hydrological factors should be considered during interpretation of observed effects (Salo *et al*., 2021).

5.2 Nitrogen dynamics and soil fertility depletion (Papers I and II)

5.2.1 Nitrogen flows and nitrogen balance (Papers I and II)

Nitrogen flows in paddy fields are governed by different processes, such as nitrification, denitrification, mineralisation and immobilisation (see summary in Figure 8). Effects of drainage intensity management on the nitrogen flows in paddy fields were evaluated in Paper I and a nitrogen balance for the system was established. Crop nitrogen uptake was found to be higher in the deep drainage systems (D4, D2) compared with the traditional shallow drainage system (S4), resulting in low total nitrogen loads in drainage water from the deep drainage treatments (Table 5) (Paper I). This was presumably because the high crop uptake in those systems left less nitrogen available for leaching from the soil. This was not the case for shallow drainage (treatment S4), indicating a beneficial effect of deep drainage in creating a suitable environment for nutrient uptake by rice plants. Higher crop nitrogen uptake is also suggested to have positively influenced rice grain yield with deep drainage, with treatments D4 and D2 displaying higher grain yields, higher water productivity and higher harvest index than treatment S4 (shallow drainage) (Paper I and Paper II). Paddy rice generally prefers flooded conditions, but it should be noted that the research in Papers I and II was conducted under saline conditions, which could interfere with nutrient and water uptake by the root. Deep drainage provides a larger volume of soil for water and nutrient uptake by plant roots, hypothetically reducing the amount of nitrogen available for leaching (Darzi-Naftchally *et al*., 2014).

Overall, mineral nitrogen fertiliser was the main nitrogen input to the cropping system. However, in season 1 soil mineral nitrogen also represented a considerable pool for crop uptake (Table 5). An observed progressive depletion in soil total nitrogen content between seasons (Paper I) reduced the availability of substrate for mineralisation and led to depletion of the soil mineral nitrogen pool. All drainage treatments had a positive nitrogen balance in season 1, indicating the presence of surplus nitrogen available for leaching from the system. However, in season 2 only the shallow drainage treatment (S4) had a positive nitrogen balance.

In season 3, all drainage treatments had a negative nitrogen balance, indicating deficiency (Table 5), *i.e.* more nitrogen was removed than was added to the system. These findings indicate a need for continuous replenishment of soil nitrogen in the study area. Since rice straw is not returned to the field in the study area, the total nitrogen pool in soil can be expected to continue to decrease if mineral fertiliser remains the major source of nitrogen for crop uptake. It should be noted that no difference was observed between the three drainage treatments in terms of soil total nitrogen content.

Although not assessed in this thesis, ammonia (NH_3) volatilisation is another potential route of gaseous nitrogen loss considering prevailing conditions in the study region, *i.e.* high soil pH, moist conditions and high temperature (Papers I-III), which are generally favourable for NH_3 volatilisation. Therefore, NH_3 is probably a major form of nitrogen loss from urea fertiliser applied in the study area, potentially shifting the N balance in the negative direction. Overall, in this thesis there was continuous depletion of soil mineral nitrogen from season to season, mainly associated with different observed nitrogen outputs (crop N uptake, N losses in drainage water) without ample nitrogen inputs (Paper I). Moreover, unobserved processes such ammonia volatilisation, denitrification, assimilation by microorganisms and roots could be potential nitrogen output pathways in such a system (Figure 8).

5.2.2 Soil organic carbon (SOC) and soil total nitrogen depletion (Paper I)

At the start of the work in this thesis, SOC content was relatively high and this was linked with soil organic matter build-up during the fallow period prior to setting up the field experiments (Paper I and Table 6). The C/N ratio was high at the end of season 1, indicating low SOC mineralisation during that rice-growing season. By the end of seasons 2 and 3 the C/N ratio had decreased, which could be explained by SOC mineralisation taking place in aerobic conditions during the transition period between season 1 and season 2, and between season 2 and season 3, combined with the fact that the organic matter stock was not replenished between seasons (Paper I). In the study region (Muvumba marshland), rice is grown in a monoculture system and the residues are removed after each harvest. Therefore there is little input of organic matter to soil, which is suggested to lead to SOC depletion in paddy fields (Wang *et al*., 2014). During the work in this thesis, gradual depletion in SOC from season to season was observed for all three drainage systems (Table 6). Proper management of rice straw on-farm after harvesting, such as returning it to the fields, should be adopted to replenish SOC and enhance nutrient inputs, for long-term soil fertility in the marshland study area (Paper I).

5.3 Salinity and rice yields (Paper II)

The second main hypothesis tested in this thesis was that deep drainage with less frequently opened weirs (D2) extends water residence time in soil while still achieving sufficient outflow to leach salts, and increases rice yield compared with traditional shallow drainage (S4) or deep drainage with more frequently opened weirs (D4). Rice yields were lower in the traditional shallow drainage treatment (S4) than in the two deep drainage treatments (D4 and D2) in seasons 1-3 (Papers I & II, Table 10). The soil salinity data obtained in Paper II did not fully confirm that there were differences in soil salinity between the three drainage systems. There were variations in soil salinity at the level of individual experimental units (*i.e.* plots), which was in line with an observed effect of experimental block on soil salinity (Paper II). This indicates that there were variations in treatment effect between the experimental blocks and possibly significant differences between means for the sets of soil water electrical conductivity (EC_{ws}) measurements. Considerable salt loads (Table 8) were detected in drainage water (Paper II), as a result of irrigation and rainfall events leading to salt leaching. Salt loads in drainage water were to some extent linked with drainage outflow, with high salt loads in drainage water potentially related to high drainage outflow (Paper II).

A positive response of rice yield to salinity decrease was observed from season 1 to season 2. A two-fold increase in yield was achieved in season 2 (Table 10), which was mainly linked with a concomitant decrease in soil salinity (EC_{ws}) of 1.0 dS m^{-1} (Table 9). However, a similar trend did not occur from season 2 to season 3, where no marked increase in rice yield was recorded despite a similar significant decrease in soil salinity as observed between seasons 1 and 2. One reason could be continuous depletion over time of the soil nitrogen pool at the study site (Paper I) preventing further increases in rice yield despite improvement in soil salinity conditions (further decrease of around 1.0 dS m^{-1} between seasons 2 and 3) (Paper II). Another reason could be that salinity levels were no longer a limiting factor in season 3, *i.e.* EC_{ws} was lower (Table 9) than the EC_e threshold for rice (3 dS m^{-1}) (Abrol *et al.*, 1988).

In the periods between seasons, there was generally a combination of water inputs (irrigation water applied during land preparation plus rainfall) and free drainage (all control structures open). This enabled more salts to leach out from the soil profile, resulting in a soil salinity decrease of one EC_{ws} unit from season to season (Paper II). During the experiments, however, the weirs were opened for only a short period (one hour) in all experimental plots and remained closed until the next opening time, meaning that there was insufficient time for salts to leach out from the soil profile during the cropping season.

5.4 Greenhouse gas emissions

The third main hypothesis tested in this thesis was that deep drains with more frequently opened weirs (D4) lower the groundwater level, and therefore reduce CH_4 and N_2O emissions, compared with deep drains with less frequently opened weirs (D2) and shallow drains (S4) with more frequently opened weirs. This hypothesis was partly confirmed by the data obtained, as deep drainage lowered the groundwater level more and therefore reduced CH_4 emissions compared with shallow drainage. However, no differences in N_2O emissions were observed between the deep and shallow drainage systems, contradicting that part of the hypothesis (Paper III). On the other hand, no differences in CH_4 emissions was observed between the two deep drainage treatments. This was probably linked to the fact that the weirs were open for a short period (one hour) for all plots and therefore weir opening might not have had time to result in considerable differences in groundwater levels between the two deep drainage treatments.

Differences in CH_4 emissions between the deep and shallow drainage treatments were mainly associated with differences in groundwater levels, which were nearer the soil surface in the shallow drainage treatment than in the two deep drainage treatments (Paper III). Regulation of groundwater levels by controlling drainage intensity is one of the approaches suggested to mitigate CH_4 emissions from paddy fields (Yang *et al*., 2014). Soil oxygen levels, vertical movement of nutrients and the activity of soil microorganisms are influenced by variations in groundwater levels in paddy fields (Xiao *et al*., 2011).

Nitrous oxide emissions were low in all drainage treatments and their contribution to overall nitrogen losses was minor (Paper III) compared with that reported in other studies (Wang *et al*., 2021). Nevertheless, the N_2O emissions recorded in Paper III were within the range reported in previous research on

African paddy fields (Kim *et al*., 2016; Nyamadzawo *et al*., 2013). In paddy rice, N_2O emissions occur periodically in connection with different growth stages and with fertilisation events (Towprayoon *et al*., 2005), with peak N_2O emissions taking place after fertiliser application (IPCC, 2006). Given that the flux measurements started in the mid-growth stage, the peak N_2O emissions associated with nitrogen fertilisation may have been underestimated in this thesis due to the fact that GHG measurements did not cover the occasion of fertilisation and the period adjacent to fertilisation (Paper III). The observed progressive depletion of soil nitrogen (Paper I) could also have led to low amounts of soil nitrogen being available in season 4, presumably not providing enough substrate (ammonium and nitrate) for denitrification and nitrification, making the soil a weak source of N_2O emissions.

