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Assessing and targeting management options for smallholder rice-based systems in Kilombero floodplain, Tanzania

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Dedication

In memory of Mrs Dr. Rosemary Sanyu Maiso

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Abstract

In sub-Saharan Africa, agriculture contributes up to 50% of the GDP. The increase in agricultural output in the region is predominantly from area expansion instead of improvements in productivity per unit area. In the past, cultivation was, for the most part, done in the upland areas. However, with changing climate and rising population pressure, cultivation has extended into wetlands. Prolonged periods of water supply and relatively fertile soils provide wetlands with great potential for expansion and intensification of agriculture production, thus contributing to food security.

The Kilombero floodplain, one of the largest rice-producing areas, was the focus of the BMBF-funded project “GlobE Wetlands”. The Wetlands project was poised to assess the potential of transforming lowland wetlands into a breadbasket of East Africa, and provide science-based guidelines, tools and policy advice to facilitate the process. The knowledge gains obtained by different project groups within the GlobE-Wetlands project shaped the design of the agronomic experiments and guided the choice of treatments and their application in this thesis.

In Kilombero, smallholder farmers produce rainfed lowland rice mainly in floodplain environments that are characterised by low soil nitrogen contents of the predominant Fluvisols and highly variable hydrological conditions, resulting in low yields and large yield variations. This thesis's studies were designed to compare farmers’ management practices, evaluate the effects of alternative management options on lowland rice performance, and define key contributing factors towards improved site-specific management. Field experiments were carried out near Ifakara, Tanzania, in three hydrological zones of Kilombero floodplain, namely the potentially drought-prone fringe, the favourable middle and the submergence-prone center positions over four years. Treatments on varying land, water and fertilizer management were implemented in researcher-managed plots, following hierarchical yield gap procedures.

Grain yields of rice (averaged over the four treatments) were higher in the fringe (6.5 t ha^{-1}) and the middle (5.7 t ha^{-1}) than in the center positions (4.6 t ha^{-1}). Farmers’ practice with no field bunding and land levelling and no fertilizer application resulted in the lowest yield (3.0 t ha^{-1}) and highest yield variability, with an adjusted coefficient of variation of up to 91% between years and positions. Simple soil and water management such as land levelling and the building of water-retaining field bunds significantly increased rice grain yields beyond farmers’ practice in the fringe and middle positions, where grain yields were generally higher than in the submergence-prone center position. Also, yield variability and hence the production risks were highest in the center and lowest in the fringe positions.

Depending on the position within the floodplain, organic treatments increased rice grain yields by >60%. Sole green or farmyard manure applications had similar effects on grain yield. In contrast, a combination of green and farmyard manure led to a significant increase in grain yield beyond both the control and sole application of organic amendments. Despite partial N balances being mostly negative, we observed positive residual effects on the non-amended rice in the fourth year of the study. Manure applications significantly increase soil C and N contents, hence enhancing soil fertility and increasing rice grain yields.

On average across years and positions, the potential, attainable, and farmers' actual yields were 11.5, 8.5, and 2.8 t ha^{-1}, respectively. Most management options tested contributed substantially to closing sizeable prevailing yield gaps. Thus, simple field bunds combined with land levelling closed up to 35% of the exploitable yield gap. Mineral N and organic amendments contributed up to 60% of the potential yield. Combinations of improved land, water management, mineral N application closed up to 80% of the exploitable yield gap. Mineral N tended to be more effective in closing the yield gap than green or farmyard manure. While fertilizer strategies improved soil fertility and reduced yield gaps, their relative benefits showed a high site-and system-specificity. Thus, this thesis provides insights on the rice performance at different hydrological positions and in different years, highlighting the potential for a sustainable increase in rice yield in highly variable floodplain wetlands. Combined with recommendations from other groups of the Wetlands consortium, these findings contribute to guiding policy formulation and agronomic recommendations for Kilombero floodplain, and possibly beyond, to environments with similar climatic, edaphic and socio-economic conditions.

Keywords: *Agronomy, Farmyard manure; Green manure,* N_2*-fixation, Oryza sativa, Wetlands, Yield gaps*

Kurzfassung

Im Afrika südlich der Sahara trägt die Landwirtschaft mit bis zu 50% zum BIP bei. Der Anstieg der landwirtschaftlichen Produktion in der Region ist überwiegend auf die Ausweitung der Fläche und nicht auf die Verbesserung der Produktivität pro Einheit zurückzuführen. In der Vergangenheit erfolgte der Anbau von Kulturpflanzen vorwiegend im Trockenfeldbau. Mit Klimawandel und steigendem Bevölkerungswachstum dehnt sich der Anbau jedoch zunehmend in Feuchtgebiete aus. Mit längeren Perioden der Wasserverfügbarkeit und relativ fruchtbaren Böden eröffnen Feuchtgebiete ein großes Potenzial für die Ausweitung und Intensivierung der landwirtschaftlichen Erzeugung und können so zur Ernährungssicherheit beitragen.

Die Kilombero-Überflutungsebene, eines der größten Reisanbaugebiete Tansanias, stand im Mittelpunkt des vom BMBF-geförderten Projekts "GlobE-Wetlands". Das Projekt untersuchte die Möglichkeiten einer Umwandlung von Feuchtgebieten in landwirtschaftliche Nutzflächen und deren zukünftige Bedeutung als mögliche Kornkammer Ostafrikas. Hierfür wurden empirische und Modell-gestütze Untersuchungen durchgeführt und wissenschaftlich fundierte Leitlinien und Instrumente für die Politikberatung entwickelt. Die von verschiedenen Gruppen im Rahmen des GlobE-Wetlands Projektes gewonnenen Erkenntnisse flossen in die Gestaltung der agronomischen Experimente ein und leiteten die Wahl der Behandlungen und deren Anwendung im Rahmen der vorliegenden Arbeit.

Kleinbauern in Ostafrika produzieren Nassreis im Regenfeldbau vor allem in den großen Überschwemmungsgebieten der Region. Diese zeichnen sich durch niedrige Stickstoffgehalte der vorherrschenden Fluvisole und stark schwankende hydrologische Bedingungen aus, die zu niedrigen Erträgen und großen Ertragsschwankungen führen. Die vorliegenden Studien verglichen die Bewirtschaftungsweisen der Landwirte, bewerteten die Auswirkungen alternativer Praktiken auf Reiserträge, und analysieren Schlüsselfaktoren, welche zu einer standortspezifischen Bewirtschaftung im Hinblick auf künftige Ertragssteigerungen beitragen. Die Untersuchungen erfolgten in der Nähe der Stadt Ifakara und wurden über einen Zeitraum von vier Jahren in drei hydrologischen Zonen der Kilombero Überschwemmungsebene durchgeführt (potenziell dürregefährdete Randgebiete, günstige mittlere und überflutungsgefährdete Zentralpositionen).

Die Kornerträge von Reis (gemittelt über die vier Behandlungen) waren in den Randbereichen (6,5 t/ha) und in der Mitte (5,7 t/ha) höher als in den zentralen Positionen (4,6 t/ha). Die übliche Praxis der Landwirte (keine Eindeichung, keine Düngereinsatz) führte zu den niedrigsten Erträgen (3,0 t/ha) und der höchsten Ertragsvariabilität, mit einem angepassten Variationskoeffizienten von bis zu 91% zwischen Jahren und Positionen.

Einfaches Boden- und Wassermanagement, wie die Nivellierung des Bodens und der Bau von wasserrückhaltenden Felddeichen, steigerte die Erträge deutlich, besonders in den Rand- und Mittelpositionen. Auch die Ertragsvariabilität und damit die Produktionsrisiken waren am höchsten im Zentrum and am geringsten in den Randpositionen der Überstauungsebene.

Abhängig von der Lage der Felder innerhalb der Überschwemmungsebene erhöhte organische Düngung die Reiskornerträge um >60%. Die Einarbeitung von Gründünger und die Ausbringung von Stallmist hatte vergleichbare Effekte auf den Kornertrag, während eine Kombination beider Dünger den Kornertrag gegenüber der ungedüngten Kontrollvariante signifikant erhöhte. Obwohl die partiellen N-Bilanzen meist negativ waren, beobachteten wir bei organischer Düngung positive Effekte auf den Ertrag einer ungedüngten Reiskultur. So erhöhten drei Jahre kontinuierlicher organischer Düngung signifikant die C- und N-Gehalte des Bodens, was mittelfristig die Bodenfruchtbarkeit verbesserte und sich in deutlich höheren Erträgen im vierten Untersuchungsjahr niederschlug.

Im Durchschnitt der Jahre und Positionen, lag der potentielle (simulierte), der erzielbare und der tatsächliche Ertrag der Landwirte bei 11,5, 8,5 und 2,8 t per ha. Die meisten getesteten Bewirtschaftungsoptionen trugen wesentlich zur Schließung der großen bestehenden Ertragslücken bei. So konnte durch einfache Feldanpflanzungen in Kombination mit einer Nivellierung des Bodens bis zu 35% der nutzbaren Ertragslücke geschlossen werden. Mineralische N und organische Düngerapplikationen trugen mit bis zu 60% zum potenziellen Ertrag bei. Eine Kombination aus verbessertem Land- und Wassermanagement sowie einer mineralischen N-Düngung vermochte 80% der nutzbaren Ertragslücke zu schließen. Insgesamt war mineralischer N wirksamer als Gründünger oder Stallmist. Während beide Düngungsvarianten ertragswirksam waren, ergaben sich deutliche standortspezifische Unterschiede in deren Wirksamkeit in Abhängigkeit der Jahre (Niederschlagsmenge) und der Feldpositionen (Wasserverfügbarkeit).

Diese Arbeit gibt Einblicke in die Ertragsleistung von Reis an verschiedenen hydrologischen Positionen und in unterschiedlichn Jahren innerhalb der Überschwemmungsebene und unterstreicht das hohe Potential einer system- und standortspezifischen Landwirtschaft für eine nachhaltige Intensivierung der Reisproduktion unter solchen hydrologisch hochgradig variablen Umweltbedingungen. Kombiniert mit Ergebnissen anderer Arbeitsgruppen im "Wetlands" Konsortium tragen die hier gewonnenen Erkenntnisse zur Formulierung von Nutzungsempfehlungen und zur Politikberatung in Kilombero und an anderen vergeichbaren Standorten der Region bei.

Schlüsselwörter: *Agronomie, Ertragslücke, Feuchtgebiete, Gründüngung,* N_2-*Fixierung, Oryza sativa, Stallmist;*

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a.s.l.	Above sea level
aCV	Adjusted coefficient of variation
AEN	Agronomic nitrogen use efficiency
ANCA-SL	Automated nitrogen carbon analyser - solids and liquids
ANOVA	Analysis of variance
APSIM	Agricultural Production Systems sIMulator
ARI	Agriculture research institute
BMBF	Federal Ministry of Education and Research
CV	Coefficient of variation
FAO	Food and agricultural organisation
FKZ	Funding number
FYM	Farmyard manure
GIS	Geographic information system
GM	Green manure
GYGA	Global yield gap atlas
HSD	Honestly significant difference
ICP-OES	Inductively coupled plasma optical emission spectroscopy
IHI	Ifakara Health Institute
IRRI	International rice research institute
KATRIN	Kilombero Agricultural Training and Research Institute
MJ	Mega joule
MNRT	Ministry of Natural Resources and Tourism
N	Nitrogen
NUE	Nitrogen use efficiencies
ORYZA1	An eco-physiological model for irrigated rice production
ORYZA2000	Rice model integrates previous ORYZA1 and ORYZA-W
ORYZA-N	Simulation modules for potential and nitrogen limited rice production
ORYZA-W	Rice growth model for irrigated and rainfed environments.
P	Phosphorus
PEN	Physiological efficiency
Ramsar	Convention on wetlands of international importance especially as waterfowl habitat
RCBD	Randomized complete block design
REN	Crop recovery efficiency
SAGCOT	Southern agricultural growth corridor of Tanzania
SARO	Semi-aromatic rice
SDG	Sustainable development goals
SE	Standard error
SOC	Soil organic carbon
SPE	Sustainable productivity enhancement
SSA	sub-Saharan Africa
TARI	Tanzania Agriculture Research Institute
TXD	Tanzania cross Dakawa
UK	United Kingdom
WRB	World Reference Base
GY	Yield gap
YG_E	Exploitable yield gap
YG_T	Total yield gap

Chapter 1

This chapter presents the general introduction and motivation for the research.

General introduction

1.1 Background

Rice as a crop, stands out in its importance to human civilisation. Independently domesticated species, the Asian cultivar *Oryza sativa* L. ~10,000 years ago, and the African cultivar *Oryza glaberrima* L. ~3,000 years ago (Stein et al., 2018), have had an outstanding contribution to world food security (Wu et al., 2018). With more than half of the world's population depending on rice for subsistence (Maclean et al., 2013), it is crucial to ensure future rice production while protecting the environment. The United Nations (UN), estimate that the world population is expected to approach 10 billion in 2050. Until then, rice farmers will have to produce 25% more rice, about 550 M tons per year to feed the growing global population (FAO, 2018a). There are many suggestions for achieving this goal, which include an expansion of the rice-growing area, a further intensification by increased use of external inputs, increasing the use efficiency of nutrients and water, raising the ceiling for yield potentials through new genotypes, and closing the large prevailing yield gap by adopting available management options. While playing some role in particular regions of few developed countries, rice farming is of greatest importance in most low- and lower-middle-income countries where it accounts for 19% of the total crop area harvested (Maclean et al., 2013). In most sub-Saharan African (SSA) countries, domestic rice production is not meeting the increasing demand, and these countries depend heavily upon imported rice from Asia. Yet SSA is considered to have vast land reserves for converting largely-unused wetlands into sites of rice production. This concerns the inland valleys of West Africa and in the East African highlands, and particularly the floodplains of East Africa, spanning from the Lake Tana basin in the South of Ethiopia and North of Kenya to the Limpopo River basin in South Africa (Finlayson et al., 2018).

Rice can grow in a wide range of environments under various climatic conditions and remains productive in situations where other staple crops such as cassava (*Manihot esculenta*), sweet potatoes (*Ipomea batatas* L.), and millet (*Eleusine coracana* L.) may fail (Seck et al., 2012). In SSA, rainfed upland and lowlands are the predominant rice-growing environment, unlike in Asia, where 55% of rice is grown under irrigation (Devkota et al., 2019). From the almost 12 M ha of land under rice cultivation in SSA in 2018 (FAO, 2018b), about 40% was in upland systems, contributing 19% to the total rice production. Rainfed lowland systems contributed 48%, and irrigated systems covering >8% of the rice-growing area (Seck et al., 2010). In lowland environments, small to moderate topographic differences can significantly affect water availability and soil fertility. Also, unpredictable rainfall patterns usually result in field conditions that are either too dry or too wet. These conditions make effective management of good agricultural practices difficult. Delaying or not applying such practices may lead to large yield losses.

1.2 Rice in East Africa

Rice has been grown in many East African countries for more than 500 years. However, it has only been in the last four decades that consumption has increased significantly. Many of the rice varieties grown in East Africa are of *Oryza sativa* L. species. They have medium to long grains that are translucent and not sticky when cooked. Their aroma is considered an important trait by consumers (Custodio et al., 2019). In most East African countries, rice was traditionally eaten only on special occasions, while today, rice is a regular part of the daily diet in most homesteads. Urbanisation, changing consumer preferences and employment of women in the services sector have been fuelling this change in dietary lifestyle (Lazaro et al., 2017).

In addition, the ease of preparation and storage of rice are accelerating factors towards increased rice consumption. In stark contrast to this fast-growing demand for rice, stands the fact that rice yields in East Africa are still very low compared to global averages. Exacerbated by the 2007/8 food crisis, African governments have directed their efforts to increase food production. Thus, in 1998, combined rice production in Burundi, Kenya, Rwanda, Tanzania, and Uganda amounted to 9.6 Mt, and almost doubled to 18.8 Mt by 2018. However, during this same period, the average rice yield increased by <22% from 1.3 to 1.5 t ha^{-1}, while the production area increased by >62% from 7.3 to 11.9 M ha (FAO, 2018b). Hence, rice production increases were, in most instances, not related to sustainable intensification of production but rather the result of an expansion of the cultivated area. The over-use and misuse of the upland regions and concomitant declines in resource base quality and yield have further accelerated the reported and wide-observed recent shift of food crop production towards wetland sites (Thorslund et al., 2017).

Wetlands are ecosystems where the water table is near or above the soil surface, either permanently or seasonally. The wet or submergence periods are long enough to induce and promote particular soil types and vegetation formations usually associated with damp or anaerobic environments. In addition to the provision of water and biodiversity support, wetlands provide a wide range of ecosystem services and multiple functions of great social, economic and environmental values and benefits for humankind (Sakané et al., 2011). Wetlands are abundant and potentially highly productive and are among the last remaining and largely untapped land resources for increasing food production in Africa. Fertile soils and a sustained and prolonged water availability make wetlands preferred ecosystems for expanding and intensifying agricultural production, and in East Africa specifically for growing lowland rice. Until the mid-1980s, most wetlands remained unused.