In the study area, rice straw is generally not returned to the fields after harvesting. In terms of GHG mitigation, not returning the rice straw to the field would reduce potential CH_4 emissions by decreasing the carbon supply for methanogenic bacteria (Wang *et al*., 2017) (see Figure 8), which could be considered a positive outcome in terms of GHG emissions. However, this practice was found to lead to depletion of SOC in this thesis (Paper I). Another factor governing GHG emissions in the study area could be the rate of nitrogen fertiliser application. The current rate for paddy fields in the study region is relatively low (80 kg N ha^{-1}) compared with the rates applied in other parts of the world, *e.g*. in China up to 300 kg N ha^{-1} are applied in paddy rice (Jiao *et al*., 2018). With ongoing rice intensification in Rwanda, increases in inorganic nitrogen fertiliser rates will be needed to boost rice yields, but this could lead to increases in N_2O emissions from paddy fields. For sustainable rice intensification in Rwanda, there is thus a need for a compromise between different management practices, in order to find a balance between achieving high rice yields while reducing GHG emissions and conserving soil fertility.

5.5 Implications of the results for saline irrigated paddy fields

The findings in this thesis suggest a need for potential implementation of regulated deep drainage, as a strategy which can play a vital role in enhancing rice yields and reducing CH_4 emissions, without compromising N_2O emissions, in paddy rice production systems with similar properties to those studied in Papers I-III. The two deep drainage systems studied (D4 and D2), regardless of weir opening frequency, performed better in terms of crop nitrogen uptake and gave higher yields and higher water productivity (Papers I - II and Figure 8) compared with shallow drainage systems (generally used in paddy rice systems in Rwanda). Both deep drainage systems produced lower CH_4 emissions than shallow drainage, with no differences in N_2O emissions between the deep and shallow drainage systems (Paper III). However, the two deep drainage systems did not differ in some of the parameters studied, such as CH_4 emissions and rice yields. Overall, there were no obvious effects of the different drainage systems on soil salinity during the cropping seasons in the study period. However, soil salinity gradually decreased from season to season, potentially mainly due to full drainage during the periods between seasons.

It should be highlighted that controlled drainage solutions are very location-specific, and that customised solutions are essential for success (Ritzema & Stuyt, 2015). In arid and semi-arid regions, the priorities are different to those in humid areas, due to insufficient rainfall and the need for irrigation. There are on-site impacts from using controlled drainage practices, as they may directly affect the soil and the plant itself. When implementing controlled drainage in arid and semi-arid regions, it is important to take account of soil salinity issues, to avoid salt accumulation in the crop rootzone (Ayars *et al*., 2006). The research presented in this thesis was conducted in a semi-arid environment under saline conditions, so the drainage intensity treatments had to consider salt balance. It was necessary to leach the salts from the soil profile to provide a better environment for the roots and ensure ample water and nutrient uptake, while at the same time balancing this against lowering nitrate losses in drainage water and reducing gaseous CH_4 and N_2O emissions. Achieving the optimal combination of these outcomes could be challenging, but is critical for the success of such drainage systems in similar environments.

Given the improvements in nitrogen uptake, water productivity and rice yields achieved in this thesis, regulated deep drainage systems could be a good long-term investment for irrigated saline soils in Rwanda and in other similar environments. As the area under irrigation in Rwanda continues to increase (MINAGRI, 2022), investment in drainage is urgently needed to sustain irrigated agriculture.

6. Conclusions

This thesis examined the effects of drainage intensity management (deep/shallow drainage, less/more frequently opened drain weirs) on nitrogen losses, rice grain yield, soil and drainage water salinity, and on N_2O and CH_4 emissions from paddy fields in a marshland in a semi-arid region of Rwanda.
The main conclusions were that:

- Overall, deep drains with more frequently open weirs (D4) had higher calculated drainage outflow values (except in season 2) than deep drains with less frequently open weirs (D2) or shallow drains with more frequently open weirs (S4).

- Nitrogen balance shifted in a negative direction from season to season, regardless of drainage treatment, suggesting that nitrogen outputs from the system exceeded nitrogen inputs to the system.

- Deep drainage systems enhanced rice grain yield, crop nitrogen uptake, harvest index and water productivity compared with the traditional shallow drainage system.

- Considerable salt leaching took place in the periods between rice growing seasons, due to a combination of water inputs (rainfall and irrigation water during land preparation) and free drainage when all weirs were open.

- Deep drainage was preferable to shallow drainage in terms of CH_4 emissions mitigation, with no marked effects on N_2O emissions.

7. Recommendations and future perspectives

This thesis demonstrated that deep drainage systems can be of great importance for poorly drained saline soils to enhance rice grain yield, crop nitrogen uptake, harvest index and water productivity. A question not studied in this thesis, but also of great importance, is whether on-farm changes in post-harvest straw management in paddy rice systems, such as returning straw to the field, could help to replenish soil carbon stocks and provide nutrient inputs to sustain long-term soil fertility in the marshland study area. Other issues to be addressed in future research include:

- Salt dynamics under surface drainage systems over a long period.
- Effects of management practices such as removal of crop residues and organic or inorganic nitrogen inputs on GHG fluxes.
- Greenhouse gas measurements that fully capture seasonal variations over the rice growing period and integrate some off-season measurements, to acquire a full picture of GHG emissions from paddy fields over the year.

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Popular science summary

Rice is consumed by billions of people worldwide and continuous flooding water management methods are commonly used to produce rice. Continuous flooding has several drawbacks, including low water use efficiency and high emissions of methane. Soil salinisation is another challenge associated with the introduction of irrigation in arid and semi-arid regions, which are characterised by low and unpredictable rainfall. In such circumstances, drainage can be used as a strategy to mitigate soil salinisation and improve crop yields. However, drainage water raises environmental concerns because it carries nutrients to receiving waters, which could lead to water pollution. Therefore, sound water management techniques are needed to ensure food security in the face of growing water competition and to mitigate climate change.

This thesis assessed the impacts of drainage intensity management on nitrogen flows, soil salinisation, rice yields and greenhouse gas emissions in paddy rice fields in a marshland in semi-arid region in Rwanda during four cropping seasons (in 2016-2018). In field experiments, traditional shallow drainage (S4, 0.6 m deep with a weir opened four times per week) was compared with two deep drainage systems (1.2 m deep), one with the weir open four times per week (D4) and one with the weir opened two times per week (D2).

In general, both deep drainage systems gave higher nitrogen uptake, higher water productivity and higher rice grain yield and also released less methane to the atmosphere than the traditional drainage system. The different drainage systems had no clear effect on soil salinity, but soil salinity decreased from season to season in the field experiments. With increasing demand for food to feed the growing global population, intensification of rice cropping is likely one of the strategies used to ensure food security in different parts of the world. In rice cropping under saline conditions in arid and semi-arid regions, deep drainage systems with managed drainage intensity could be a good way to enhance nitrogen uptake and water productivity and to improve rice yields while minimising methane emissions and other impacts on the environment.

Populärvetenskaplig sammanfattning

Ris, ett baslivsmedel för miljarder människor världen över, behöver vanligtvis stående vatten på markytan för att växa bra och ge en god skörd. Odlingen har tyvärr flera negativa konsekvenser, som hög vattenförbrukning, stora utsläpp av växtnäring och växthusgasen metan. För odling av ris i torra och halvtorra regioner krävs bevattning, som kan göra att salter anrikas i jorden med minskande skördar som följd. I detta arbete testades om det var möjligt att genom dikning minska risken för saltanrikning och öka risskörden. Genom dikningen kan dock tyvärr ett nytt problem uppstå, dräneringsvattnet kan tänkas förorena vattenkällor nedströms.

Därför undersöktes hur tre olika dräneringsmetoder påverkade kväveflöden, saltanrikning i jorden, risproduktion och utsläpp av växthusgaser i bevattnade risodlingar. Försöken genomfördes på en sumpmark i Rwanda under fyra växtsäsonger. Traditionell grund dränering med 0,6 m djupa diken, där en fördämning öppnades fyra gånger i veckan för att släppa ut dräneringsvatten, jämfördes med två metoder med djupa diken (1,2 m), där fördämningen öppnades fyra gånger i veckan i den ena metoden och två gånger i veckan i den andra metoden.

De senare dräneringsmetoderna med djupa diken ledde till ett högre kväveupptag i riset, effektivare vattenutnyttjande och högre risproduktion, samtidigt som mindre metan släpptes ut jämfört med det traditionella dikessystemet. Markens salthalt minskade från säsong till säsong, ingen tydlig skillnad i minskningen mellan de olika dräneringsmetoderna observerades. Eftersom det globala livsmedelsbehovet för att försörja en växande befolkning ökar, kommer intensifiering av risodling vara av högsta prioritet. Som visat här är dräneringsmetoder med djupa diken en lovande strategi för att öka grödans kväveupptag, förbättra vattenhushållningen och öka risproduktionen och samtidigt minska utsläpp av metan.

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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

Olive Tuyishime[a,b], Abraham Joel[b], Ingmar Messing[b], Francois Naramabuye[a], Muthiah Sankaranarayanan[c] and Ingrid Wesström[b]

[a]University of Rwanda, College of Agriculture, Animal Sciences and Veterinary Medicine, Musanze, Rwanda; [b]Department of Soil and Environment, Swedish University of Agricultural Sciences, Uppsala, Sweden; [c]University of Rwanda, College of Agriculture, Animal Sciences and Veterinary Medicine, Nyagatare, Rwanda

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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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.

CONTACT Ingrid Wesström Ingrid.Wesstrom@slu.se Department of Soil and Environment, Swedish University of Agricultural Sciences, P.O. Box 7014, Uppsala SE-75007, Sweden

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).

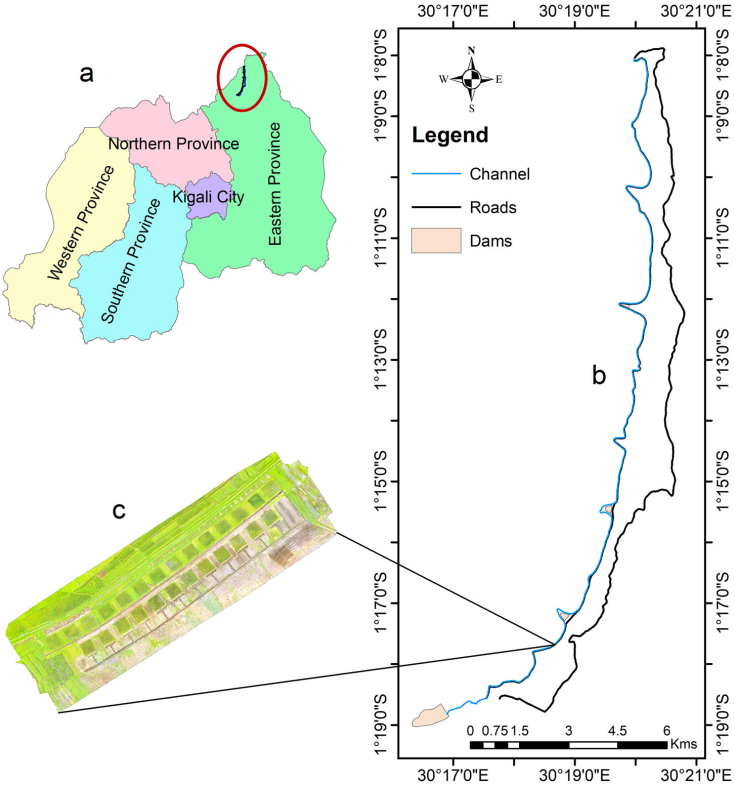

Figure 1. Map of Rwanda showing (a) location of the site in north-eastern Rwanda, (b) outline of Muvumba Marshland, and (c) position/ sketch of the experiment.

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

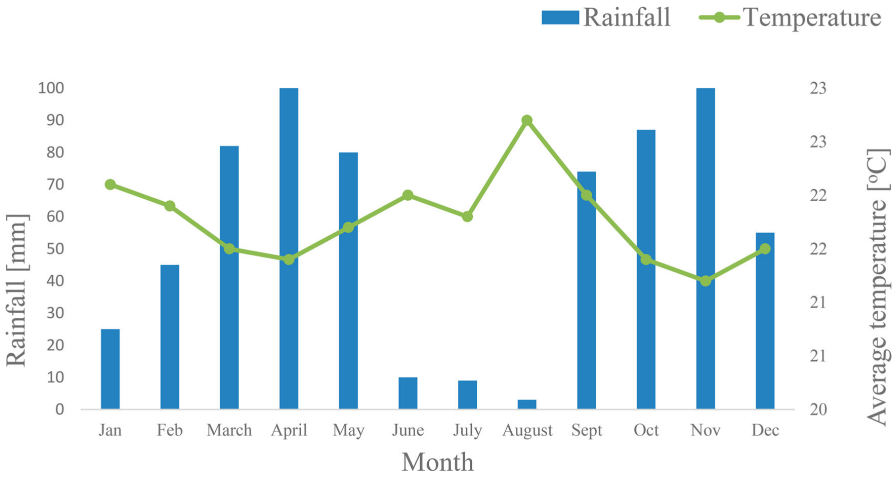

Figure 2. Mean monthly rainfall and temperature in the Muvumba Marshland area (Nyagatare station, 1984–2013).

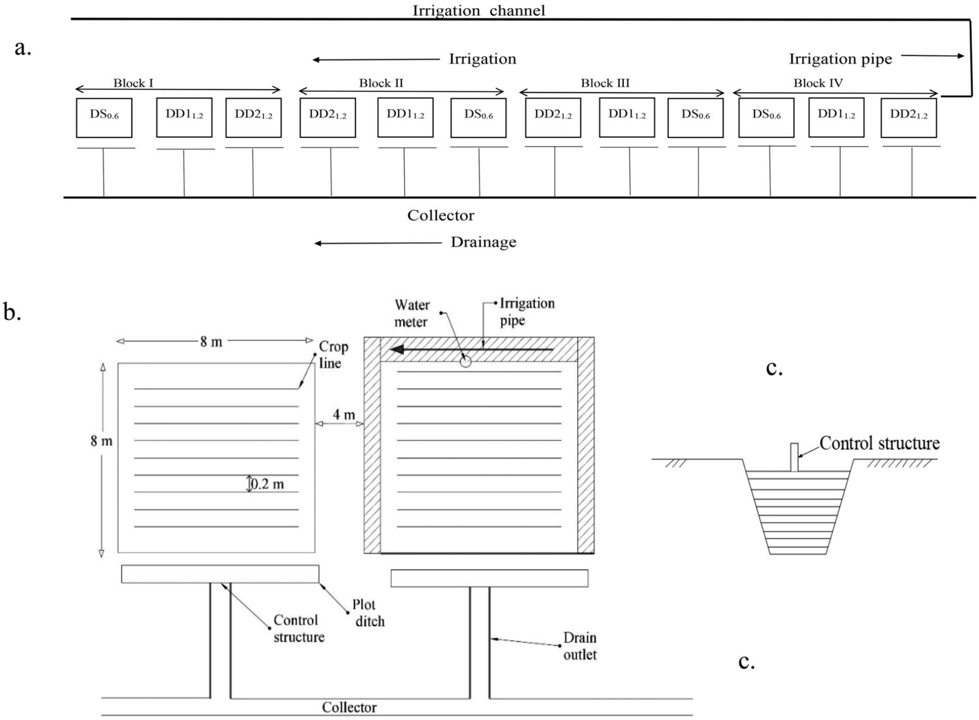

Figure 3. Sketch of a) blocks and treatments in the experimental set-up $DS_{0.6}$ (0.6 m deep drain, control structure open four times per week), $DD1_{1.2}$ (1.2 m deep drain, control structure open four times per week) and $DD2_{1.2}$ (1.2 m deep drain, control structure open two times per week), 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:

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

where Dr_i is drainage outflow (mm) when the control structure is open on day *i* (i.e. accumulated water between two drainage events), $Dr_{i\text{-}1}$ 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:

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

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:

$$ET_{c,\,i} = ET_{o,\,i} * K_{c,\,i} \tag{3}$$

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:

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

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):

$$\text{N balance} = \text{Total N input - Total N output} \tag{5}$$

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):

$$\text{WUE} = \frac{\text{GY}}{\text{Ir} + \text{P}} \tag{6}$$

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-} 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$_{0.6}$ (***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

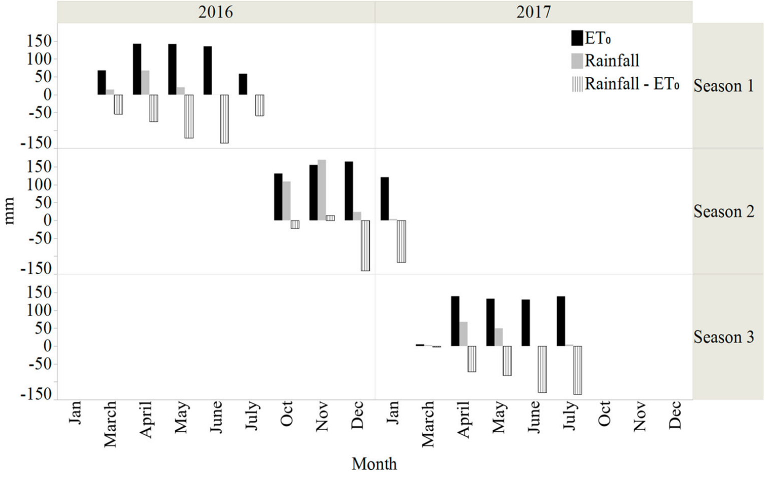

Figure 4. Reference evapotranspiration (ET$_o$), rainfall, and rainfall-ET$_o$ during the study period, in Season 1, Season 2 and Season 3.