However, for the past four decades, mounting pressure on wetlands due to demographic growth and emerging shortages of suitable upland areas have accelerated the conversion of new wetlands into sites of agricultural (mainly food crop) production. Wetland types with potential for crop production consist mainly of lake basins, inland valleys and alluvial floodplains along rivers. The floodplain wetlands are of particular relevance for both sedentary and nomadic ruminant production systems (Sakané et al., 2011). They constitute by far the largest share of wetlands along the eastern coast of the African continent. Their large size and high abundance in the region, have made floodplains a focus for agricultural development, however with minimal impacts on yield to date. Thus, it appears a priority requirement to increase rice yields, close the large rice production gaps, and contribute further research on wetlands' distribution, uses production potentials, and on their likely or required transformation in space and time.

1.3 Rice in Tanzania

Tanzania is the largest rice producer and consumer in East Africa. Rice is one of the strategic cereal crops for the country's food security and ranks third after maize (*Zea mays* L.) and cassava (*Manihot esculenta* Crantz). In 2018, rice was cultivated on 6% of the 21 M ha suitable for growing rice with a total production of 2 M tons of milled rice (FAO, 2018b). About 60% of Tanzanians eat rice at per capita consumption of >23 kg. In the early 2000s, the Tanzanian government formulated the vision to develop a self-sustaining rice sector that can contribute to poverty reduction and rice self-sufficiency by 2025 (van Oort et al., 2015). By 2009, the establishment of the national policy *Kilimo Kwanza"* ('agriculture first') was undertaken to commercialise and modernize agriculture in the country. In support of the *Kilimo Kwanza* resolution, the Southern Agricultural Growth Corridor of Tanzania (SAGCOT) was established in 2010 as the first major program under this new policy (Milder et al., 2013). SAGCOT follows a public-private partnership strategy aimed at facilitating investors, local organisations and donors for agricultural development, and related infrastructure (Milder et al., 2013). The corridor stretches from the Tanzania port in Dar es Salaam to Malawi and Zambia along the existing road and train infrastructure. One of the three priority areas for agricultural intensification within the SAGCOT initiative comprises the Kilombero floodplain (NRGF, 2017).

Kilombero floodplain is Tanzania's largest seasonal wetland, covering a catchment area of 40,000 km^2 (Figure 1). The surrounding mountains and highlands are important catchment areas crucial to the hydrology of the wetland. The floodplain is an intact natural wetland ecosystem comprising a myriad of rivers. These make up the largest seasonally freshwater lowland in the region, covering approximately 7,000 km^2. The Kilombero River system regulates the flow of the Rufiji River and is an important source of nutrients and sediments for downstream (Wilson et al., 2017).

In 2002, the Tanzanian government designated Kilombero floodplain as a wetland of international importance under the Ramsar Convention on Wetlands (Wilson et al., 2017), committing to conserve and promote the wise use of the floodplain for sustainable development. While the Ministry of Natural Resources and Tourism (MNRT) is responsible for the implementation of the Ramsar convention guidelines (Materu et al., 2018), the Ministry of Agriculture is responsible for implementing land use and agricultural intensification. Reconciling intensified management with conservation is challenging, given conflicting interests of the concerned ministries on the one hand, and in the face of complex social dynamics, growing demands for access to land, and weak implementation of policies on the other hand (Alavaisha et al., 2019; Leemhuis et al., 2017).

The population in the floodplain is heavily dependent on its natural resources. The floodplain serves as a source of water for farming, livestock, fishing and domestic use. The main cash crops grown include rice predominantly, but also maize, sweet potatoes (*Ipomea batatas* L.), and cowpea (*Vigna unguiculata* L.), mainly cultivated as flood recession crops during the early dry season, while industrial crops include sugarcane (*Saccharum officinarum* L.) and teak (*Tectona grandis* L.) (Balama et al., 2016). However, the resource base within the floodplain is under growing pressure due to the increasing population of both pastoral, agro-pastoral and crop farming communities.

1.4 Motivation and Hypothesis

Little is known about the effects of soil and fertilizer management practices on rice performance attributes, on the prevailing large yield gap and on the variability of yields in hydrologically-variable floodplain environments of East Africa. Although the focal interest in developing and using these environments for large-scale crop production predates colonial times, no substantial increase in rice yields has materialized to date. One reason is the limited research on the attributes and functioning of floodplain environments in East Africa and their specific crop production problems. Thus, the response of improved “modern” rice genotypes to, but also the effectiveness of recommended management practices in the unique biophysical rainfed floodplain environments are still poorly understood. Consequently, many recommended production technologies such as bunding, levelling and N fertilizers application are rarely adopted by farmers and may not be suitable for the diverse hydro-edaphic situations and their large spatio-temporal dynamics. Thus, floodplains show distinct spatial units related to the central river's distance, comprising potentially drought-prone fringe and submergence-prone center positions with each specific soil attributes. Also, each spatial position is subjected to distinct hydrological dynamics both between years and within a season.

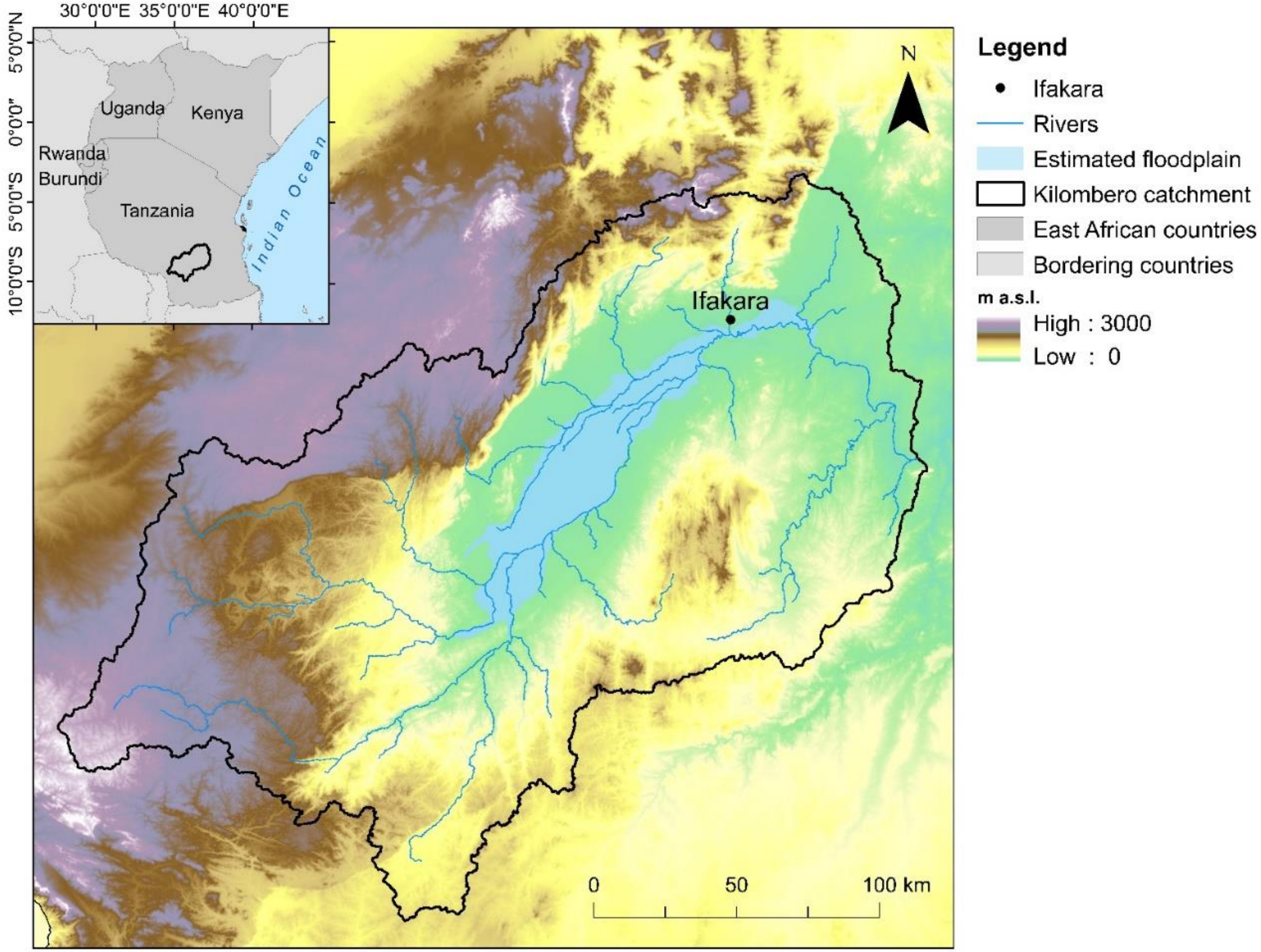

Figure 1. Location of the Kilombero catchment (black line) and floodplain (green and blue areas) in Tanzania.

There is a need to disentangle these spatio-temporal variations in view of clearly defining niches, targeting promising interventions and agronomic practices to specific biophysical conditions and specific production system types, such as low-input smallholders and higher-input large-scale rice farmers. Therefore, we hypothesize that;

i. Rice productivity and its variability are affected by the interaction between management practices and hydrological positioning.
ii. Mineral and organic amendments can improve rice grain yields; however, their effectiveness will also vary by position.
iii. Yield gap analysis can site-specifically differentiate the benefits of agronomic interventions and help formulate management recommendations.

1.5 Objectives

This study aimed to understand the differentiated effects of existing rice management practices, while spatio-temporally targeting agronomic management options may counteract key rice production constraints in floodplain environments. These management options are part of and contribute to the Sustainable Productivity Enhancement (SPE) program of the Africa Rice Center (AfricaRice) in view of developing sustainable lowland rice-based systems and thus contributing specifically to the Sustainable Development Goal (SDG) 2 (Zero hunger), the success of which is measured among others through indicator 2.4.1 "Proportion of agricultural area under productive and sustainable agriculture." Thus, we analysed actual and potential rice yields, while quantifying site-specifically limiting factors to guide future intervention strategies in the Kilombero floodplain, addressing the following objectives:

i. Assess land and water management effects on grain yield and yield variability of rainfed lowland rice,
ii. Evaluate the effect of mineral fertilizers and organic amendments on the productivity of rainfed lowland rice,
iii. Quantify rice yield gaps and yield-determining factors in smallholder systems.

1.6 Project framework

The study was implemented within the Food Security funding initiative Globale Ernährung (GlobE) of the German Federal Ministry of Education and Research - BMBF to develop innovative, regionally adapted approaches for sustainable food production the value chain. The activities presented here were conducted as part of the project "*Wetlands in East Africa - Reconciling future food production with environmental protection*" (https://www.wetlands-africa.uni-bonn.de) (FKZ: 031A250A-H). The Wetlands project's overall aim was to assess the potential for transforming wetland areas into the food basket of East Africa while providing science-based guidelines, tools, and policy advice that facilitate an agricultural intensification process sustainably. The project had four primary goals: i) understanding the wetland system, ii) optimising the wetland use, iii) integrating data and assessing scenarios, and iv) extrapolating and formulating recommendations at different scales. The goals were addressed at different spatial and temporal scales through collaborative research in the German–Africa research consortium.

The project's intervention sites constituted national priority areas and reflected the prevailing diversity of wetlands attributes and use regarding gradients of altitude, population, pressure and land-use intensity. The project's framework involved ascertaining if and how wetlands were going to become the food basket of East Africa. The project defined five interdisciplinary research clusters complementary in nature while building on each other (Figure 2). These clusters aimed at; a) analysing the current wetland use systems and comparing the major use strategies for regional food security (status quo), b) identifying, assessing and spatial targeting of innovative land use options at different scales and organisational levels (management), c) developing integrated tools for assessing/ evaluating use options under regional scenarios of global change (integration), d) spatio-temporal extrapolation, guidance and planning for wetland use (extrapolation), and e) implementation of the training and other capacity-building measures (capacity building).

The research presented within this thesis's frame contributed primarily to the work clusters (i) / b. Management options*; operationalized by a disciplinary interplay of agricultural production (this thesis), water and soil management, agricultural economics, and crop modelling. The agronomic studies aimed to provide an in-depth evaluation of management options' effects on production attributes. Also, on other performance indicators while defining target environments or production niches for likely future extrapolation domains.

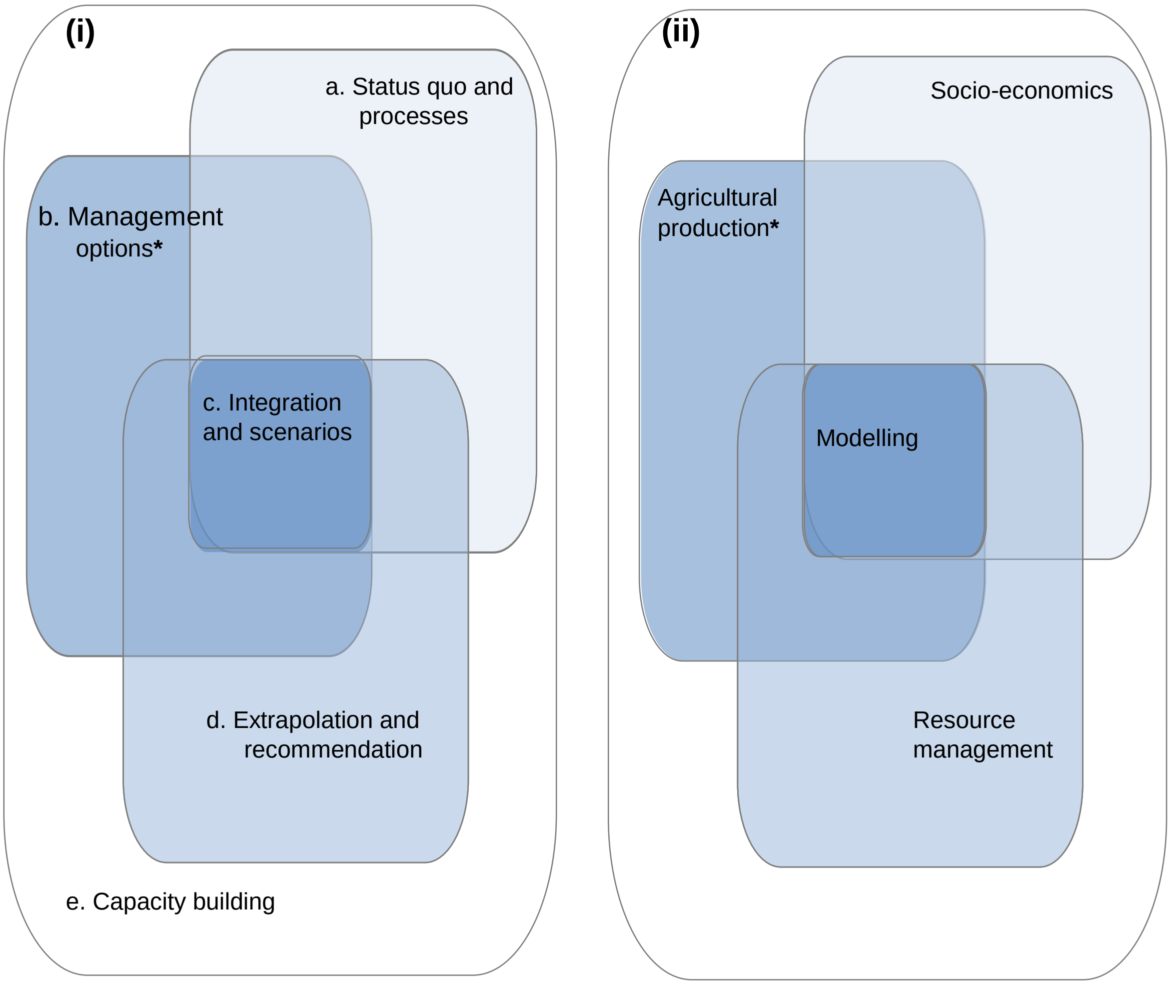

Figure 2. A conceptualisation of linkages between (i) work clusters and (ii) disciplinary areas for the GlobE project “Wetlands in East Africa - reconciling future food production with environmental protection”. * represents the cluster and disciplinary area under which the thesis is embedded.