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

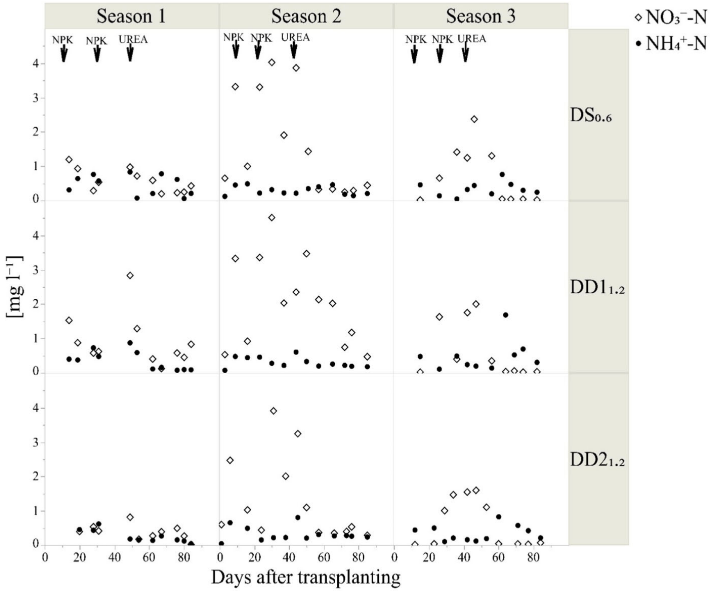

Figure 5. Measured nitrate-nitrogen (NO_3^--N) and ammonium-N (NH_4^+-N) concentrations in drainage water in treatments $DS_{0.6}$, $DD1_{1.2}$ and $DD2_{1.2}$ in Season 1, 2 and 3. $DS_{0.6}$ = 0.6 m deep drain, control structure open 4 times/week, $DD1_{1.2}$ = 1.2 m deep drain, control structure open 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: ***$p < 0.001$; **$p < 0.01$; *$p < 0.05$.

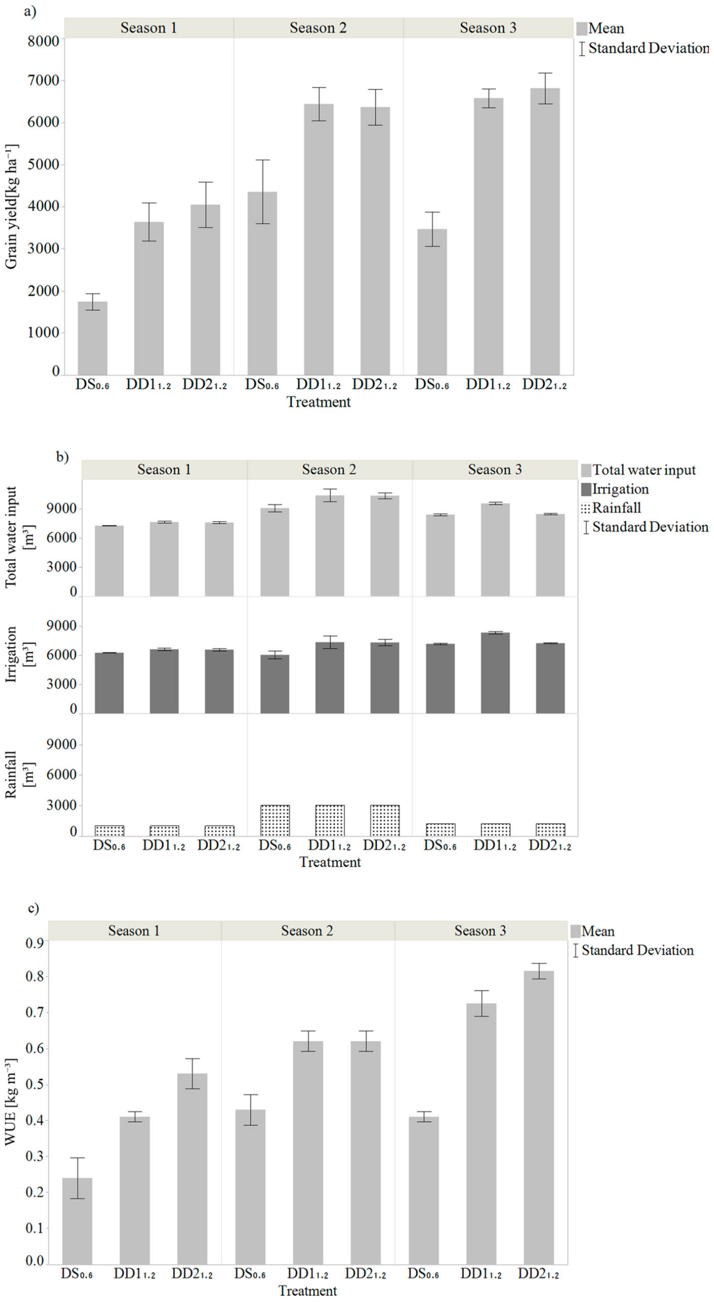

Figure 6. Mean and standard deviation ($n = 4$) of a) grain yield, b) total water input, irrigation and rainfall amount, and c) water use efficiency (WUE) in Seasons 1, 2 and 3 in treatments $DS_{0.6}$ (0.6 m deep drain, control structure open 4 times/week), $DD1_{1.2}$ (1.2 m deep drain, control structure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

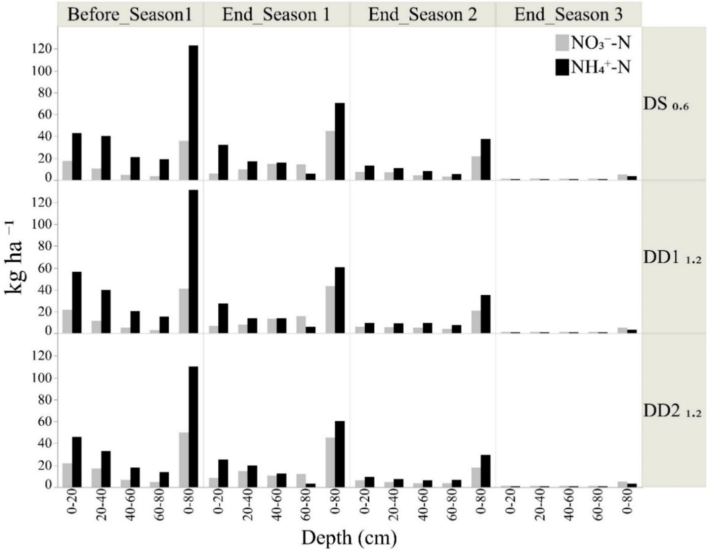

Figure 7. Nitrate-nitrogen (NO_3^--N) and ammonium-N (NH_4^+-N) concentrations in soil in treatment $DS_{0.6}$ (0.6 m deep drain, control structure open 4 times/week), $DD1_{1.2}$ (1.2 m deep drain, control structure open 4 times/week) and $DD2_{1.2}$ (1.2 m deep drain, control structure open 2 times/week)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

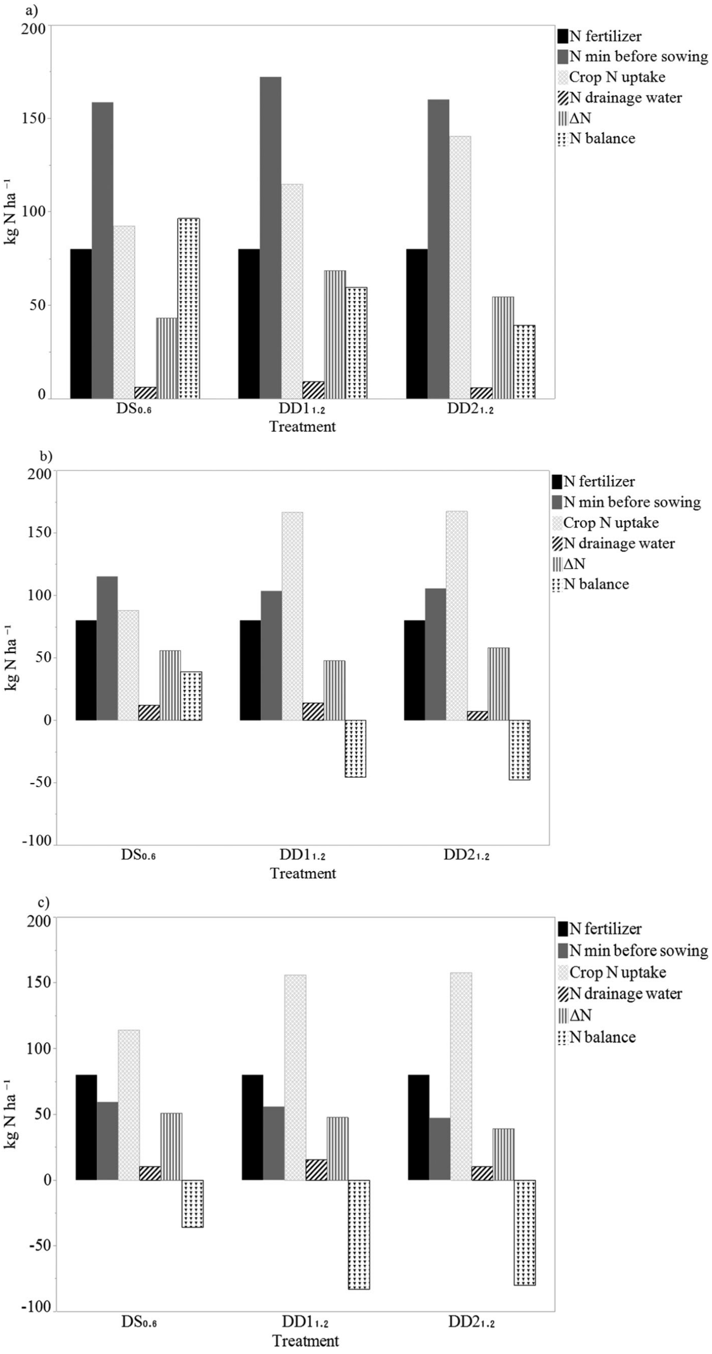

Figure 8. Nitrogen (N) budget, including N fertiliser and soil mineral N (N_{min} before sowing) as input and crop N uptake, N loads in drainage water, and ΔN (N_{min} before sowing – N_{min} residual) as output in kg N ha^{-1}, and N balance calculated as the difference between total input and total 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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Notes on contributors

Olive Tuyishime is a PhD student at the Swedish University of Agricultural Sciences. Her PhD work focuses on soil and water management in agricultural production with aim to optimize agricultural production while minimizing negative environmental side effects. Currently working on nitrogen losses management and salinity control in irrigated paddy fields. She received her MSc degree in Integrated soil fertility management at Kenyatta University.