1.7 Structure of the thesis

The doctoral thesis is structured in the cumulative style, consisting of five chapters. Following a general introduction (chapter 1), chapters 2, 3 and 4 present the empirical research findings and have all been published in the peer-reviewed scientific journal "*Agronomy*". These result chapters contain a section on abstract, introduction, results, discussion, and conclusion. As the three result chapters constitute the published papers, certain redundancies, especially in describing the study sites and the methodology used, were unavoidable. In the section on "*Site and management effects on grain yield and yield variability of rainfed lowland rice in the Kilombero Floodplain of Tanzania*" (chapter 2), we investigated the hydro-edaphic conditions, while evaluating the effects of field bunding and levelling and of mineral N-fertilizer application on rice yields. We assess the fertilizer N use efficiency, grain yields, yield variability and their interactions. In the section on "*Effect of organic amendments on the productivity of rainfed lowland rice in the Kilombero Floodplain of Tanzania*" (chapter 3), we focus on the direct and residual effects of alternative (organic) fertilizer sources (farmyard manure, green manures, others) on rice grain yield, soil properties and partial N balances. Finally, the section on "*Rice yield gaps in smallholder systems of the Kilombero Floodplain in Tanzania*" (chapter 4), determined actual and potential rice yields and their variabilities in space and time, using this information to quantify yield gaps while identifying the causes of prevailing gaps by applying available land and fertiliser management options at different hydrological positions. Chapter 5 presents the general discussion and concluding remarks referring to each of the initially stated research objectives, and formulating implications for future research and policy recommendations. The thesis ends with the listing of the cited references and appendix.

Chapter 2

This chapter has been published as: Kwesiga, J.; Grotelüschen, K.; Neuhoff, D.; Senthilkumar, K.; Döring, T.F.; Becker, M. Site and Management Effects on Grain Yield and Yield Variability of Rainfed Lowland Rice in the Kilombero Floodplain of Tanzania. Agronomy 2019, 9, 632. https://doi.org/1.3390/agronomy9100632

Site and management effects on grain yield and yield variability of rainfed lowland rice in the Kilombero floodplain of Tanzania

Abstract

In East Africa, smallholder farmers produce rainfed lowland rice mainly in floodplains. Low nitrogen contents of the predominant Fluvisols and highly variable hydrological conditions result in low yields and large yield variations, and hence, result in high production risks for farmers. We investigated crop management strategies aimed at increasing yield and reducing yield variability. The field trials were carried out in the Kilombero floodplain near Ifakara in Tanzania, in three hydrological zones (potentially drought-prone fringe, favourable middle and submergence-prone center positions) over three years. The study compared farmers' management practices (no field levelling and bunding, no fertilizer input), with the effect of bunding and levelling alone, or in combination with mineral N use at 0 (bunding), 60 (recommended rate) and 120 kg + 60 kg PK ha^{-1} (attainable yield). Rice mean grain yields (averaged over the four treatments) were higher in the fringe (6.5 t ha^{-1}) and the middle (5.7 t ha^{-1}) than in the center positions (4.6 t ha^{-1}). Farmers' practice resulted in lowest yield (3.0 t ha^{-1}) and highest yield variability, with an adjusted coefficient of variation (aCV) of up to 91% between fields, years and positions. Simple bunding of the plots and field levelling increased yields by 40% above farmers' practice, particularly in the fringe and middle positions, while reducing yield variation (aCV of 36–61%). Mineral N application resulted in the highest yields (7.0 t ha^{-1}) and further reduced yield variation (aCV of 14–27%). However, only in bunded fields of the floodplain fringe rice could benefit from N application beyond 60 kg ha^{-1}, while mineral N use efficiency was lower in middle and center positions. Improved crop management options are most beneficial in floodplain fringe positions, where they can increase yields and reduce production risks. Due to low yield, high production risks and poor responsiveness to management interventions, the center may be taken out of rice production and could be considered for future use as protection zones.

2.1 Introduction

Rice production in East Africa has significantly increased over the past decades, particularly in Ethiopia, Kenya, Madagascar, Malawi, Rwanda, Somalia, South Sudan and Tanzania (FAO, 2018b). Income increases in urban areas favour the consumption of rice compared to other staple foods (Saito et al., 2015), and this is expected to increase further (UN, 2014). In Tanzania, urbanization and the rise of a middle-income class are likely to shift the main staple from maize to rice (Lazaro et al., 2017). Rice production, however, is not keeping pace with such demand developments (FAO, 2015; Touré et al., 2009). Despite its high rice self-sufficiency of 83% (van Oort et al., 2017), rice imports are still required to meet the gap between demand and domestic production (Lazaro et al., 2017; van Oort et al., 2017). Thus, rice imports of 240,000 tonnes (<half of the countries' rice exports) covered 12% of Tanzania's rice consumption in 2016 (FAO, 2018b). At the same time, it is estimated that only <4% of the land area suitable for rice production is currently cultivated (Seck et al., 2010), providing abundant opportunities for the expansion of rice areas.

In Tanzania, lowland rice is produced mainly in floodplain environments. A feature of floodplains in general and of Kilombero (one of the largest rice producing areas of Tanzania) in particular is their diverse hydrological conditions. Areas located in proximity to the central river are flooded by the spill-over water from the river (ex-situ rainfall in the upper watershed), while in-situ rainfall and subsurface interflow water from adjacent slopes determine the hydrology in the fringe positions of the floodplain (Näschen et al., 2018). The middle positions are variably affected by both hydrological processes (Gabiri et al., 2018). The soils are relatively low in C and N contents and usually fine-textured close to the river (Daniel et al., 2017), resulting in a pattern of hydrological and edaphic situations across the floodplain that can roughly be differentiated as submergence-prone center, favourable middle and potentially drought-prone fringe positions that also differ in their suitability for rice cultivation.

Rice grain yields in Kilombero are relatively low (typically <2 t ha^{-1}) and highly variable, with the hydro-edaphic differences highlighted, and with poor crop, soil and water management practices by farmers being the main culprits (Mombo et al., 2013). A low soil N content combined with low application rates of mineral fertilizers or organic amendments result in wide-spread N deficiency in rice. Additionally, low and variable productivity may be exacerbated by the use of landraces or traditional genotypes with a low yield potential (1.0–2.0 t ha^{-1}) and reduced responsiveness to applied inorganic fertilizers (Senthilkumar et al., 2018).

There is substantial knowledge on the effects of seasonal soil N dynamics on lowland rice (Asante et al., 2017; Becker and Johnson, 2001), on the effects and use efficiency of applied mineral N along valley toposequence (Fageria et al., 2014), and on interactions between N use efficiency and S application in a floodplain environment in West Africa (Tsujimoto et al., 2017). However, little is known about the effects of soil and N management practices on rice performance attributes and yield stability in hydrologically-variable floodplain environments of East Africa. The present study investigated the agronomic effects of flooding regimes in different positions and the role of land and N fertilizer management on yield and yield variability of the Kilombero floodplain. We hypothesize that rice productivity and its variability are affected by the interaction between management practices and the dominant soil attributes and hydrological positions in the floodplain. Our objectives were to: i) assess the effect of the hydro-edaphic conditions (position in the floodplain) on rice yields, ii) evaluate the effects of field bunding and levelling and of N-fertilizer application on rice yields and their variability and iii) assess interactions of management practices and hydrological positions on N use and use efficiency.

2.2 Materials and methods

2.2.1 Geographical location

Experiments were carried out in the Kilombero floodplain, which is located between 7.65°–10.02° S latitude and 34.56°−37.79° E longitudes (Figure 3) on farmers' fields. The Kilombero floodplain receives about 1200 to 1400 mm of annual rainfall in a bi-modal distribution pattern (Koutsouris et al., 2016). Some 80−90% of the annual rainfall occurs between December and April, while the period from June through September is relatively dry with typical monthly precipitation <10 mm. Climate data were obtained from a weather station installed at the Ifakara Health Institute (IHI) research station, about 5 km West of Ifakara town (Figure 3).

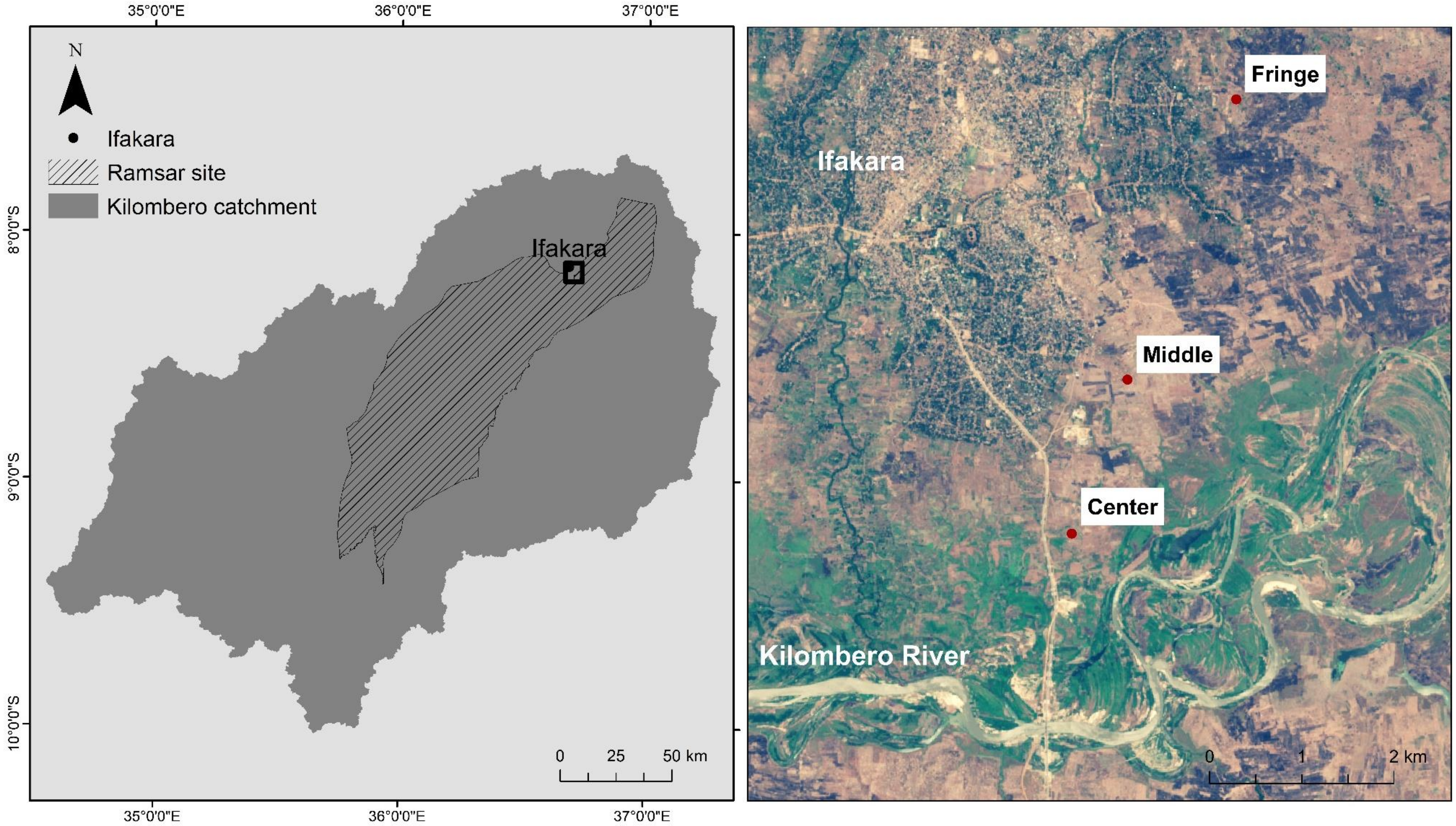

Figure 3. Location of the experimental sites in the Kilombero floodplain. The fringe position is furthest from Kilombero River, while the center position is closely located near the river.

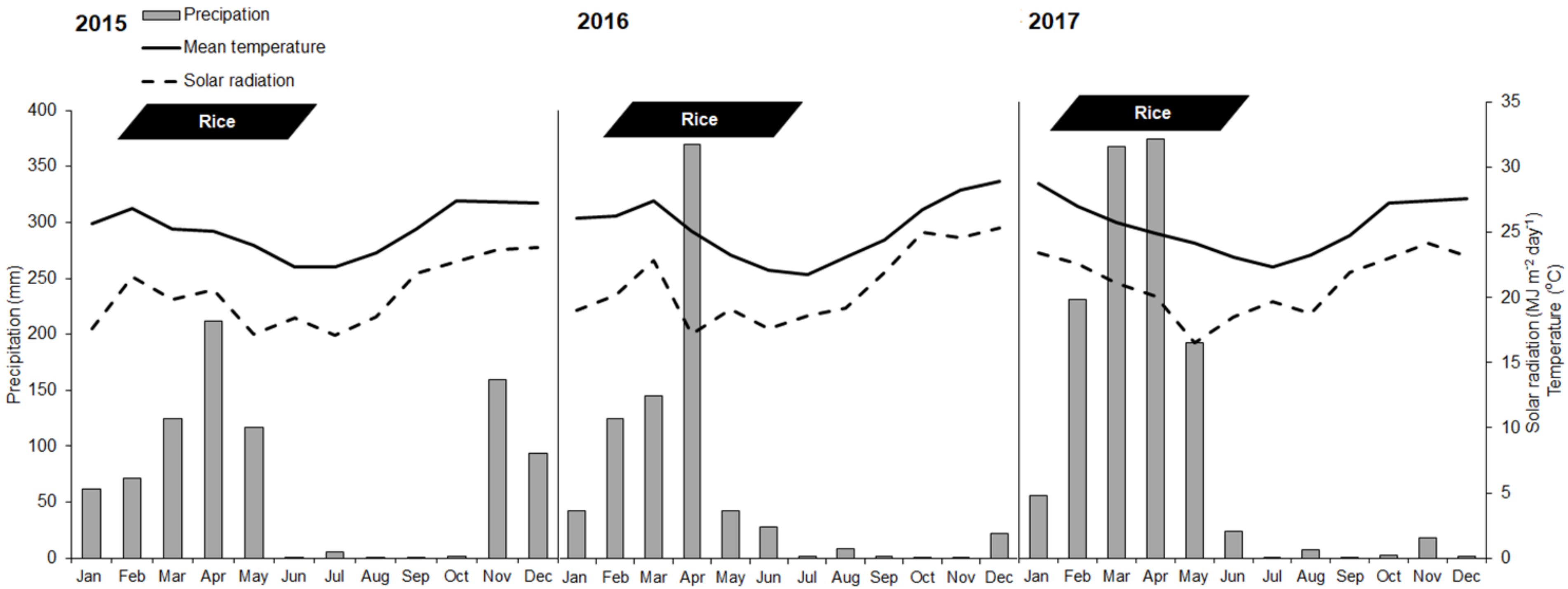

Figure 4. Meteorological data for Ifakara (261 m a.s.l.) for 2015, 2016 and 2017, showing monthly total rainfall (solid bars), average daily mean temperature (solid line) and average daily total solar radiation (dotted line). Rice was transplanted from late February to early March and harvested between early and late June with rainfall of 453 mm, 582 mm and 941 mm during the growing period from March to May (2015, 2016 and 2017, respectively).

2.2.2 Hydrological and edaphic characteristics

The areas representing the three hydrological positions had a slope of <0.01% and were selected based on inundation depth and duration relative to the river during the rainy season (Gabiri et al., 2018). The fields were located along a gradient between the areas adjacent to Kilombero River to the outer fringes of the floodplain (Figure 3). The distances between positions ranged from 2.2 km to 3.2 km, with the most low-lying position located at 1 km distance from the river (Table 1).

The rarely submerged and occasionally drought-prone field plots referred to as being located in the “fringe” position are located close to the village of Katindiuka at 255 m above sea level (a.s.l.) and at an elevation of 10 m above the mean water line of the river before the onset of the rainy season. The *in-sit*u rainfall, as well as water contribution by subsurface interflow from adjacent upland slopes, influence the hydrological regime at plot level, with plot water levels ranging from 0.5 to 31 cm for about 17 days.

The area close to the village of Kiyongwire is prone to extended periods of not less than 22 days of moderate soil submergence (3−74 cm above the soil surface). Located at an elevation of 249 m a.s.l. or 4 m above the mean water line. Soil water regimes in this “middle” position are influenced by in-situ rainfall as well as some spill-over from Kilombero River. The area close to the village of Kivukoni is located at an elevation of 247 m a.s.l. or 2 m above the water line and close to Kilombero River. Severe and extended soil submergence (> 28 days with up to > 100 cm above the soil surface) is contributed mainly by the spill-over of the river in this “center” position.

All soils were formed from fluvial sediments and are classified as Fluvisol according to the World Reference Base (FAO, 2014). Soil attributes differed between positions with coarse-textured soil and relatively low C and N contents characterizing the middle position, while fine-textured clay soils with higher C and N contents occurred in the center position (Table 1). Data are based on composite samples (five points sampled diagonally per plot and position) from the topsoil (0−20 cm depth) that were taken before the onset of the experiment in November 2014. Soil samples were air-dried and ground to be passed through a 2 mm sieve and analysed for soil physical and chemical properties.

Table 1. Selected characteristics of the different experimental sites and topsoils (0–20 cm) in the Kilombero floodplain.

Characteristic	Fringe	Middle	Center
Distance from river (km)	6.4	4.2	1.0
Cumulative evaporation (mm) ‡	843	713	786
Evapotranspiration (mm) ‡	1044	896	969
Ground water discharge (mm) ‡	220	196	109
Change in soil water storage (mm) ‡	120	233	263
Maximum flooding depth (m)	0.3	0.7	1.4
Flooding duration (days)	17	22	40
Soil texture	silt loam	silt loam	silt clay loam
Clay (%)	14.0	20.2	35.7
Silt (%)	58.2	60.1	52.1
Sand (%)	27.8	19.7	12.2
pH (H_2O)	6.0	5.8	4.9
Total C (g kg^{-1})	16.5	15.0	22.5
Total N (mg kg^{-1})	1.0	0.9	1.7
Available P (mg kg^{-1})	47.5	16.0	9.7
Available K (mg kg^{-1})	71.4	70.6	79.2
Bulk density (g m^{-3})	1.41	1.31	1.26

*Initial soil sampling conducted at the beginning of the experiment in 2014; available P and K extraction were done according to Mehlich-3 extraction. ‡data from (Gabiri et al., 2018).

2.2.3 Treatment application

The experiments were set up in field plot areas that had previously been cropped for >5 years with lowland rice and were located in the three hydrological positions. Before the establishment of the experiments, the fields were tilled using a tractor-driven disk plough and manually harrowed. Sixteen individual plots of 5 × 6 m, separated by bunds of 0.5 m width and 0.5 m height, were marked in each of the three hydrological positions. The experiment was conducted at the same sites and field plots in 2015, 2016 and 2017. The treatments were applied and arranged in a randomized complete block design (RCBD) including four treatments × four replications × three positions = 48 plots repeated over three years. Blocks were separated by a 1 m depth and 1 m wide trench. For the center position, only 32 plots could be considered due to complete crop failure resulting from prolonged submergence in 2015.

The four treatments included: (1) farmers' practice, i.e., no field bunding or levelling, no fertilizer application and one single hand-weeding at 20 days after transplanting, representing the traditional management with no external input use, (2) bunding, i.e., field bunding, manual puddling (> 20 cm), levelling and weeding at 20, 40 and 60 DAT, (3) 60 kg Urea-N (Urea, 46% N), i.e., treatment 2 + 60 kg Urea-N ha^{-1} with 75% applied basally and 25% at the panicle initiation stage and (4) 120 kg Urea-N + 60 kg PK, i.e., treatment 2 + 120kg N ha^{-1} split-applied, 60 kg of P (Single Super Phosphate) and K (KCl,) applied basally (Table 2). This treatment aimed at reaching the attainable yield level. To ensure ceteris paribus conditions, treatment (1) served as a control for treatment (2), which served as a control for treatments (3) and (4). All fertilizers were broadcast manually, and those applied basally were incorporated during puddling in the topsoil layer (0−20 cm). Choice of treatments was based on recommendations from AfricaRice (Senthilkumar et al., 2018).

Table 2. Treatment applied in three hydrological positions of Kilombero floodplain in 2015, 2016 and 2017.

No.	Treatment	Quantification	Details
1	Farmers practice	Yield gap baseline	No bunding, levelling, no mineral N, single weeding
2	Bunding	Yield gap due to bunding	Bunding, levelling, No mineral N, clean weeding
3	60 kg N	Yield gap due to N	Bunding, levelling, 60 kg urea- N $ha^{-1,}$ clean weeding
4	120 kg N+ 60 kg PK	Achievable yield in single crop system	Bunding, levelling, 120 kg N + 60 kg P+ 60 kg K + supplementary irrigation

Certified seeds of the locally-recommended high-yielding semi-dwarf 120-day lowland indica rice (Oryza sativa L.) variety SARO 5 (TXD 306) were obtained from the Kilombero Agricultural Training and Research Institute (KATRIN) now called Tanzania Agriculture Research Institute (TARI), Ifakara Center. Twenty-five-day-old seedlings were transplanted at 20 × 20 cm spacing into the water-saturated soil with two seedlings per hill, resulting in 25 hills m−2. Transplanting dates between positions varied by a maximum of three days, and between years by up to 3 weeks depending on the onset of the rains.

2.2.4 Measurements

Rice was harvested from 2 × 3 m areas in the center of each plot, and grain yield is reported adjusted to 14% grain moisture (IRRI, 2013). Total biomass, harvest index and yield parameters (tiller and panicle numbers per m^2, grains per panicle and 1000-grain weight) were assessed based on 12 hills per plot at physiological maturity. Only grains with a specific gravity ≥ 1.06 g cm^{-3} were considered filled grains and expressed as a percentage share of all spikelets per panicle (Zakaria et al., 2002). To determine biomass accumulation and crop N uptake, biomass samples were oven-dried at 60 °C to constant weight and ground in preparation for analysis by a C/N analyser (EURO-EA, Eurovector, Pavia, Italy).

The nitrogen use efficiencies (NUE) were calculated in terms of (1) partial factor productivity (PEPN) (kg grain yield kg^{-1} N applied), (2) agronomic N use efficiency (AEN) (kg grain increase kg^{-1} N applied), (3) crop recovery efficiency (REN) (kg N increase kg^{-1} N applied) and (4) physiological efficiency (PEN) efficiency (kg grain increase kg^{-1} N uptake) as follows.

$$PEPN = (YN / FN),$$

$$AEN = (YN - Y0) / FN,$$

$$PEN = (YN - Y0) / (UN - U0),$$

$$REN = (UN - U0) / FN,$$

whereby YN is crop yield with applied mineral N (kg ha^{-1}), FN refers to the amount of mineral fertilizer N (kg N), Y0 is the crop yield in the non-amended control treatment (kg ha^{-1}), UN refers to the total plant N uptake in aboveground biomass with applied mineral N and U0 to the plant N uptake in the non-amended control treatment (kg ha^{-1}) (Dobermann et al., 2008).

2.2.5 Statistical analyses

Before being analysed by ANOVA, data were tested for normality using the Shapiro-Wilk test and homogeneity of variance using the modified Levene's test (Brown and Forsythe, 1974). Descriptive statistics, including means and variances, were calculated for the main effects of management practices, over the years and for the three hydrological positions. A linear mixed model fit by Restricted Maximum Likelihood (ReML) and Satterthwaite`s method was used for the t-tests using R software 3.5.0

version. To select the most parsimonious model, we evaluated models by Akaike's Information Criterion (Burnham and Anderson, 2002). Where applicable, mean comparisons were performed using post-hoc tests (Tukey's HSD, $\alpha = 0.05$).

The yield variability for different combinations of hydrological position and treatment was measured using various approaches. First, we calculated the coefficient of variation ($CV = \sigma \mu^{-1} 100\%$, where σ is the standard deviation and μ the mean). Each CV contained data points from all years and all replicates, thereby combining spatial and temporal variation into a joint variable called 'environment'. This was done because farmers are restricted in the choice of the location where rice can be grown. Therefore, properties of the soil where rice is grown are partly a 'given' for farmers, similar to differences in climatic conditions between years. Replicates and positions are thus seen as representing the spatial component of the environment. Second, with the same data structure, a scale-adjusted coefficient of variation (aCV, also expressed as % of the mean) was calculated as a further measure of yield variability. The adjustment was made to account for potential scale effects that can result in underestimation of variability at high mean values; in particular, the aCV takes into account scaling effects that occur when the yield means are very different between cropping systems (Döring and Reckling, 2018). In such cases, i.e., when some cropping systems have overall low yields and others comparatively high yields, the large yield ranges between systems mean that the unadjusted CV is biased as it tends to be generally lower at high mean yields. This bias is rectified by the aCV.

A further complementary approach aimed at determining to which extent the factors "replicate" or "year" contributed to yield variability. Using the lme4 library in R, we employed a linear mixed model with year and replicate as random factors and hydrological position and treatment as a fixed factor to compare the relative contribution of replicate and year to the total variance.

Finally, the CV was calculated across all years for each replicate, to check whether yield variability was solely due to year effects. The average of CVs for the year, treatment and position combination were subsequently calculated across all replicates. The resulting values of $\overline{(CV)}$ were linearly correlated with the aCV via Pearson's correlation coefficient.

2.3 Results

2.3.1 Environmental characteristics

Analysis of initial soil samples revealed differences in the physico-chemical attributes between fringe, middle and center positions (Table 1). In general, lighter textured soils (sandy silt loam) and heavier textured soils (clay loam) characterized the middle and center positions, respectively. There were significant differences in soil pH (H2O) between the hydrological positions with the lowest (pH = 4.9) at the center and highest (pH = 6.0) in the fringe. Total C and N tended to be low but were higher in the center than in the fringe and middle positions. Available P content (Mehlich-3) was lower in center and middle than in fringe soils, but was always within the sufficiency range for lowland rice. Exchangeable soil K was high to very high, irrespective of the position (Table 1). A bi-modal distribution pattern separated into the short rains (November−January) and the long rains (March-May) characterized the rainfall pattern at the study site (Figure 4). Cumulative rainfall during the crop growth periods of rice were 453, 582 and 941 mm for 2015, 2016 and 2017, respectively. However, the rainfall periods were longer in 2015 and 2017, while rains ceased early in 2016. Extended periods of dry spells and low precipitation during the vegetative growth phase of rice were observed in 2016 and 2017. Moreover, in 2016, the onset of the rains was delayed by several weeks, affecting rice crops particularly in the in-situ rainfall-fed fringe and middle positions.

The flooding depth and flood duration increased from the fringe to the center positions. In the center position, severe soil submergence of up to 90 cm was observed during the late vegetative and the early reproductive growth stages in 2015 and 2016, and throughout the rice-growing period in 2017. No differences were observed in terms of the temperature ranges with maxima of 34−36 °C and minima of 16−17 °C in the three years of experimentation.

2.3.2 Grain yield and its variability

Overall, rice grain yield differed significantly across hydrological positions, years and management practices, ranging from 1.2 to 11.7 t ha^{-1} (Figure 5). The fringe position generally had the highest mean yield of 6.5 t ha^{-1} while lowest yields were recorded in the center position with 4.6 t ha^{-1} (Figure 5a). In 2015 we recorded the highest mean yield of 6.5 t ha^{-1}, followed by 2017 with 5.9 t ha^{-1} and 2016 with 5.1 t ha^{-1} (Figure 5b).

Regardless of year and position, farmers’ practice resulted in the lowest mean yield of 3.0 t ha^{-1} with a high yield variation (Figure 5c). Simple soil management by the construction of field bunds and land levelling increased the mean yield to 4.4 t ha^{-1}. With intensive management (bunding, levelling and the application of 60 or 120 kg N+PK ha^{-1}), grain yield varied from 7.0 t ha^{-1} to 8.8 t ha^{-1}. Figure 5c shows the variability of rice grain yields by treatment, applying mean values across hydrological positions and years. The yield variability of concern to a farmer, however, is the one within a given position where his/her field plot is located. Thus, yield responses and variabilities are further differentiated by hydrological positions (Figure 6).

Significant interactions of rice grain yields (Table 3) between hydrological positions and treatments can further substantiate the repeated trends. All treatments, apart from farmers practice, recorded a general increase in rice grain yield from the center to the fringe position. The lowest yields were observed in the middle position with farmers’ practices.

According to the mixed model, replicates and years contributed 4.9% and 18.7% to the total variance, respectively. Values of the aCV, which measured variability across years and replicates and within a hydrological position, were generally higher (median 38%) and showed a larger range (14−91%) than the $(\overline{CV})$ (median 16, range 7−28%), which accounts for variability across years only. However, the positive linear correlation between aCV and (CV) across positions and treatments with an r^2 of 0.78, suggests little effect of the method of calculation on the order of the observed yield variability.

In the absence of N application, yield variability was highest in the center with aCV of 91% ($(\overline{CV})$ = 23%), under farmers’ practice followed by 61% with bunding and levelling only ($(\overline{CV})$ = 28%). The application of fertilizers increased yields and reduced yield variability (aCV) to 27%, 20% and 14% for fringe, middle and center positions, respectively (11%, 9% and 8% for $(\overline{CV})$). The year × position interaction was significant for all yield components, while the position × management practices interactions were only significant for grain yield. Mostly, mean grain yields were highest in the fringe and lowest in center positions.

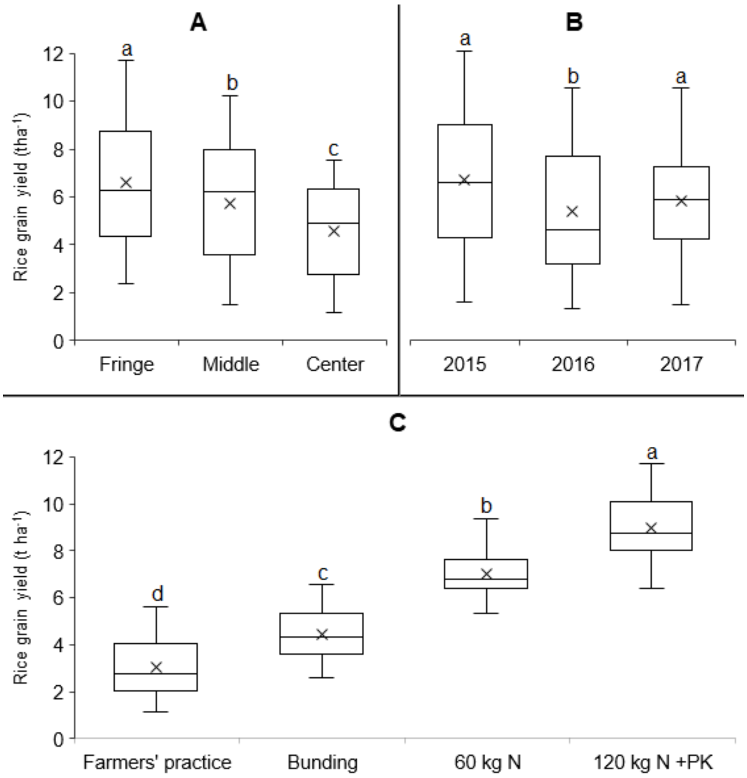

Figure 5. Source of grain yield variation of lowland rice due to (A) hydrological position, (B) year and (C) land and mineral N management with farmers practice as a control, X = arithmetic mean, = median. Different letters indicate significant differences by Tukey test at p ≤ 0.05.

Table 3. Analysis of variance (F values) of the effect of year, position and treatment on rice grain yield, panicles, harvest index, % filled grain, 1000 grain weight and dry biomass production.

Source of variation	Df	Grain ($t\ ha^{-1}$)	Panicles (m^{-2})	Harvest index	Filled grain (%)	1000 Grain weight (g)	Biomass ($t\ ha^{-1}$)
Year	2	18.48***	6.08**	10.87 ***	92.62***	30.04***	7.86**
Position	2	44.55***	55.48***	23.64**	1.59 ns	2.83 ns	4.14*
Rep (year X Position)	24	3.21***	2.87***	1.57 ns	1.17 ns	2.47**	2.41**
Year X position	3	0.84ns	9.16***	6.93***	8.38***	5.81**	2.14 ns
Treatment	3	291.8***	71.34***	9.73 ***	4.19**	23.94***	107.3***
Year X treatment	6	0.89 ns	1.29 ns	1.82 ns	2.7*	6.35***	1.02 ns
Position X treat	6	8.06***	0.91 ns	2.20 ns	0.25 ns	0.44 ns	5.24***
Year X position X treatment	9	0.39 ns	1.45 ns	3.15**	0.24 ns	3.341**	1.71 ns

***significant at $p \leq 0.001$, **significant at $p \leq 0.01$, *significant at $p \leq 0.05$, ns: not significant.

2.3.3 Management effects

Irrespective of the year or the hydrological position, the combination of mineral fertilizer (60 kg N) and bunding increased rice grain yield by 125% above farmers' practice and 60% over sole field bunding. Total N uptake (straw plus grain) at harvest ranged from 40 to 140 kg ha^{-1} (Figure 7). Field bunding increased the total N uptake of rice by >15 kg ha^{-1} over farmers' practice. Mineral N addition further stimulated total N uptake by 98 kg N ha^{-1} and 135 kg N ha^{-1} with the application of 60 kg and 120 kg mineral N + 60 PK ha^{-1}, respectively.

The hydrological positions resulted in significant differences in the partitioning of the total N uptake. The fringe position had the highest grain N uptake while the center exhibited the highest straw N uptake with recovery efficiencies ranging from 55 to 82% of the applied mineral N. In the center position, the recovery efficiency of applied N was highest with 60 kg N ha^{-1}. Increasing the mineral N application from 60 to 120 kg N reduced the partial factor productivity by 33, 39 and 43% in the fringe, middle and center positions, respectively.

The effect of position on the agronomic use efficiency of applied mineral N was significant only at an application rate of 120 kg N and ranged between 28 and 39 kg grain kg^{-1} N applied at the center and fringe positions, respectively (Figure 8). The effect of position on crop recovery efficiency was significant at 60 kg N with 80% at the center and 57% at the fringe positions.