Abraham Joel is an Associated Professor at the Swedish University of Agricultural Sciences. His research focuses on soil and water management in agriculture with special attention to understanding and assessing the dynamics of runoff, soil erosion, water fluxes in soil/field. Currently working on development of methods for assessing soil physical properties such as infiltration capacity, particle size distribution, soil erodibility and soil shear strength. The more applied research includes technologies for soil and water management such as irrigation, water harvesting, soil conservation, water diversion and storage and crop production systems.

Ingmar Messing is a Professor at the Swedish University of Agricultural Sciences. His research focuses on soil science, especially soil physical processes and properties of importance for sustainable land use. Areas of application are: soil structure, water movements in the system soil-plant-atmosphere, soil and soil water management, land evaluation and land use planning. Currently working on the technology of laboratory methods for determining particle size distribution (laser diffraction and sieve and sedimentation methods), their respective protocols and applicability for different particle size ranges and soil types

Francois Naramabuye is a full Professor at the University of Rwanda. His research focuses on soil science and environmental management. He is involved in PhD supervision in a number of countries including Sweden-SLU, Belgium-ULg, Germany-University of Bonn, Ghana-Kwame Nkrumah University, and Uganda-Makerere University. Currently working in FABLE-SDSN research projects on Food, Agriculture, Biodiversity, Land and Energy. His expertise is extended in investigating the impacts of land use on soil fertility properties and updating soil data accordingly as well as proposing evidence based fertilizers recommendations.

Muthiah Sankaranarayanan is a full Professor of Agricultural Engineering in the University of Rwanda. His research focused on agricultural engineering during his 42 years of university experience, especially irrigation, drainage, soil and water engineering and agricultural mechanization. He has guided many research projects of BSc, MSc and PhD students in India as well as in Rwanda. He served as national consultant for the Task Force on Irrigation and Drainage, Carbon Credit baseline studies for manure management and developed 18 different Rwanda Standards and Regulation for the process machinery related to Post Harvest Handling and Storage of grains and pulses. He is recently retired from his service.

Ingrid Wesström is an Associate Professor at the Swedish University of Agricultural Sciences. Her research focuses on agricultural water management, especially soil physical processes, soil water holding capacity and soil fertility. Areas of application are: soil water movement, agricultural drainage, storage and reuse of drainage water, irrigation and nutrient leaching. Currently working on adapting farming practices for optimizing the use of land and water resources while minimizing negative environmental side effects.

ORCID

Ingrid Wesström http://orcid.org/0000-0002-9816-469X

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Deep Drainage Lowers Methane and Nitrous Oxide Emissions from Rice Fields in a Semi-Arid Environment in Rwanda

Olive Tuyishime [1,2,*], Monika Strömgren [2], Abraham Joel [2], Ingmar Messing [2], Francois Xavier Naramabuye [1] and Ingrid Wesström [2]

[1] College of Agriculture, Animal Sciences and Veterinary Medicine, University of Rwanda, Musanze P.O. Box 210, Rwanda
[2] Department of Soil and Environment, Swedish University of Agricultural Sciences, P.O. Box 7014, SE-75007 Uppsala, Sweden
* Correspondence: olive.tuyishime@slu.se; Tel.: +250-788527700

Abstract: Few studies have explored greenhouse gas (GHG) emissions from arable land in sub-Saharan Africa (SSA), and particularly from rice paddy fields, which can be a major source of methane (CH_4) and nitrous oxide (N_2O) emissions. This study examined the effect of drainage on CH_4 and N_2O emissions from rice fields in Rwanda under shallow drainage to 0.6 m, with the drain weir open four times per week, and deep drainage to 1.2 m with the weir open four times or two times per week. CH_4 and N_2O fluxes from the soil surface were measured on nine occasions during rice flowering and ripening, using a closed chamber method. Measured fluxes made only a minor contribution to total GHG emissions from rice fields. However, drainage depth had significant effects on CH_4 emissions, with shallow drainage treatment giving significantly higher emissions (~0.8 kg ha^{-1} or ~26 kg CO_2-equivalents ha^{-1}) than deep drainage (0.0 kg) over the 44-day measurement period. No treatment effect was observed for N_2O fluxes, which ranged from low uptake to low release, and were generally not significantly different from zero, probably due to low nitrogen (N) availability in soil resulting from low N fertilization rate (in the region). Overall, the results suggest that deep drainage can mitigate CH_4 emissions compared with traditional shallow drainage, while not simultaneously increasing N_2O emissions.

Keywords: greenhouse gas; CH_4; N_2O; paddy rice

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1. Introduction

Around 20–25% of total greenhouse gas (GHG) emissions from all human activities derive from food production and related land use change [1]. Methane (CH_4) and nitrous oxide (N_2O) are two of the most important GHGs emitted from agriculture, with global warming potential (GWP) of 34 and 298 CO_2-equivalents, respectively, in a 100-year time horizon [2]. Rice fields are responsible for approximately 11% of global anthropogenic CH_4 emissions, and rice has the highest GHG emissions of all staple food crops [3,4]. Nutrient management, tillage practices and water management are the main factors influencing rice yield and GHG emissions. Increases and decreases in CH_4 and N_2O emissions have been reported with increasing rice yield [5–7]. Studies have shown that climate change benefits in terms of reducing CH_4 emissions can be offset if there is an associated increase in emissions of N_2O, because N_2O has higher GWP than CH_4 [8].

Methane is produced in anaerobic environments by obligate anaerobic microorganisms, through CO_2 reduction or transmethylation [9], while N_2O is produced via nitrification under aerobic conditions and through denitrification under anaerobic conditions [10,11]. The microbial processes by which these gases are produced are influenced by soil moisture content and water management [12,13]. Reviews have shown that there may be some consumption of N_2O (i.e., flux from atmosphere to soil), usually in association with low mineral nitrogen (N) content and high moisture content in the soil [14,15]. Field drainage is one way to reduce CH_4 emissions from fields [16], but N_2O production is enhanced by aeration of paddy field soil through drainage [17]. Therefore, when using drainage as a GHG mitigation strategy, it is necessary to find a compromise between CH_4 and N_2O emissions [17]. Decisions on drainage depth should aim to maximize rice yield while mitigating GHG emissions [18], but there are contradictory findings on the effect of deep drainage on GHG production and rice yield. Some studies have observed no effect of deep drainage in reducing GHG emissions or increasing rice yield compared with shallow drainage [19], while others have found that deep drainage can enhance rice grain yield in a semi-arid environment [20].

Controlled drainage, i.e., regulating groundwater levels and reducing the percolation rate, could be a feasible option to reduce GHG emissions from rice fields [21,22]. Fluctuations in groundwater level affect the oxygen content in paddy soil, vertical migration of chemicals, and microbial activity [23,24]. However, controlled drainage has been found to have inconsistent effects on GHG emissions, including possibly N_2O release through denitrification due to periods with higher soil water content [25].

Emissions of CH_4 and N_2O are affected by fertilizer and crop residue management, and by variations in soil pH and soil salinity. The effect of fertilizer on N_2O emissions depends on the dose [26,27]. High rates of N fertilizer increase emissions by stimulating CH_4 production from rice fields, increasing rice plant growth and thereby the carbon supply for methanogenic bacteria [28,29]. Addition of crop residues, such rice straw to paddy soils, increases CH_4 emissions [30,31], with the magnitude of increase depending on straw application rate and timing and weather conditions [31,32]. Methanogenic bacteria are very sensitive to variations in soil pH, with the highest CH_4 production rates at neutral pH and with small changes in soil pH sharply lowering CH_4 production [33]. High soil salt content decreases CH_4 emissions, through suppressing the activities of soil microbes, including methanogens [34,35]. The reported effects of soil salinity on N_2O emission are inconsistent (increase, decrease or no response) [36,37]. Overall, the available data suggest that soil salinity-induced GHG emissions can influence global GHG dynamics, but GHG emission responses to soil salinity have not been fully identified [34].

Agricultural production intensity and associated agricultural GHG emissions are relatively low in sub-Saharan Africa (SSA) compared with other parts of the world [38]. However, GHG emissions released in SSA play an important role in the global GHG budget [39–41]. Further, food production in SSA will need to increase in the coming decades to match the strongly growing demand for food, and therefore GHG emissions from agriculture can be expected to increase in the region [42]. However, there is great uncertainty regarding the GHG emissions originating from agriculture, forestry, and land use change in Africa, and therefore GHG flux measurements need to be performed throughout Africa [43].