On the other hand, the highest and lowest physiological efficiencies were observed in the fringe and center positions, respectively. Independent of management practice and years, the crop N uptake and utilization was generally higher in the fringe than in the center positions. While the center position showed a relatively high recovery efficiency of 70−80% of the applied N, its poor translocation into the grain leads to a low physiological N use efficiency of 40−44 kg kg^{-1} N absorbed.

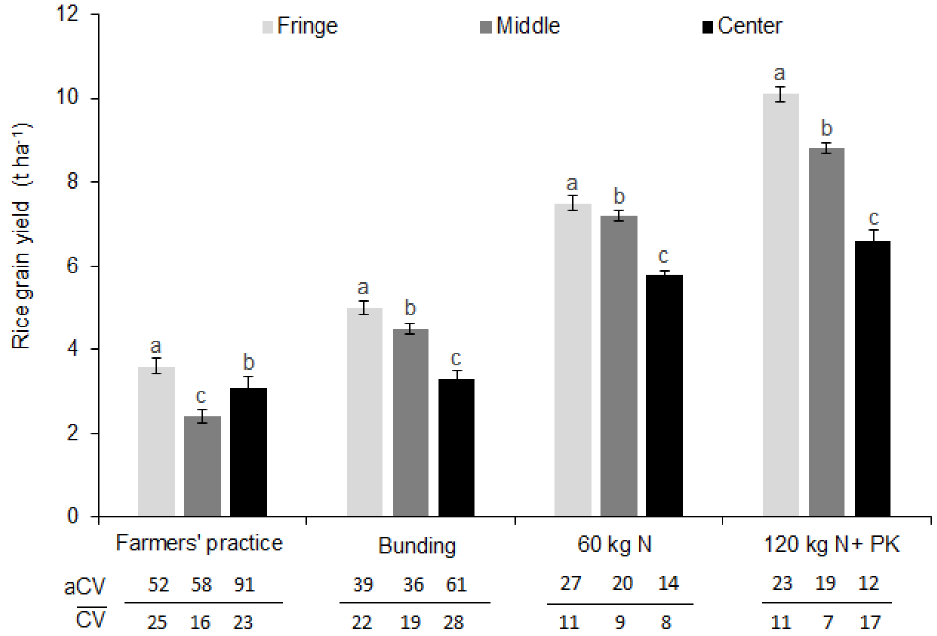

Figure 6. Effect of management practices on the grain yield (t ha^{-1} 86% dm) of lowland rice, differentiated by hydrological positions and their associated percentage adjusted coefficients of variation across years and replicates (aCV presented below the graph), and mean unadjusted coefficients of variations across years ((CV)̅) in Kilombero floodplain, Tanzania, 2015–2017. Different letters indicate significant differences by Tukey test at p ≤ 0.05 between position.

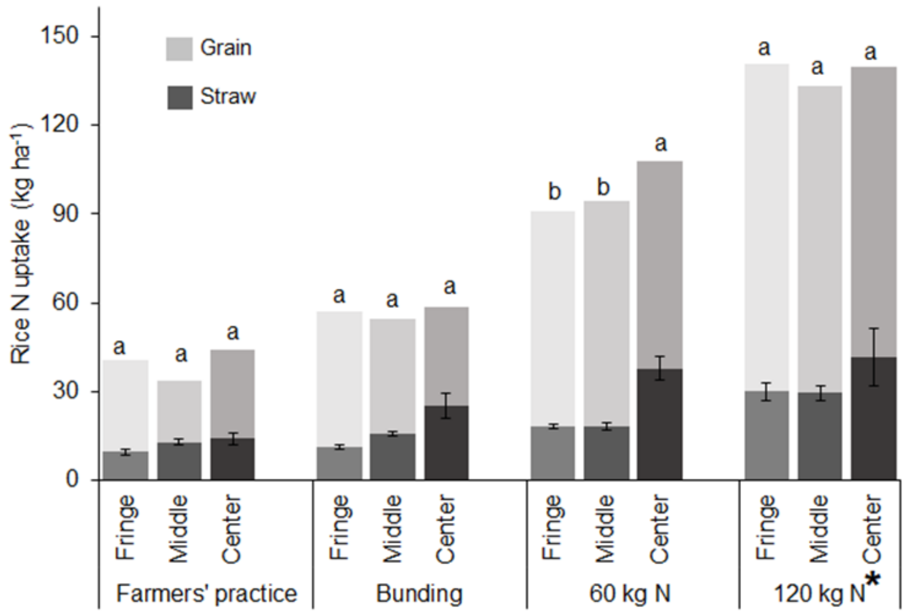

Figure 7. Nitrogen uptake by rice grain and straw across years (2015–2017) as affected by management practices. Different letters indicate significant differences by Tukey test at p ≤ 0.05 between positions. * “Attainable yield” treatments comprised of supplementary application of P and K.

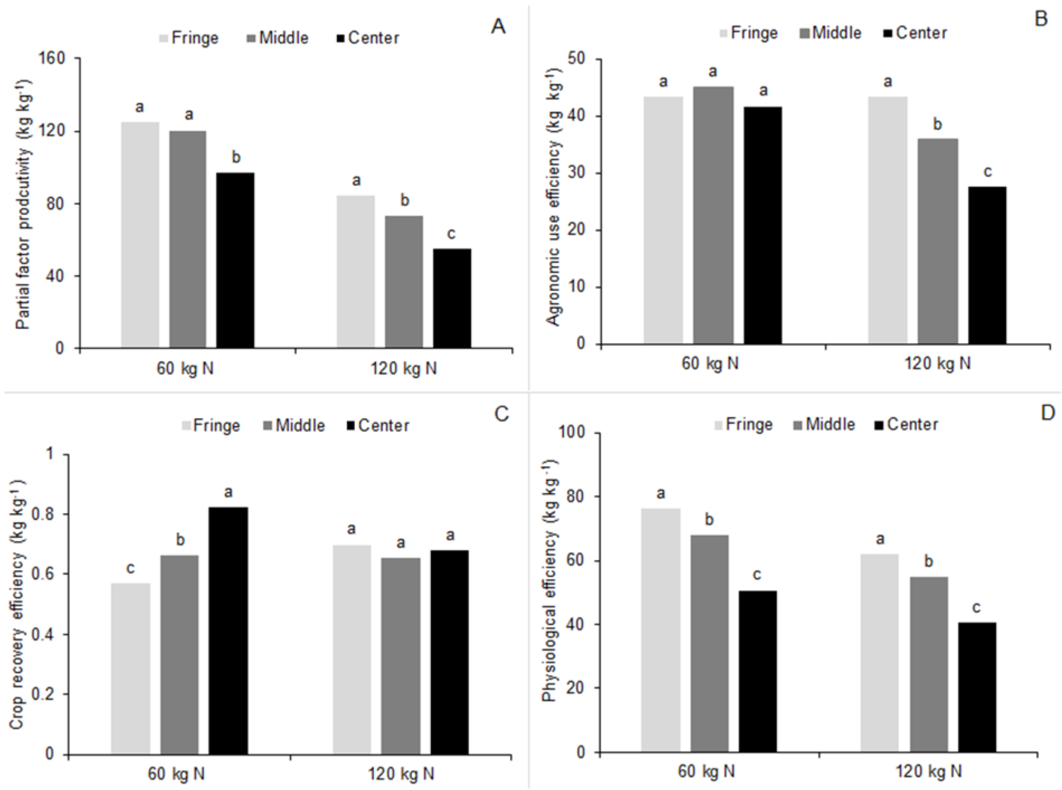

Figure 8. Use efficiencies of applied mineral fertilizer N averaged over years and differentiated by hydrological position: (A) partial factor productivity (kg grain yield kg^{-1} N applied), (B) agronomic N use efficiency (kg grain increase kg^{-1} N applied), (C) crop recovery efficiency (kg N increase kg^{-1} N applied) and (D) physiological N use efficiency (kg grain increase kg^{-1} N uptake). Different letters indicate significant differences by Tukey test at $p \leq 0.05$ between positions.

2.4 Discussion

2.4.1 Environmental characteristics

Our field trials highlight large differences in the response of the grain yield and yield variability of lowland rice to management practices ate different hydro-edaphic conditions. The soil's chemical and physical attributes and hydrological properties partially explain the observed differences between positions. The C and N content was generally low, specifically in the fringe and middle positions, as reportedly being typical for the Kilombero floodplain (Daniel et al., 2017; Senthilkumar et al., 2018). The observed high temperature and low humidity shortly after the rains entail a high vapour pressure deficit, leading to soil drying (Borken and Matzner, 2009). The resulting variations in soil aeration status stimulate the activity of decomposing soil microorganisms leading to subsequent losses of soil organic matter (Powlson et al., 2001). Similarly, the cyclic occurrence of short submergence periods in the fringe and middle positions (Gabiri et al., 2018) may explain the low observed C and N contents (Emmett et al., 2004). In the center position, extended anaerobic periods resulting from prolonged soil submergence explain the relatively higher C and N content (Omengo et al., 2016). Thus, different frequencies and durations of drying and wetting periods may have differentially affected position-specific soil C and N mineralisation (Jarvis et al., 2007). In addition, C and N losses may have further been exacerbated by the traditional use of fire in land clearing (Becker and Johnson, 2001). The P and K contents were always above the critical values of 8 mg P kg^{-1} and 60 mg K kg^{-1}, according to Mehlich-3 soil extraction (Sawyer and Mallarino, 1999), and tended to be much higher than those reported from floodplains in West Africa (Buri et al., 1999). In the absence of P application in Kilombero, this high P content is probably related to the deposited alluvial materials in the center (Ogbodo, 2011) as well as lateral flow contributions from adjacent mountain slopes to the fringe (Näschen et al., 2018). The seasonal *in-situ* burning of rice straw can recycle most of the plant-absorbed K and together with the annual deposition of K-rich sediments by Kilombero River (Alavaisha et al., 2019), probably explain the high soil K contents at all positions. The low C and N contents combined with the high to very high P and K contents may well entail the high-observed crops responsiveness to added N and the high rice grain yields.

2.4.2 Grain yield and yield variation

The findings of our study revealed large rice grain yield differences ranging from <1 up to >10 t ha^{-1} in the researcher-managed trials in Kilombero floodplain. These yields were generally higher than those reported from farmer-managed on-farm trials with a maximum yield of 7.2 t ha^{-1} (Senthilkumar et al., 2018). The higher yield in the researcher managed compared to farmer-managed trials has been attributed in other studies to better crop management including weed control, timely planting and the split application of mineral N fertilizers (Niang et al., 2017). The yields obtained with the application of 120 kg N (plus supplementary P and K), were assumed to represent the attainable yield level. Grain yields were in fact within the range of both the potential yield based on agro-climate zonation) and the water-limited yield potentials reported in the Global Yield Gap Atlas (GYGA) project (www.yieldgap.org) for Southern Tanzania (van Ittersum et al., 2013).

The observed large yield range and variability represents not only the high production risks and uncertainties in the outcome of farmers' investments in improved management practices but also indicates an enormous potential for smallholder farmers to achieve substantial yield gains by adopting site-specifically adapted agronomic management practices (Niang et al., 2018). In our study, year-to-year yield variability was reduced by fertilizer application as also reported from previous research on long-term fertilizer trials in Asia (Li et al., 2011). The high mean yields in 2015 and 2017 were associated with near-permanent moderate soil flooding (5−20 cm). Although total rainfall during the 2015 season was lower compared to 2016 and 2017 (Figure 4), water supply in the critical stage of panicle initiation in May was relatively high (116 mm). Conversely, the observed low yields in 2016 (El Niño year) were associated with an uneven distribution of rainfall with only 43 mm in May, resulting in temporary soil drying below field capacity.

The high observed rice grain yields at the fringe position were probably related to a combination of high P availability, favourable soil texture, a relatively high soil N supplying capacity, and the permanent and constant availability of water, also from the shallow groundwater table throughout the crop growth period (Gabiri et al., 2018). Low yields at the center position were linked to severe soil and crop submergence during the early reproductive and the grain filling stages of rice. Crop submergence affected specifically the percentage of filled grains, increasing the share of unfilled grains and concomitantly reducing the harvest index (Table 3).

The effect of soil and N management on rice grain yield and yield stability strongly differed between hydrological positions. Thus, lowest rice grain yields were observed under farmers' practice (non-bunded and non-levelled fields) in 2016, when alternating conditions of temporary soil drying and severe soil submergence occurred. The simple building of field bunds and soil levelling increased water retention and harmonized the floodwater level within plots (Becker and Johnson, 2001). These effects were most pronounced in the fringe and middle positions implying that improved soil management, even without mineral N application, can substantially increase rice grain yield. However, this was not the case at the center. While slightly reducing the yield variability, the water level during submergence largely exceeded the height of the field bunds and hence bunding did not enhance mean yields. Additionally, the application of mineral N fertilizers showed little yield effect in the center position. In contrast, our field trials also suggest that soil fertility and yield can be increased by green and farmyard manure application. In summary, the response to soil and fertilizer management increased from a little-responsive center towards highly-responsive fringe positions, to where the implementation and future extension of such management practices should be targeted.

2.4.3 Nitrogen use efficiency

Differential yield response to applied mineral N entailed significant differences to its use efficiency in different hydrological positions. Combined with field bunding and levelling, the use efficiency of mineral N increased as reported from several studies in Asia (Dobermann et al., 2008). Particularly water management (water retention and supplementary irrigation) and the maintenance of favourable hydrological conditions (permanent shallow soil flooding) is reportedly critical for effective use of applied N by rice (Singh, 2017). However, only in bunded fields of the fringe rice could benefit from N application rates beyond 60 kg ha^{-1} in the present study. The high partial factor productivity of up to 125 kg grain kg^{-1} N is comparable to that reported elsewhere (Dobermann, 2005). Thus, favourable environmental conditions and improved soil management increased the partial factor productivity of N in our study. High recovery and physiological efficiencies on the one and low agronomic N use efficiency at the center position, on the other hand, imply that less of the absorbed N was translocated into the reproductive organs and was instead retained in the straw.

The agronomic N use efficiencies of 28 up to 41 kg grain yield increase per kg of applied mineral N were considerably higher than efficiencies reported from different irrigated and rainfed sites in Asia (Cassman et al., 1998) and West Africa (Niang et al., 2017). Our findings are, however, in agreement with a recent report from China (Huang et al., 2019). Achieving high AEN has been associated with conditions of (1) low inherent soil N supplying capacity (Cassman et al., 2002), (2) minimal losses of applied mineral N (Omonode et al., 2017; Singh et al., 2014) and (3) efficient N partitioning into grains (Mae et al., 2006). In our study, the low inherent soil N content in the fringe and middle positions have been attributed to frequent cycles of alternate soil drying and wetting under hot climatic conditions as well as possible soil C losses related to the practice of burning for land clearing. The observed high response to added mineral N may additionally have been the result of the so-called priming effect (Jenkenson et al., 1985), whereby the addition of mineral N was able to overcome the N barrier for soil N mineralization by microbial communities in the floodplain soils with their wide CN-ratios of 16−18. A minimization of N losses in the researcher-managed trials was possibly achieved by multiple splitting and the timely application of urea, thus achieving a high degree of synchrony between N supply and N demand (Becker and Ladha, 1997; Cassman et al., 2002). Finally, highly N efficient genotypes such as SARO 5 can as reported (Singh et al., 1998) efficiently partition the acquired N into the grain, particularly under conditions of high solar radiation (Fletcher et al., 2013), thus also improving the physiological efficiency PEN (Fageria and Baligar, 2003). The factors mentioned above were thus likely responsible for the high observed N use efficiencies.

Our results show that improved land and fertilizer management options are most beneficial in the fringe positions where they contribute to enhance N use efficiencies, increase grain yield and reduce production risks as highlighted by the low yield variability between plots and years. Tall traditional cultivars are popularly grown in submergence-prone valley bottoms (Meertens, 1999), and modern genotypes containing the SUB1 gene (Xu et al., 2006) can withstand submergence conditions for up to 12 days (Singh et al., 2009). However, the severe and prolonged submergence conditions with >3 m for >26 days in the floodplain center (Gabiri et al., 2018) are likely to exceed by far the adaptive capacity of the rice genotypes mentioned above. As a consequence, and due to comparatively low yields, high production risks and reduced responsiveness to improved management interventions, submergence-prone floodplain centers appear largely unsuited for boosting future rice production.

2.5 Conclusions

For the hydrologically highly variable floodplain environment as represented by the Kilombero floodplain in Ifakara, we can conclude that rice intensification strategies need to be hydrological position-specific. Thus, considerable benefits derived from improved management can be expected from floodplain fringe and middle positions where the suggested land and fertilizer options are associated with production and productivity gains as well as reduced production risks. On the other hand, due to their poor input responsiveness to improved management, submergence-prone floodplain centers, e.g., in the Kilombero floodplain, could be taken out of production and may be considered for future use as protection zones for biodiversity conservation and the provision of a wide range of water-related ecosystem services.

Chapter 3

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Effect of organic amendments on the productivity of rainfed lowland rice in the Kilombero floodplain of Tanzania

Abstract

Organic amendments can reportedly sustain and increase lowland rice productivity in smallholder systems. Few studies have assessed substrates locally available in hydrologically variable floodplain environments. We investigated the effects of green and farmyard manures on rice yields, and total soil C and N in the Kilombero floodplain, Tanzania. At both the fringe and the middle positions, five treatments were applied in 2016 and 2017, comprising (1) non-amended control, (2) farmyard manure, (3) pre-rice legumes, (4) post-rice legumes and (5) a combination of green and farmyard manures. Residual treatment effects were assessed in 2018 when rice plots were uniformly non-amended. Depending on the year and the position, organic amendments increased rice grain yields by 0.7–3.1 t ha^{-1} above the non-amended control. Sole green and farmyard manure applications had similar effects on grain yield, while a combination of green and farmyard manure led to a significant increase in grain yield above both the control and sole applications of organic amendments in both years. The contribution from biological N_2 fixation by legumes ranged from 4 to 61 kg N ha^{-1}. Despite partial N balances being mostly negative, we observed positive residual effects on the yield of the non-amended rice in the third year. Such effects reached up to 4 t ha^{-1} and were largest with post-rice legumes, sole or combined with farmyard manure. Irrespective of the position in the floodplain, manures significantly increased soil C and N contents after two years, hence enhancing soil fertility and resulting in increased rice grain yields. Comparable benefits may be obtained along the hydrological gradients of other large river floodplains of the region and beyond.

3.1 Introduction

Tanzania is one of the largest rice producers in East Africa, accounting for about 50% of the total regional output (FAO, 2018b). Rice grain yields are generally low, ranging between 0.5 to 2.1 t ha^{-1} across all rice-growing environments (Diagne et al., 2013). Tanzania will need to double its current rice production by 2030 to meet the rapidly-growing domestic demand (Seck et al., 2010; Wenban-Smith et al., 2016). Most rice is produced in rainfed lowland floodplain environments and it is predominantly grown by smallholder farmers. With yields attainable by best farmers of >5 t ha^{-1}, the yield gap is large, reaching up to 3.4 t ha^{-1} (Senthilkumar et al., 2020; Tanaka et al., 2017). Rice yields and total annual production in floodplains are highly variable, partly due to erratic rainfall and unpredictable soil submergence regimes but also because of low and variable soil fertility and poor management practices (Kwesiga et al., 2019; Senthilkumar et al., 2018). While mineral fertilizers are still considered being the primary option for soil fertility restoration (Barrett and Bevis, 2015), increasing the current low use of mineral N fertilizers will depend on their availability and affordability (Tsujimoto et al., 2017). These latter conditions are rarely met in the remote rural villages of the Kilombero floodplain, which is one of the largest rice-growing areas of Tanzania and the focal environment of the present study.

Organic amendments, in contrast, have the potential to increase soil fertility without using external inputs. The effects of organic amendments on rice production have been widely studied. After the first review on historical uses of organic amendments in China, Korea and Japan by F.H. King in his book "Farmers of forty centuries" (Paull, 2011), the first scientific journal papers appeared in the 1950s. Since the mid-1980s, a large array of studies and later review papers on leguminous green and animal manures (Becker et al., 1995b; Xie et al., 2016) and on food legume residues appeared (Siddique et al., 2012). In-situ or ex-situ (cut-and-carry) grown legume manures, sole or in combination with mineral fertilizers (Das et al., 2020; Ding et al., 2018), have shown to increase rice grain yields on average by 35% and in some cases by >50% (Becker and Johnson, 1999a).

Apart from reported yield benefits, the incorporation of organic amendments has further been shown to improve aggregate stability and other soil attributes by increasing total soil organic C and N, as well as available P, K, S, and Zn (Ding et al., 2018). They also improve water infiltration, hydraulic conductivity and the soil's water-holding capacity (Seufert et al., 2012), thus reducing negative effects of dry-spells and counteracting soil degradation (Place et al., 2003). In-situ-grown green manures during the pre-rice niche are additionally able to save nitrate from leaching and denitrification losses (Asante et al., 2017; Becker et al., 2007) and to reduce negative effects of iron toxicity (Gao et al., 2017), while promoting soil microbial and enzyme activities (Patra et al., 2006). Organic amendments also can reduce plant pathogenic nematode communities and soil-borne diseases (Zhang et al., 2019) and suppress weed growth (Becker et al., 1995b). There is evidence that locally-available organic amendments can be economically viable and resource-conserving alternatives to mineral fertilizers with a high promise to sustain and increase production in small-scale agriculture (Adamtey et al., 2016).

Despite beneficial effects, the adoption of organic fertilizer strategies in rice-based systems of Africa has remained low. Besides labor limitations, farmers lack the knowledge of the benefits derived from organic amendments (Mafongoya et al., 2007). Other authors pinpointed the lack of both available farmyard manure and seeds of appropriate legume species as a hindrance to adopting strategies based on organic inputs (Ali, 1999). Particularly in favorable irrigated lowland environments, the competitiveness of organic amendments with cheap and readily-available mineral fertilizer sources is reportedly low (Becker, 2001). In addition, niches for growing green manure legumes are often non-existent in intensive irrigated production systems or too short or water-limited in extensive rainfed environments (Becker et al., 1995b). Most of these reported constraints to the use of organic amendment strategies refer to (irrigated) lowland rice in South and South-East Asia and upland rice in West Africa (Becker and Johnson, 1999a) and are not, or only partially, applicable to rainfed floodplains in East Africa. Such floodplain environments are edaphically and hydrologically highly variable, and soil fertility is often low (Daniel et al., 2017). Consequently, the use efficiency of applied mineral N is highly variable and tends to be low. In addition, mineral fertilizers are often unaffordable for smallholders or not available in a timely manner (Chianu et al., 2012). In the absence of mineral fertilizers, farmers have to rely largely on the native supplying capacity of minerals by the soil, often resulting in nutrient mining (Nhamo et al., 2014).

Organic amendments appear as a promising alternative strategy for soil fertility restoration and for increasing the yield of rainfed lowland rice, particularly in floodplains. Many farmers in the Kilombero floodplain own cattle and have thus the possibility to apply farmyard manure. One single crop of rainfed rice during the main rainy season (Kwesiga et al., 2019) leaves available cropping niches for growing green manure, grain, or forage legumes either before rice planting (pre-rice niche) or after rice harvest (post-rice niche). The duration of these cropping niches depends on water availability for the establishment and the growth periods of green manure crops and thus on the onset of the rains for the pre-rice niche and on the soil moisture retention for the post-rice niche. These conditions of water availability differ spatially depending on the physical position of fields within the floodplain (distance from the central river) between the drought-prone fringe and wetter middle positions (Gabiri et al., 2018). Due to severe submergence risks, the center positions closest to the river are largely unsuited for green manure growth, and even rice production is highly risky due to high production uncertainty and yield variability (Kwesiga et al., 2019). Conditions of water availability further vary temporally according to rainfall patterns within the season or between years (Näschen et al., 2019). Hence, the effectiveness of organic amendments in enhancing lowland rice performance in floodplains is expected to differ by amendment type, field position and year. We further assume that the repeated application of organic amendments can improve soil attributes with associated residual effects on subsequent non-amended crops.

To date, no studies have assessed the effects of different organic amendments on rainfed rice performance in the often remote rural floodplain environments of East Africa. We, therefore, quantified the effects of (a) sole farmyard manure application, (b) pre–rice green manure (c) post-rice green manure, and (d) of a combination of post-rice green and farmyard manure on rice grain yield (direct and residual effects), on soil C and N contents, and on partial N balances. The field experiments were conducted at the fringe and middle positions in the Kilombero floodplain between 2015 and 2018.

3.2 Materials and methods

3.2.1 Edaphic and climatic conditions of the experimental sites

Field experiments were conducted in farmers' fields between 2015 and 2018 in two villages located near Ifakara town in the Kilombero District of Tanzania. The Kilombero floodplain is part of the Rufiji River Basin extending from 7.65° to 10.02° S latitude and from 34.56° to 37.79° E longitude and is the largest rice-growing environment of Tanzania. The floodplain is divided into three hydrological positions (fringe, middle and center) based on the origin of the water and submergence duration (Gabiri et al., 2018). Only the fringe and middle positions were considered in this study after the complete submergence of the center position in 2015 (Kwesiga et al., 2019). The two test sites have been under continuous extensive rainfed rice production for >15 years. In Table 4, both sites had similar soil textural classes (silt loam) and a similar soil pH (5.8–6.0).

The soils of the fringe position contained more available P (48 mg kg^{-1}) than the middle position (16 mg kg^{-1}), but both were above the critical limit for rice growth of < 8 mg P kg^{-1} and of plant-available (exchangeable) soil K of <60 mg K kg^{-1} according to Mehlich-3 soil extraction as earlier reported (Kwesiga et al., 2019). The experimental site has a sub-humid tropical climate, with average annual temperatures of 22–23 °C and maximum and minimum peaks in December and July, respectively. Rainfall occurs in a pseudo-bimodal pattern with erratic rains between November and January and intensive rain between March and May. The dry season extends from June to October. Long-term average annual rainfall is 1100 mm. During the experimental period, rainfall varied between 632 mm (2018) and 1262 mm (2017) (Figure 9). Besides in-situ rainfall, the hydrology of the floodplain differs with the distance of fields from the central river.

Table 4. Selected physical and chemical properties of the experimental topsoil (0–20 cm) in Kilombero floodplain at the onset of the experiment in November 2015.

Soil Characteristics	**Fringe**	**Middle**
Classification (WRB)	Fluvisol	Fluvisol
Soil texture	Silt Loam	Silt Loam
Clay (%)	14.3	26.6
Sand (%)	33.7	14.1
Silt (%)	52.0	59.3
Bulk density (g cm^{-3})	1.4	1.3
pH (H_2O)	6.0	5.8
Total C (g kg^{-1})	16.5	14.5
Total N (g kg^{-1})	0.9	0.9
Available P (mg kg^{-1}) *	47.5	16.0
Available K (mg kg^{-1}) *	71.4	79.2

* Mehlich-3. WRB-World Reference Base of the Food and Agriculture Organization of the United Nations (FAO). Presented values are means of n = 20 replicate samples.

The hydrology in the middle position is determined mainly by overbank flow from the Kilombero River, while the fringe positions receive lateral subsurface flow contributions from adjacent mountain ranges (Burghof et al., 2018). Early rainfall events in November/December provide the moisture required for the growth of short-duration green manure crops before the establishment of the rice crop in March (pre-rice niche). Shallow groundwater and residual soil moisture after flood recession in June provide water for cultivating deep-rooted legumes during the dry season (post-rice niche), resulting in specific cropping sequences, and interactions of surface and groundwater determined the dynamics of water availability or submergence regimes (Figure 10) .

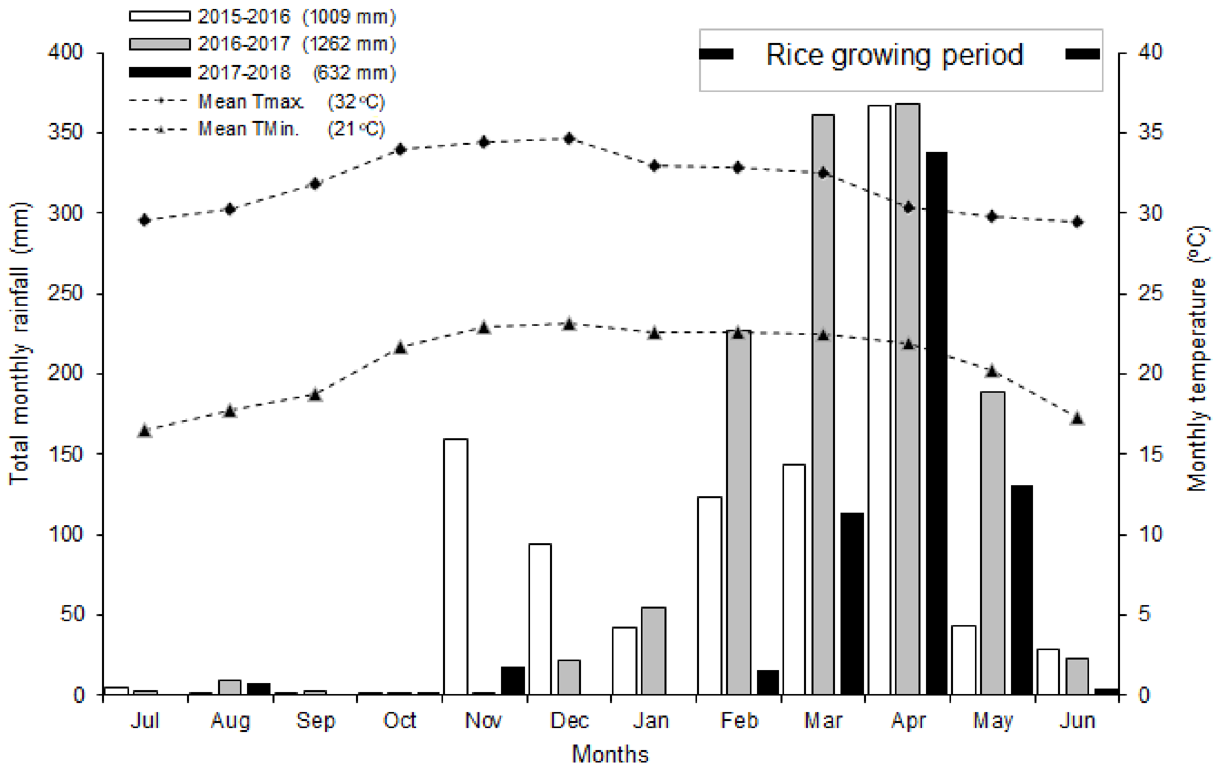

Figure 10. Monthly and total annual rainfall and mean minimum and maximum air temperature distribution during the three-year experimental period. Data were recorded at a weather station installed at Ifakara Health Institute research station, about 5 km West of Ifakara town

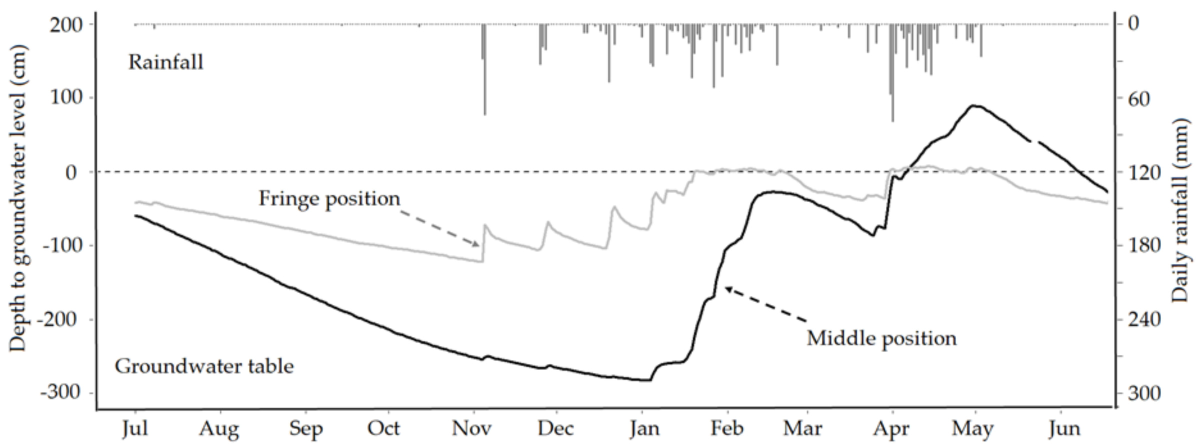

Figure 9. Depth to ground water level dynamics resulting from the surface water and groundwater interaction during dry, short- and long-rain season for the fringe and middle positions of the Kilombero floodplain, Tanzania from July 2015 to June 2016. Adapted from (Gabiri et al., 2018)

3.2.2 Experimental design and treatment application

Four strategies using organic amendments were compared with a non-amended control in a randomized complete block design (RCBD) with four replications. The experiments were implemented at two contrasting locations within the floodplain (fringe and middle positions) and included: (i) farmyard manure, (ii) lablab (*Lablab pur pureus* L.) as pre-rice green manure, (iii) stylosanthes (*Stylosanthes guianensis L.*) as post-rice green manure, (iv) a combination of cowpea (*Vigna unguiculata L*.) as post-rice green manure and farmyard manure application before rice planting and (v) the non-amended control treatment (Figure 11). The treatments were applied in the same plots for two consecutive years (2015 and 2016), their direct benefits were evaluated in 2016 and 2017, while the residual effect on a non-amended rice crop was assessed, with all plots being treated uniformly (no organic amendment) in 2018. The trial were established at the two different hydrological positions using individual experimental plot sizes of 6 × 5 m (30 m^2). Plots were manually tilled to a depth of 15 cm, bunds of 50 cm height and 30 cm width were built and compacted around each plot to prevent lateral flows of water and nutrients. Additionally, one-meter-wide trenches were installed to separate the treatment blocks (replications). Field areas within the bunded plots were puddled and manually levelled.