Very few studies have explored GHG emissions from arable land in SSA and particularly from rice production systems. Previously reported contributions of rice fields in SSA to global CH_4 and N_2O emissions are mainly estimates based on very few measurements, and there is a risk of this very important source of GHG emissions being overlooked [44].

Rice is grown on around 36,000 ha in Rwanda (2017 data) [45]. Assuming an emission factor of 70 kg CH_4 ha^{-1}, total emissions of CH_4 from Rwandan rice production are around 22×10^5 kg, or 464×10^5 kg CO_2-equivalents [45]. In order to identify mitigation measures and other climate-smart interventions for Rwanda and for the SSA region in general, it is important to quantify baseline GHG emissions and assess the impacts of different management strategies on these emissions [46].

This study examined the effect of varying drainage depth and frequency on soil-surface fluxes of CH_4 and N_2O in paddy rice cultivation in a marshland area in Rwanda. The hypothesis tested was that groundwater lowering through deeper drainage and more frequent opening of drain weirs reduces CH_4 emissions, but increases N_2O emissions, compared with deeper drainage and less frequently opened drain weirs or conventional shallow drainage.

2. Materials and Methods

2.1. Study Site

The study was performed at an experimental site in a rice production marshland in north-eastern Rwanda (1°17′33.0′′ S 30°18′48.2′′ E, 1513 m above sea level). 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 [47,48]. Rainfall is distributed over two rainy seasons (mid-February to May, September to mid-December), with precipitation peaks in April and November.

According to the FAO soil classification system [49], the soil at the study site is a former Vertisol changed to a Vertic-Fluvic-Gleysol due to the continuous deposition of alluvial and colluvial materials and waterlogged conditions. Analysis of samples collected from 0–80 cm depth showed that the soil at the site has a high pH (7.1–7.6), medium total N content (0.26–0.28%), and medium soil organic matter content (7.7–9.0%), with C/N ratio ranging between 16 and 19. The soil texture is sandy loam to sandy clay loam, with dry bulk density of 1.31–1.43 g cm^{-3} [20]. Based on the FAO system [50], the soil is moderately saline.

2.2. Experimental Design

The field experiment comprised four blocks of three treatments (plots) arranged in a randomized complete block design (Figure 1). The area of individual plots was 8 m × 8 m, and a 4 m wide zone separated adjacent plots and blocks. The treatments were: shallow drainage to 0.6 m depth, with drain weir open four times per week (S4) and deep drainage to 1.2 m depth with drain weir open four times per week (D4) or two times per week (D2). The shallow drainage depth corresponds to the traditional drainage system in the area, while the deep drainage treatments correspond to conventional (D4) and controlled drainage (D2). During the experiment, the drain weirs were opened for one hour for outflow measurements and then kept closed until the next scheduled opening time.

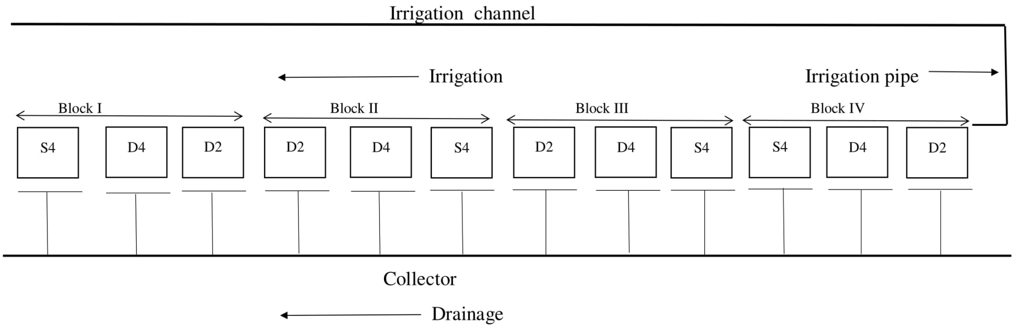

Figure 1. Experimental set-up of blocks (I–IV) and plots within blocks with three treatments: shallow drainage to 0.6 m depth, with weir open four times per week (S4), and deep drainage to 1.2 m depth, with weir open four times per week (D4) or two times per week (D2).

2.3. Experimental Procedure

Rice (*Oryza sativa*) seedlings were transferred from the nursery to the experimental plots after three weeks, and planted with 0.2 m spacing between rows and 0.2 m between plants within rows. Fertilizer was applied according to the Rwandan fertilization regime for irrigated rice [51], with a total of 80 kg N ha^{-1} applied (Table 1). Pests were controlled according to recommendations [52] and weeds were controlled manually by hoeing.

Table 1. Field management practices, fertilizer type, and fertilizer application rate (N = nitrogen, P = phosphorus, K = potassium) in the experiment.

Field Operation	**Date (2018)**	**DAT** [a]	**Fertilizer Type**	**N kg ha^{-1}**	**P kg ha^{-1}**	**K kg ha^{-1}**
Seeds germination	8 March					
Rice transplanting	29 March					
1st fertilizer application	4 April	6	NPK	10	4	8
2nd fertilizer application	18 April	20	NPK	24	11	20
3rd fertilizer application	7 May	39	Urea	46		
First GHG [b] sampling	24 May	56				
Last GHG [b] sampling	8 July	100				
Last irrigation event	15 July	107				
End of weir regulation	16 July	108				
Rice harvesting	1 August	122				

[a] Days after transplanting. [b] Greenhouse gas.

2.4. Irrigation and Drainage Management

Water from a nearby river (the Muvumba) was used for irrigation. The irrigation system consisted of a main pipeline, that conducted water from an existing irrigation channel to a surface drainage system with open ditches in the experimental area. Laterals connected to the main pipeline supplied water to each plot. The actual amount of irrigation water applied was recorded using water meters. Irrigation was scheduled so that the plots were irrigated three times per week until a standing water layer developed on the soil surface. The system consisted of a sub-drain for each experimental plot, an outlet, and a main collector channel. Weirs made of wood were installed in the sub-drains to regulate drainage depth. During the rice cropping season, the weirs were open or closed depending on drainage treatment. 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 collector channel via the plot ditch. There were generally, no irrigation events on the days of GHG sampling days.

2.5. Fluxes of CH_4 and N_2O from Soil

Fluxes of CH_4 and N_2O from the soil surface were measured by the closed chamber method at one point in the center of each plot on nine occasions from 24 May to 8 July 2018 (rice flowering to ripening). For these flux measurements, a collar (diameter 18.7 cm) was installed to 2 cm depth before rice transplanting, and two seedlings were planted inside the collar. The collars were left permanently at the same spot during the whole measurement period. Wooden walk boards were installed in each plot to prevent disturbance by trampling.

During each GHG flux measurement, a dark PVC chamber (diameter 18.7 cm, height 16 cm) was fitted on the pre-installed collar, which was equipped with a rubber gasket to keep the joint airtight. The height of the chamber varied from 24 to 67 cm, depending on crop height, i.e., chambers of lower height were used at the start of the study. One chamber was deployed in each rice plot and six plots (i.e., two blocks) were measured at the same time. After closing the chamber, the air between chamber and vial was circulated for 60 s using a pump with capacity ~0.5 L min^{-1} and then an air sample was collected in a 22 mL glass vial. Three more samples were taken in the same manner, with one measurement every 24 min. The CH_4 and N_2O concentrations in the air samples were analyzed using a gas chromatograph (Clarus 500, PerkinElmer Inc., Shelton, CT, USA), equipped with an automatic head-space injector (TurboMatrix 110, PerkinElmer Inc., USA), a flame ion detector (FID) for CH_4 analysis, and an electron capture device (ECD) for N_2O analysis. Linear regression was used to estimate the CH_4 and N_2O fluxes [53], based on linear slope of concentration against time using all gas samples analyzed (except a few with obvious errors linked to leaking vials). The flux values were corrected for air pressure, air temperature, and chamber volume.

Measurement of fluxes in all plots was performed within a 160 min session from morning to midday (generally 10:00 to 12:40), to minimize possible effects of diurnal variation in fluxes. The diurnal pattern of GHG fluxes was assessed during one day (30 June 2018) in which measurements were performed at 6, 9, 12, and 15 h.

Previous tests of the chambers against a known flux have revealed that the flux is slightly overestimated (7%) when calculated by linear fit [54]. To eliminate the effects of disturbance from ebullition caused by chamber deployment, measurements with initial concentration above 2.4 ppm CH_4 or 0.5 ppm N_2O were discarded. To eliminate effects of other disturbances caused by, e.g., leaky vials, measurements were also discarded if the standard deviation of the residual between the concentration estimated from the linear relationship and the measured concentration exceeded 0.2 ppm CH_4 or 0.1 ppm N_2O. In total, 10 and two measurements of CH_4 and N_2O, respectively, out of a total of 144 measurements, were discarded.

2.6. Groundwater Level and Temperature Measurements

Groundwater level and soil temperature (10 cm depth) were measured on all GHG measurement occasions. The groundwater level was monitored before each GHG measurement in a 60 cm deep pipe permanently installed in the center of each plot. Measurements of soil temperature at 10 cm depth were performed with a portable EC probe (Testrs® 11 series).