Farmyard manure: Fresh cattle manure was obtained from one local farmer in the area. Subsamples were dried and analyzed for N content (Table 5). Fresh farmyard manure was homogenously applied at a rate equivalent to 60 kg N ha^{-1} and manually incorporated into the topsoil (0–15 cm) one week prior to soil puddling and rice transplanting. Depending on the N content, farmyard manure application rates varied by year between 5.0 and 6.7 t ha^{-1}.

Green manures: Three green manure species were selected, i.e., (i) lablab, (ii) stylosanthes and (iii) cowpea based on them being locally known and seeds being available. The choice of the specific genotypes used was informed by their multi-purpose use attributes. Besides being used as green manures, stylosanthes and the specific cowpea were forage types, and the grains of cowpea and lablab can potentially be used for human consumption. Such multi-purpose considerations have been pointed out being key factors for farmers' adoption of green manure technologies (Becker et al., 1995b).

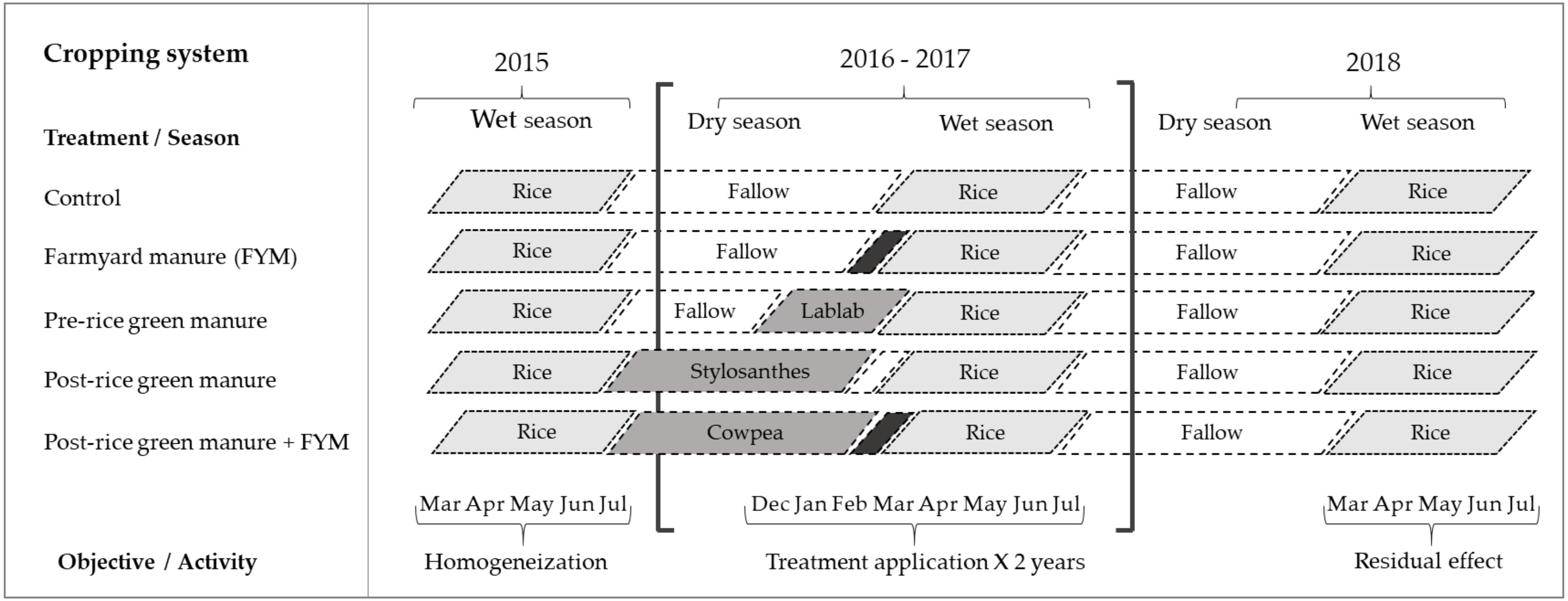

Figure 11. Characterization of the applied cropping systems, including crop species, i.e., rice, cowpea, lablab and stylosanthes, and their temporal sequence in Kilombero floodplain, Tanzania during the experimental period (2015–2018). Main rainy season extends from March to May, main dry season from July to February. Shaded black areas represent the period for farmyard manure (FYM) application.

Legume seeds were obtained from the Agriculture Research Institute (ARI) in Ilonga, Tanzania (stylosanthes), and the National Semiarid Research Resources Institute (NaSARRI), Uganda (lablab and cowpea). Lablab was used as pre-rice green manure and established after the first rains in early or mid-December at a 40 × 40 cm spacing. Long-duration multi-purpose cowpea and the forage legume stylosanthes were established as post-rice green manures by dibble-seeding at a 20 × 10 (stylosanthes) or 20 × 40 cm spacing (cowpea) 2–5 days after rice harvest. The post-rice legumes grew on residual soil moisture for initially 2–3 months into the dry season, and re-greened and continued to grow for another 1–2 months after the onset of the short rains until the land preparation for rice in the subsequent year. No rhizobia inoculum was applied as all legumes nodulated spontaneously.

Biomass samples for weight, N content and the share of N derived from biological N_2 fixation were obtained from a 2 × 3 m harvest area in the middle of each plot at 45 (pre-rice legumes) and 150 days after seeding (post rice legumes). The biomass was chopped and incorporated manually into the topsoil (0–15 cm) two weeks before rice transplanting. Only in the cowpea treatment, farmyard manure was additionally applied at a rate of 60 kg N ha^{-1} and incorporated together with the fresh legume biomass two weeks prior to rice transplanting. In one corner of each legume plot, six maize plants were established at the time of legume seeding and were used as non-fixing references for $\delta^{15}N$ analysis after harvest at 45 days (pre-rice green manure) or 110 days (post-rice green manures). In the final experimental year (2018), rice was grown without any amendments to assess the residual effect of repeated manuring under ceteris paribus conditions (Figure 11).

Rice: Seeds of the high-yielding indica variety SARO-5 were obtained from the Tanzania Agriculture Research Institute (TARI) in Ifakara. Seeds were pre-soaked for 24 h, incubated for 48 h and sown in a nursery bed. Twenty-five days-old rice seedlings were transplanted into the puddled and levelled field plots at a 20 × 20 cm spacing at two seedlings per hill (25 hills m^{-2}) in late February or early March of each year, depending on the onset of the main rainy season. Plots were hand-weeded homogenously in all plots at 28 and 56 days after transplanting.

Table 5. Characterization of the organic amendments (biomass and N accumulation and the shares and amounts of N_2 fixed by legumes) applied at the fringe and the middle positions of Kilombero floodplain in 2016 and 2017.

Organic Amendment	2015						2016					
	Biomass (Mg dm ha^{-1})	N content (%)	N accum. (kg ha^{-1})	$\delta^{15}N$ (‰)	Nfda (%)	N fixed (kg ha^{-1})	Biomass (Mg dm ha^{-1})	N content (%)	N accum. (kg ha^{-1})	$\delta^{15}N$ (‰)	Nfda (%)	N fixed (kg ha^{-1})
Fringe												
Farmyard manure	5.0 ^{a}	1.2	60 ^{a}	–	–	–	6.7 ^{a}	0.9	60 ^{a}	–	–	–
Lablab	1.3 ^{c}	1.6	18 ^{b}	4.6	23	4 ^{c}	1.0 ^{c}	1.3	13 ^{b}	4.5	51	7 ^{c}
Stylosanthes	1.9 ^{bc}	1.9	36 ^{b}	4.4	25	9 ^{b}	5.2 ^{b}	1.4	73 ^{a}	5.9	39	28 ^{b}
Cowpea	2.1 ^{b}	3.6	76 ^{a}	3.0	39	30 ^{a}	2.5 ^{c}	3.1	78 ^{a}	3.1	59	46 ^{a}
Middle												
Farmyard manure	5.0 ^{a}	1.2	60 ^{b}	–	–	–	6.7 ^{a}	0.9	60 ^{b}	–	–	–
Lablab	1.8 ^{c}	1.8	18 ^{c}	4.6	27	5 ^{c}	1.1 ^{c}	1.9	21 ^{c}	4.4	29	6 ^{c}
Stylosanthes	2.5 ^{bc}	2.5	63 ^{bc}	4.3	29	18 ^{b}	3.1 ^{b}	2.0	62 ^{b}	4.4	28	17 ^{b}
Cowpea	3.8 ^{b}	3.4	122 ^{a}	4.2	29	35 ^{a}	3.8 ^{b}	3.2	122	2.3	50	61 ^{a}

%Nfda–Nitrogen derived from the atmosphere, $\delta^{15}N$–atom per cent excess above 0.366% (atmosphere). Maize was used as a non-fixing reference crop with $\delta^{15}N$ values of 10.7%o, 6.4%o for fringe and 6.7%o, 6.8%o for middle position in 2015 and 2016, respectively. 'B–value' refers to isotopic discrimination in N-free medium and was applied as 1.36%o for lablab (Ojiem et al., 2007), 1.76%o for stylosanthes (Nguluu et al., 2002), and 2.20%o for cowpea (Nyemba and Dakora, 2010). Different letters within a column denote significant differences at $p < 0.05$ according to Tukey Test. N accum= biomass × N content, N fixed = %Ndf × N accum. ed at the fringe and the middle positions of Kilombero floodplain in 2016 and 2017.

Rice was harvested from 2 × 3 m sampling areas in the center of each plot in late May or early June. After manual threshing, measured with a digital grain moisture meter (Satake Moistex SS7) and adjusted to 14% grain moisture content. Additionally, 12 adjacent hills were cut at ground level to determine biomass accumulation and yield components, including the number of tillers and panicles m^{-2}, percentage filled grains, and 1000-grain weight.

3.2.3 Data collection and analyses of plant material and soil

Samples of approximately 100 g of rice grain and straw, of farmyard manure and of legumes were oven-dried at 105 °C for ~48 h until constant weight. Sub-samples of about 1 g were fine ground and analyzed for their N content using an elemental analyzer (EURO EA Elemental Analyzer series 3000, EURO-EA Vector Pavia, Italy). The share on N derived from the atmosphere (%Ndfa) by legumes was estimated using the $\delta^{15}N$ natural abundance method. Above-ground plant parts were analyzed for N isotope ratios using a Europa Scientific Ltd. Geo 2020 mass spectrometer coupled to the ANCA-SL elemental analyzer (Welsh S. Sercon Ltd., Crewe, Cheshire, UK). The $\delta^{15}N$ signatures were calculated according to equation 1, with atmospheric N_2 serving as standard. The shares of Ndfa (%) were assessed as shown in equation 2. The B value is the $\delta^{15}N$ share of the same N_2 fixing legume when grown with N_2 as sole N source (natural discrimination of the heavy ^{15}N isotope by the nitrogenase enzyme complex). The B-values were −1.36%o for *Lablab purpureus* (Ojiem et al., 2007), −1.76%o for *Stylosanthes guianensis* (Nguluu et al., 2002), and −2.2 for *Vigna unguiculata* (Nyemba and Dakora, 2010). All ^{15}N data were expressed as atom% in excess of the natural ^{15}N background abundance of the atmosphere of 0.3663%.

$$\delta^{15}\text{N} = \left[\left(\frac{^{15}\text{N}}{^{14}\text{N}}\text{sample} \Big/ \frac{^{15}\text{N}}{^{14}\text{N}}\text{ standard}\right) - 1\right] \text{x}1000 \quad (1)$$

$$\%\text{Ndfa} = \frac{\left(\delta^{15}\text{N of reference crop} - \delta^{15}\text{N of legume}\right)}{\left(\delta^{15}\text{N of reference crop} - \text{B}\right)} \text{x } 100 \quad (2)$$

$$\text{N accum.} = \text{Biomass x N content} \quad (3)$$

$$\text{N fixed} = \text{N accum. x \%Ndfa} \quad (4)$$

Based on N contents and biomass accumulation, partial N balances were calculated for the different treatments as (N added by amendments)–(N removed with harvested grain) (Becker et al., 2007). Nitrogen input by dry and wet deposition, N_2 fixation by free-living organisms or N losses by volatilization, denitrification and leaching were not considered.

Composite samples of seven topsoil cores per plot (0–20 cm) were collected before rice transplanting in 2015 and after rice harvest in 2017 to assess changes in soil C and N contents after two years of treatment application. The samples were air-dried, ground to pass through a 2 mm sieve, and analyzed for total N by dry combustion method at 950 °C using an Elemental Analyzer (vario-ELcube Elementar Analysesysteme GmbH, Langenselbold, Germany). Plant-available P and K were extracted from the initial soil samples (2015) using the Mehlich-3-extraction method (Ziadi and Tran, 2007). Phosphorus was colourimetrically analyzed using molybdenum-blue complex (Specord 50Plus, Analytik Jena AG, Jena, Germany), while K was analyzed using ICP-OES (Spectro Arcos, Spectro Analytical Instruments GmbH, Kleve, Germany).

3.2.4 Statistical analysis

A linear mixed model fit by Restricted Maximum Likelihood (ReML) variance components analysis was used for data on soil, yield, yield parameters and N uptake in each position. The fixed model included position, treatment and year, while replications were considered as a random factor. Descriptive statistics on means and standard errors of the means were calculated for main effects over years and for both hydrological positions. A two-way ANOVA was used for comparing soil nutrient concentrations and rice grain yield. Where applicable, mean separations were done using the Tukey test ($p < 0.05$).

3.3 Results

3.3.1 Nitrogen accumulation and N_2 fixation by legumes

Above-ground biomass accumulation, N content, N accumulation and the amounts of N derived from biological N_2 fixation by green manures differed between legume species, position and cropping season (Table 5). The relatively more extended growth period during the post-rice niche compared to lablab, application of stylosanthes and cowpea produced higher biomass of 0.9–3.4 and 1.1–2.0 t ha^{-1} respectively. While, biomass accumulations by lablab and cowpea were comparable in both years and positions, the biomass of stylosanthes was much higher in 2016 (3.1–5.2 t ha^{-1}) than in 2015 (1.9–2.5 t ha^{-1}) and differed between positions. Also, the in-field variability (establishment and stand densities) was much higher with small-seeded stylosanthes than with the large-seeded legumes (data not shown).

The amount of N added by farmyard manure was fixed at 60 kg ha^{-1}. On the other hand, the amounts of N incorporated into the soil with legume biomass (N derived from both the soil and the atmosphere) varied widely between species and years. The highest N-accumulation was recorded in cowpea with 76–78 kg N ha^{-1} in the fringe and 122 kg N ha^{-1} in the wetter middle position. Similar to biomass, the N accumulation by stylosanthes was highly variable, ranging from 36–73 kg N ha^{-1}. The lowest N-accumulation range of 1.3–2.0 kg N ha^{-1} was recorded in lablab. The measured mean shares of N derived from N_2 fixation were higher in cowpea (44% Ndfa) than in lablab (32% Ndfa) or stylosanthes (30% Ndfa). Resulting amounts of N fixed differed between legumes, positions and years, ranging from 4 kg N ha^{-1} (lablab in the fringe position) to 61 kg N ha^{-1} (cowpea in the middle position). The amounts of N_2 fixed were higher in 2016 than in 2015, independent of the position.

3.3.2 Effect of organic amendments on rice grain yield

Rice grain yields differed between treatments, positions and years (Table 6). The overall mean was 5.5 t ha^{-1} with higher average yields in the wet year of 2017 (6.1 t ha^{-1}) than in the relatively dry year of 2016 (4.8 t ha^{-1}). The yield of the non-amended control ranged from 3.6 (2016) to 4.9 t ha^{-1} (2017) and tended to be higher in the wet middle than the drier fringe positions, particularly during the dry year of 2016. Sole farmyard manure application at a rate of 60 kg ha^{-1} increased yields by

22% in the first and by 31% in the second years of treatment application. The rice yield response to green manure application showed a similar pattern (stronger response in 2017 than in 2016) and was significant in both years, irrespective of whether the legume was grown in the pre-rice (lablab) or the post-rice niche (stylosanthes). The N application rate was much lower with green manures compared to farmyard manure, pointing to a large N accumulation and fixation by the below ground biomass. The strongest yield response was observed in both years and positions with combined incorporation of the post-rice green manure (cowpea) and the application of farmyard manure, with yield increases of 86% in the dry (2015) and 45% in the wet year (2016).