2.7. Data Analysis

The distribution of the data was checked for normality and homoscedasticity. One extremely high flux value out of 134 values for CH_4 and two extremely high values out of 142 values for N_2O failed to meet the requirements, and were excluded from the statistical analysis. Effects of drainage treatment on CH_4 and N_2O fluxes over the whole period were tested by mixed model analysis of variance (ANOVA) in SAS Statistical software (v9.4, SAS Institute, Cary, NC, USA), with drainage treatment as a fixed effect in the model. Since the measurements were made in the same plots on every occasion, they could not be assumed to be independent of time, so "measurement date" was used as a repeated measure. If treatment was found to be significant in ANOVA, pair-wise comparisons were used to identify significant ($p \leq 0.05$) differences between treatments. Testing for the presence of a diurnal pattern of CH_4 and N_2O fluxes was performed using a mixed model in which treatment and time of day were used as fixed effects.

The total flux of CH_4 and N_2O over the study period was estimated for each treatment using the mean flux from the measurement occasion closest in time. Hence, for measurements on day 0 and day 10, the mean of day 0 was used for the first five days and the mean of day 10 for the next five days. Total flux was transformed into CO_2-equivalents using a GWP factor of 34 for CH_4 and 298 for N_2O [2].

3. Results

3.1. Treatment Effects on Groundwater Level

Groundwater depth in the treatment plots varied from 0 to around 35 cm during the study period (Figure 2). The ANOVA results showed that drainage treatment was a significant fixed effect (p = 0.03) for ground water level (Table 2). Significantly higher groundwater level was observed with shallow drainage than deep drainage, but there was no difference between the two deep drainage treatments. In shallow drainage plots, the groundwater was close to the soil surface on several measurement occasions.

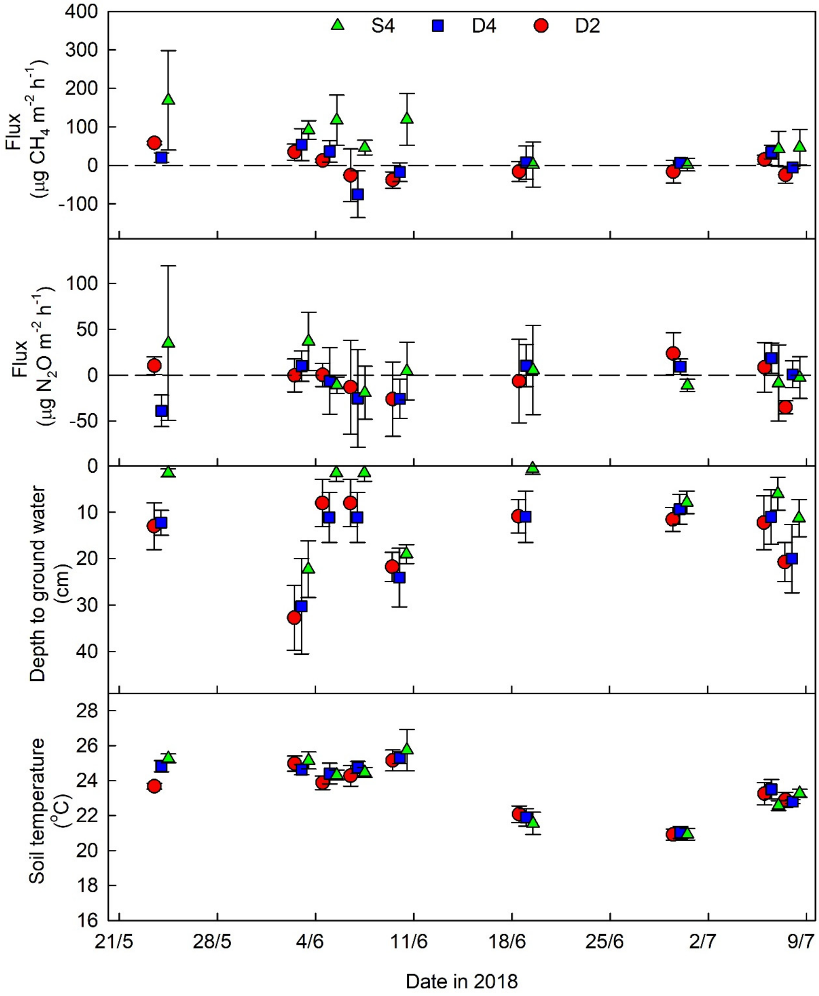

Figure 2. Flux of methane (CH_4) and nitrous oxide (N_2O), groundwater level, and soil temperature in the period May-July 2018 in treatments with: shallow drainage to 0.6 m with weir open four times per week (S4) and deep drainage to 1.2 m, with weir open four times per week (D4) or two times per week (D2). Error bars denote one standard error ($n \leq 4$). The flux values represent fluxes from soil-surface including vegetation, negative values indicating uptake of CH_4 or N_2O.

Table 2. *p*-values obtained from analysis of variance (ANOVA) of effects of drainage treatment on methane (CH_4) flux, nitrous oxide (N_2O) flux, groundwater level (GWL) and soil temperature.

Fixed Effects	CH_4 Flux	N_2O Flux	Groundwater Level	Soil Temperature
Drainage	0.03	0.60	0.03	0.83

3.2. Soil Temperature

Mean soil temperature at 10 cm depth did not vary greatly between treatments or between GHG measurement occasions (Figure 2). The measured values ranged between 20.9 °C (30 June 2018) and 25.8 °C (10 June 2018). Soil temperature was slightly higher in the first part of the season (May to mid-June) than in the second part (mid-June to mid-July).

3.3. Treatment Effects on CH_4 and N_2O Fluxes

Mean CH_4 flux varied from uptake of around 80 $\mu g\ m^{-2}\ h^{-1}$ to release of around 170 $\mu g\ m^{-2}\ h^{-1}$, depending on treatment and occasion (Figure 2). Significant treatment effects on CH_4 flux were observed (Table 2), with shallow drainage giving significantly higher CH_4 emissions (p = 0.03) than both deep drainage treatments. The N_2O flux was generally low, with small uptake or release, for all days and treatments and there was no significant treatment effect.

3.4. No Significant Diurnal Pattern in CH_4 and N_2O Fluxes

Test for presence of a possible diurnal pattern in GHG emissions revealed a significant diurnal pattern in soil temperature with the lowest values at 6 am (19.4 °C) and the highest at noon (22.7 °C) (Figure 3). The CH_4 and N_2O fluxes remained low throughout the day (Figure 3) and mixed model ANOVA test revealed no significant effect of time of day or drainage treatment on either CH_4 or N_2O flux (Table 3). However, there was a tendency for CH_4 flux to be higher in the afternoon than at other times of the day (Figure 3).

Table 3. *p*-values obtained from analysis of variance (ANOVA) of effects of drainage treatment and time of day (during 30 June 2018) on methane (CH_4) flux, nitrous oxide (N_2O) flux, groundwater level (GWL) and soil temperature.

Fixed Effects	CH_4 Flux	N_2O Flux	Groundwater Level	Soil Temperature
Drainage	0.17	0.74	0.61	0.82
Time of day	0.07	0.67	0.87	0.00

3.5. Accumulated GHG Fluxes

Accumulated CH_4 emissions from the deep drainage treatments were close to 0.0 kg ha^{-1} throughout the 44-day measurement period (Table 4). Accumulated CH_4 emissions from the shallow drainage treatment were estimated to be around 0.8 kg ha^{-1}, corresponding to approximately 26 kg CO_2-equivalents ha^{-1}.

Table 4. Accumulated methane (CH_4) and nitrous oxide (N_2O) emissions over the 44-day period from treatments with: shallow drainage to 0.6 m with weir open four times per week (S4) and deep drainage to 1.2 m with weir open four times per week (D4) or two times per week (D2). Note that a negative value corresponds to accumulated uptake of the gas.

Treatment	CH_4		N_2O	
	kg ha^{-1}	kg CO_2-eq. ha^{-1}	kg ha^{-1}	kg CO_2-eq. ha^{-1}
S4	0.8	26	0.04	11
D4	0.1	3	−0.06	−17
D2	0.0	0	−0.05	−14

Accumulated N_2O emissions were not significant (Table 4). In absolute terms, uptake of 0.06 kg ha^{-1} to release of 0.04 kg ha^{-1} was observed, depending on treatment, corresponding to uptake of 17 kg CO_2-equivalents ha^{-1} to emissions of 11 kg CO_2-equivalents ha^{-1} for the period.

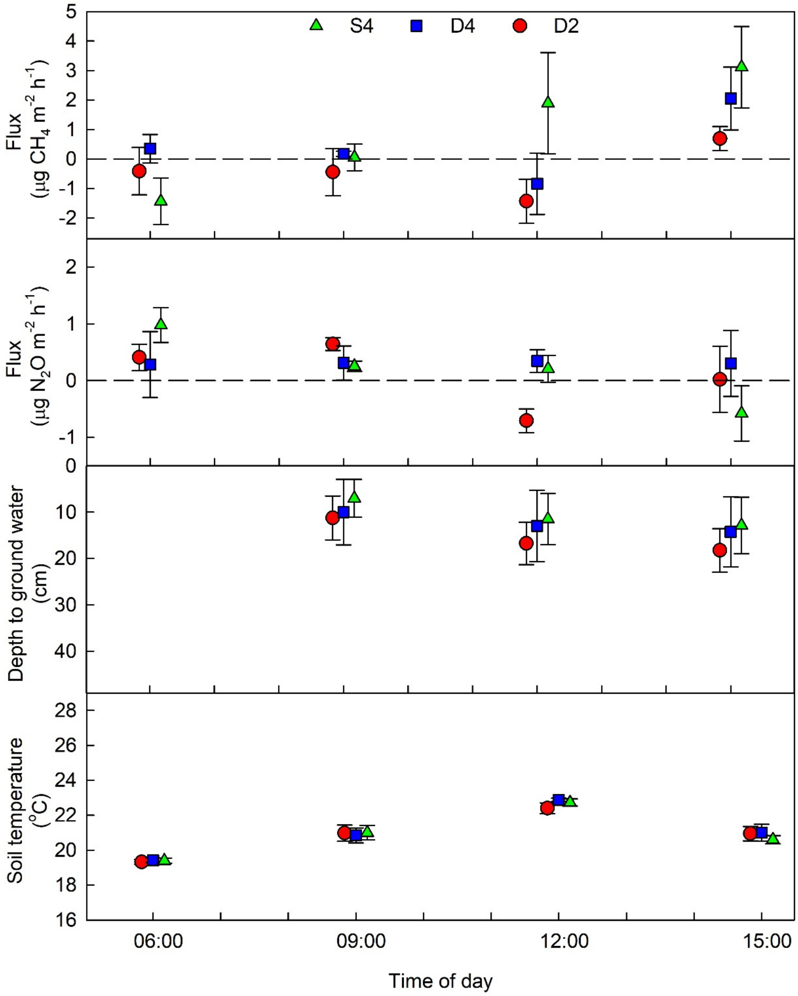

Figure 3. Diurnal pattern in methane (CH_4) and nitrous oxide (N_2O) fluxes, groundwater level, and soil temperature in treatments with: shallow drainage to 0.6 m with weir open four times per week (S4) and deep drainage to 1.2 m with weir open four times per week (D4) or two times per week (D2). Error bars denote one standard error ($n \leq 4$). The flux values represent fluxes from the soil-surface including vegetation, with negative values indicating uptake of CH_4 or N_2O.

4. Discussion

4.1. Drain Depth and CH_4 Emissions

Deep drainage lowered the groundwater level more and therefore reduced CH_4 emissions compared with shallow drainage, partially confirming the starting hypothesis. The treatment with shallow drainage (representing traditional practice in the study region) had significantly higher CH_4 emissions and the shallowest groundwater level of all treatments. Previous studies have found that drainage strongly reduces CH_4 emissions from rice paddy fields compared with poorly drained fields, indicating that improved water management can be an important strategy for reducing CH_4 emissions from rice paddy fields [55]. In an earlier study at the study site, we found that the deep drainage treatments also increased yield [20].

However, there were no differences in CH_4 emissions, or in groundwater level, between the two deep drainage treatments with different weir opening frequency (D4 and D2). This was probably because all plots were irrigated three times per week, so opening the weir two or four times per week did not result in considerable differences in groundwater level, or in soil water content [20].

Estimated CH_4 emissions (0–0.8 kg ha^{-1}) were low compared with those reported in other studies [56,57]. One probable explanation for the low CH_4 emissions was that the groundwater level was below the soil surface on all measurement occasions in our study. Another possible explanation is depletion of soil organic carbon and total N at the experimental site, because of the local practice of not returning crop residues to the soil. In addition, the soil at the study site is moderately saline and studies on paddy fields have found that soil salinity affects CH_4 emissions through suppressing the activities of soil microbes, including methanogens [34,35]. However, the soil salinity conditions were improved prior the present study and the soil salinity effect was probably limited.

The IPCC [58] emissions factor for CH_4 emissions from rice fields is 1.3 kg ha^{-1} day^{-1}, while in statistics on CH_4 emissions from rice cultivation compiled by FAO [45], an emissions factor equivalent to 0.19 kg CH_4 ha^{-1} day^{-1} is used for Rwanda. These values would correspond to CH_4 emissions of 57 and 8.4 kg ha^{-1} during a 44-day period, which is much greater than the observed flux of 0.0–0.8 kg CH_4 ha^{-1} at our study site. The difference between estimates obtained using the IPCC factor and the FAO factor demonstrates the uncertainty in estimating CH_4 emissions and the need for empirical measurements at a range of sites. Empirical studies of GHG emissions from African rice fields are rare. In the only case reported in the literature, in Zimbabwe, the field studied emitted 12.5 kg CH_4 ha^{-1} during a growing period of 150 days [44], which would equate to 3.7 kg CH_4 ha^{-1} for a 44-day period. This is much lower than the IPCC estimate and half the FAO estimate, but still exceeds the emissions observed in our study.

4.2. Groundwater Level and N_2O Emissions

The hypothesis that deep drainage and more frequent weir opening (D4) lowers the groundwater level more, and therefore increases N_2O emissions, compared with shallow or less frequently opened deep drains was not supported by the results. There are several possible reasons for this. One is that groundwater level was not very much deeper numerically in the deep drainage treatments than with shallow drainage (although the difference was significant), and no obvious effect on N_2O was observed even when the groundwater was at its lowest level (30 cm). A previous study on the effect of groundwater level on N_2O emissions observed, an increase in emissions at deep groundwater level (40 cm) compared with shallow (10 cm) [59].

Apart from soil moisture, soil N_2O emissions flux is affected by use of nitrogen fertilizers as this acts as a substrate for nitrifying and denitrifying microorganisms [19]. Considering the nutrient-poor soil at our study site and the low amount of added N (80 kg N ha^{-1} per season), there was probably insufficient ammonium and nitrate available for denitrification and nitrification (cf. [29,60]), resulting in the soil being a poor source of N_2O in all drainage treatments.

The fifth IPCC report [8] considers N_2O emissions from flooded land to be negligible unless there is significant input of organic or inorganic nitrogen [61]. A review has shown that the lowest yield-scaled N_2O emissions occur with N application rates ranging between 100 and 150 kg ha^{-1} [43], and the N application rate used in our study was below that lower threshold. The small uptake of N_2O we observed in the present study may also be explained by low N availability [14,15].

It should be noted that our first GHG measurement took place on day 17 after fertilization and that peak N_2O flux tends to coincide with fertilization [58]. Later N_2O emissions may occur episodically [62], associated with initial stage of growth and fertilization occasion [63]. In all, this implies that the N_2O emissions were underestimated in this study. However, the values were consistent with those reported in other studies on African paddy fields [43,44], although lower than the estimated value of 0.6 kg N_2O ha^{-1} when using the IPCC-recommended emissions factor for a dry climate of 0.5% [64]. In comparison, emissions of 4.4 kg N_2O ha^{-1} have been reported at a fertilizer rate of 276 kg N ha^{-1} for rice fields in China, which is close to the recommended N rate (300 kg N ha^{-1}) for paddy rice in China [65]. To meet increasing future demand for food in SSA, intensive farming with high fertilization rates will be required [42]. Increasing N fertilizer application could have an important impact on future N_2O gas emissions creating a need to find sound management strategies for reducing the agricultural emissions impact in the region.

5. Conclusions

This field study on the effect of varying drainage depth and frequency on soil-surface fluxes of CH_4 and N_2O from paddy rice cultivation in Rwanda revealed that traditional shallow drainage (0.6 m) gave higher CH_4 emissions than the two deep drainage systems (1.2 m), with no associated effect on N_2O emissions. There were no differences between conventional and controlled deep drainage treatments. Thus, deep drainage can mitigate CH_4 emissions from Rwandan paddy fields without increasing the associated N_2O emissions through greater aeration of soil. Prior investigations at the site showed that deep drainage treatments also increased rice yield.

The contribution of CH_4 and N_2O fluxes to total GHG emissions from the moderately saline soil at study site was generally minor. The observed fluxes were much lower than potential fluxes calculated using emission or reported fluxes in other parts of the world. This indicates that applying standard emission factors to saline soils with low N fertilizer inputs in SSA may overestimate actual emissions. To reduce the uncertainty in GHG estimates for the region, future studies should include measurements that fully capture seasonal variations during the rice-growing period.

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Abbreviations

ANOVA	Analysis of variance
CH_4	Methane
CO_2	Carbon dioxide
D4$_{:}$	1.2 m deep drain, weir open four times per week
D2	1.2 m deep drain, weir open two times per week
FAO	Food and Agriculture Organization
GHG	Greenhouse gas
GWP	Global warming potential
IPCC	Intergovernmental Panel on Climate Change
K	Potassium
N	Nitrogen
N_2O	Nitrous oxide
P	Phosphorus
SSA	sub-Saharan Africa
S4	0.6 m deep drain, weir open four times per week

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This thesis investigated the effects of drainage intensity management on nitrogen losses, salinity, rice grain yield, methane (CH_4) and nitrous oxide (N_2O) emissions on a marshland in semi-arid region of Rwanda. Deep drainage performs better than shallow drainage in semi-arid paddy fields, as it enables a balance between maintaining water in the soil, having sufficient drain outflow to leach salts, reduce CH_4 emissions, and achieve high rice yield.

Olive Tuyishime received her PhD education from the Department of Soil and Environment, SLU, Uppsala. She obtained her Master of Science degree in Integrated Soil Fertility Management at Kenyatta University, Kenya.

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