ANOVA showed significant effects of treatment and year for most yield parameters (Table 7), while positions only affected the percentage of filled grains and thousand-grain weight. Significant interactions between treatments and years required a differentiated presentation of the findings by years (Table 6).

Panicle numbers ranged between 156 (2016) and 163 m^{-2} (2017), and in all cases, manuring resulted in significant increases. Panicle numbers tended to be higher (significant only in 2016) after incorporation of the post-rice green manure compared to pre-rice green manure or farmyard manure application. No treatment effect was observed regarding the percentage of filled grains and 1000-grain weights. However, the share of filled grains was higher in 2016 (94%) than in 2017 (80%). A combined application of green manure and farmyard manure in 2015 and 2016 not only provided highest yields but also resulted in highest N removal by the grain with 70 and 80 kg N ha^{-1} in 2016 and 2017, respectively.

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Table 6. Effect of organic amendments on grain yield, N uptake and yield components of rainfed lowland rice in Kilombero floodplain, Tanzania in 2016 and 2017 (means across two positions).

Treatment	Rice Grain Yield ($t\ ha^{-1}$)	Panicle Number (m^{-2})	Filled Grains (%)	1000 Grain Weight (g)	Grain N Removal ($kg\ ha^{-1}$)
2016					
Control	3.6^{c}	103^{c}	92.3^{d}	30.0^{b}	35.7^{c}
Farmyard manure	4.4^{b}	146^{b}	93.4^{bc}	30.6^{a}	39.0^{b}
Pre-rice GM *	4.3^{b}	167^{b}	93.9^{b}	30.1^{b}	39.6^{b}
Post-rice GM *	4.3^{b}	186^{a}	92.7^{cd}	29.4^{b}	35.1^{c}
Post-rice GM + FYM#	6.7^{a}	181^{a}	94.5^{a}	30.8^{a}	70.4^{a}
Mean	**4.8**	**156**	**93.5**	**30.3**	**44.0**
2017					
Control	4.9^{d}	131^{b}	82.3^{a}	31.2^{a}	52.9^{d}
Farmyard manure	6.2^{bc}	162^{a}	79.8^{a}	31^{a}	68.4^{b}
Pre-rice GM	6.4^{b}	173^{a}	76.6^{a}	31.1^{a}	64.5^{b}
Post-rice GM *	5.7^{c}	167^{a}	79.4^{a}	30.7^{a}	59.2^{c}
Post-rice GM + FYM	7.1^{a}	174^{a}	81.1^{a}	30.7^{a}	80.0^{a}
Mean	**6.1**	**163**	**79.7**	**30.9**	**65.5**

* GM = green manure, # FYM = farmyard manure. Different letters within a column/year denote significant differences at p <0.05 according to Tukey Test. Presented values are means of n = 8 replicates.

Table 7. Analysis of variance for grain yield, N uptake and yield components (means of the years 2016 and 2017).

Source of Variation	Rice Grain Yield ($t\ ha^{-1}$)	Panicle Number (m^{-2})	Filled Grains (%)	1000 Grain Weight (g)	Grain N Removal ($kg\ ha^{-1}$)	Total Crop N Uptake ($kg\ ha^{-1}$)
Treatment	***	**	ns	**	**	**
Position	ns	ns	***	**	ns	*
Year	***	ns	**	**	**	**
Year x Treatment	**	*	***	ns	**	**
Position x Treatment	ns	ns	ns	***	ns	ns
Year x Position	ns	ns	ns	**	ns	ns
Treatment x Position x Year	ns	ns	ns	ns	ns	ns

Significant level '***' 0.001 '**' 0.01 '*' 0.05, ns—not significant.

3.3.3 Partial N balances, soil attribute changes and residual yield effects

Partial N balances (N added from farmyard manure and legume Ndfa–N removed with harvested rice grain) varied widely between −59 and +38 kg N ha^{-1} (Table 8). While partial N balances were always negative in the non-amended control, they were negative to neutral with pre- and post-rice green manures and consistently positive across years and positions in the combined green and animal manure treatments with N surpluses of +22 to +38 kg N kg N ha^{-1}. These trends in the partial N balances are also reflected in changes of selected soil fertility attributes (Table 9).

The soil C and N contents declined in control treatments by −4.4 to −1.1% between the start of the experiment in 2015 and the harvest of the rice crop in 2017. The application of organic amendments significantly improved the soils fertility status, increasing topsoil C contents (0–20 cm) by up to 29% in the fringe and up to 46% in the middle positions. Concomitant increases in soil N due to organic amendments were about 16% with lablab and ranged from 8–44% with stylosanthes across all positions.

In relative terms, a sustained application of sole farmyard manure in the fringe and middle increased soil C and N least compared to green manure legumes. However, the combination of post-rice green manure and farmyard manure showed strongest effects, increasing soil C from initially about 15 to up to 20 g kg^{-1} and soil N from about 0.9 to >1.3 g kg^{-1} after two years of treatment application.

The reported partial N balances (Table 8) and the changes in soil C and N contents following two years of organic amendments (Table 9) were associated with significant residual yield effects in the non-amended rice crop of 2018. Although the initial soil C contents were not significantly correlated with residual grain yields, there was a significant positive correlation between final total soil C content in June 2017 and rice grain yield in 2018 (Figure 12).

Table 8. Partial N balances of the lowland rice-based systems in Kilombero floodplain as affected by different organic amendments (2016–2017).

Treatment	2016			2017		
	N Input (kg ha^{-1})	N Removal (kg ha^{-1})	N Balance (kg ha^{-1})	N Input (kg ha^{-1})	N Removal (kg ha^{-1})	N Balance (kg ha^{-1})
Fringe						
Control	0.0	35.8^{b}	−35.8^{c}	0.0	54.8^{c}	−54.8^{d}
Farmyard manure (FYM)	60.0	35.6^{b}	24.4^{a}	60.0	65.7^{b}	−5.7^{b}
Pre-rice green manure (GM)	4.1	38.4^{b}	−34.3^{c}	6.7	60.7^{b}	−54.0^{d}
Post-rice GM	8.9	37.0^{b}	−59.1^{b}	28.1	54.5^{c}	−26.4^{c}
Post-rice GM + FYM	89.6	68.0^{a}	21.6^{a}	106.0	76.2^{a}	29.8^{a}
Control	0.0	35.6^{c}	−35.6^{d}	0.0	56.0^{d}	−56.0^{d}
Middle						
Farmyard manure (FYM)	60.0	42.4^{b}	17.6^{b}	60.0	71.1^{b}	−11.1^{b}
Pre-rice green manure (GM)	4.8	40.7^{b}	−35.9^{d}	6.0	68.3^{bc}	−62.3^{d}
Post-rice GM	18.1	33.2^{c}	−15.1^{c}	17.0	63.8^{c}	−46.8^{c}
Post-rice GM + FYM	95.4	72.8^{a}	22.6^{a}	121.9	83.9^{a}	38.0^{a}

N Input = Biomass × N content, N removal = rice grain yield × N content, N balance = N input- N removal. Legume N input = (N fixed (%Ndf × N accum.)) N removal = (grain N uptake (N harvested in the grain)), N balance = N input-N removal. Presented values are means of *n* = 4 replicates. Different letters within a column denote significant differences different at *p* <0.05 according to Tukey test.

While grain yields in the control treatment reached 4.4 t ha^{-1} in the fringe and 3.2 t ha^{-1} in the middle position, yields were significantly higher following pre-rice green manures in the middle (+34% yield increase) and following post-rice green manure at both positions (+43% to >100% yield increase). No significant residual effects were detected with sole farmyard manure and pre-rice green manure application in the fringe position.

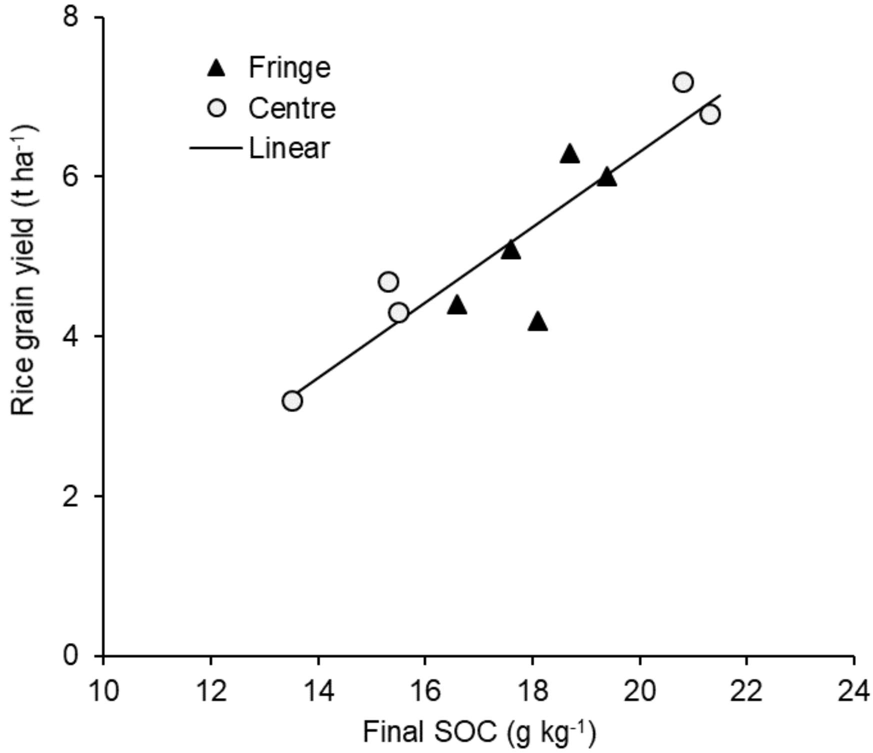

Figure 12. Relationship between final soil organic C and rice grain yield in 2018; $y = -3.13 + 0.47x$, adjusted $r^2 = 0.81$, df = 8, $p < 0.001$; there was no significant interaction between position and the relationship between soil organic carbon (SOC) and rice grain yield.

Averaged across treatments, the residual yield effects of previously applied organic amendments tended to be higher in the middle than in the fringe positions with 80% and 23% higher yields than in the non-amended control, respectively. N additions by dry and wet deposition or by free-living nitrogen fixation as well as removal by volatilization and denitrification and leaching are not considered.

Table 9. Residual effect of treatment application on changes in topsoil (0–20 cm) concentration of total carbon and nitrogen before the start of the experiment in 2015 (initial) and after harvesting the third crop in 2017 (final) and on the grain yield of an unamended crop or rainfed lowland rice in 2018.

Position/Treatment	**Total Soil Carbon ($g\ kg^{-1}$)**			**Total Soil Nitrogen ($g\ kg^{-1}$)**			**Rice Yield ($t\ ha^{-1}$)**
	Initial	**Final**	**%Δ**	**Initial**	**Final**	**%Δ**	
Fringe							
Control	17.0 ±1.07 a	16.6 ±0.52 b	−2.4	0.92 ±0.07 a	0.91 ±0.00 c	−1.1	4.4 ±0.57 c
Farmyard manure (FYM)	17.0 ±1.48 a	17.6 ±1.63 b	3.5	0.85 ±0.07 a	0.98 ±0.04 b	15.3	5.2 ±0.56 bc
Pre-rice green manure (GM)	16.0 ±1.07 a	18.1 ±1.18 ab	13.1	0.87 ±0.05 a	0.98 ±0.05 ab	12.6	4.3 ±0.41 c
Post-rice green manure	17.5 ±2.27 a	18.7 ±0.69 a	6.9	0.92 ±0.09 a	0.99 ±0.00 a	7.6	6.3 ±0.45 a
Post-rice GM + FYM	15.1 ±1.42 a	19.4 ±0.94 a	28.5	0.81 ±0.07 a	1.12 ±0.08 a	38.3	6.0 ±0.61 ab
Middle							
Control	13.7 ±1.59 a	13.5 ±1.09 c	−1.5	0.90 ±0.12 a	0.86 ±0.08 c	−4.4	3.2 ±0.26 c
Farmyard manure (FYM)	14.8 ±2.13 a	15.3 ±2.56 b	3.4	0.92 ±0.14 a	1.01 ±0.18 b	9.8	4.7 ±0.74 b
Pre-rice green manure (GM)	13.7 ±3.42 a	15.5 ±2.09 ab	13.1	0.89 ±0.21 a	1.03 ±0.13 ab	15.7	4.3 ±0.23 b
Post-rice green manure	16.0 ±1.00 a	21.3 ±3.00 a	33.1	0.97 ±0.00 a	1.40 ±0.20 a	44.3	6.8 ±0.22 a
Post-rice GM + FYM	14.3 ±1.93 a	20.8 ±1.69 a	45.5	0.97 ±0.15 a	1.44 ±0.09 a	48.5	7.2 ±0.49 a
Source of variation							
Treatment	ns	*		ns	*		*
Location	ns	ns		ns	ns		ns
Location x Treatment	ns	ns		ns	ns		ns

Residual response for the unamended rice crop in 2018. Values (means ± SE) followed by different letters within a column denote significant differences at p <0.05 according to Tukey Test. Significant level '*' 0.05, ns—not significant.

3.4 Discussion

3.4.1 Niches for organic amendments

Despite the undisputed large potential of organic amendments for enhancing the productivity and sustainability the availability of farmyard manure is often limited for farmers who don't have animals or it has contested alternative uses, i.e., as amendment in home-gardens or as domestic fuel (Reddy et al., 2005) and only few legumes species are used as green manures in Africa (Dakora and Keya, 1997). Thus, the rice-growing area under green manure legumes or receiving farmyard manure has declined from >20 Mio. in the 1980s to <5 Mio. ha in the early 2000s (Becker, 2001). Such trends raise the question if organic amendments in general and leguminous green manures in particular have not loomed larger in scientists' minds than in those of farmers. In consequence, since the mid-1990s, scientists have analyzed the agronomic and socio-economic constraints to adopting organic amendments at farm level and tried to define niche environments where organic amendments outcompete mineral nutrient sources (Mtei et al., 2013).

Such analyses point to legume seed availability, land limitations for legume growth and labor constraints for manure transport and incorporation to be the main culprits for low adoption rates (Becker and Ladha, 1996). Niche environments where green manures out-compete mineral N fertilizers were identified as rainfed systems with variable hydrology and sandy soil texture (Becker et al., 1995b). In consequence, the use of organic amendments is likely to have the largest impact in environments with little or no labor constraints (small field sizes in densely populated areas or availability of mechanical implements) and in hydrologically-variable environments with light-textured soils. These latter conditions negatively affect the use efficiency of applied mineral N fertilizer and favor the mineralization and effective N uptake by rainfed lowland rice from organic sources. Such social-ecological conditions are largely provided in Kilombero floodplain with land-holdings of <1 ha, the availability of tractor-based tillage implements (Kassie et al., 2013). In addition, the absence and the relatively high cost or the untimely availability of mineral N fertilizers (Chianu et al., 2012), leave smallholder farmers in the Kilombero floodplain with organic amendments as the more attractive option to improve soil attributes, supply N and increase the performance of the prevailing low-input rainfed rice production systems.

Furthermore, hydrology is a major factor affecting the crop sequence and determining the integration of green manure legumes into rainfed rice production systems. The unreliable water availability associated with many rainfed situations also increases the riskiness of green manure use. Climate projections for Tanzania indicate trends of increasing rainfall amounts in the short (November-December) while decreasing in the long (March-May) rainy seasons (Gebrechorkos et al., 2019). While these projections are expected to favor the integration of legumes in the pre-rice niche, the delay in the onset of the main rainy season with more intense but short rainfall events may also attenuate the moisture deficit in the early dry season (Näschen et al., 2019), thus favoring diverse crop options, including green manures in the post-rice niche. This situation was exemplified in the present study by a relatively better performance of both the pre- and the post-rice green manures in the wet middle position and during the wet year of 2017.

3.4.2 Direct benefits of organic amendments

The present study considered the application of both farmyard manure and the in-situ growth of green manures as organic amendments for rainfed lowland rice in different floodplain environments of Kilombero (Figure 10). Depending on the position and the year, such strategies resulted in yield increases of 18–62% above the non-amended control. The positive effects from organic amendments can be attributed to the improvement in soil fertility compared to the low indigenous soil fertility in the control treatment. The extent of these yield-increasing effects was in a comparable order of magnitude as effects reported from annual green manure legumes in irrigated rice of the Philippines (Becker et al., 1995a), of perennial legume residues in Zimbabwe (Chikowo et al., 2004), and of farmyard manure on rainfed rice in the Indian Punjab (Ladha et al., 2004a). However, in these studies, application rates of organic N sources were either substantially higher than in the present study, or organic amendments were supplementing an application of mineral N (Wei et al., 2016). Furthermore, beneficial effects of legume green manures were shown to occur in relatively fertile Gleysols in inland valley wetland with subsurface water and nutrient flow contributions from adjacent valley slopes in West Africa (Bado et al., 2011).

The observation is that relatively modest N application rates suffice to enhance the performance of lowland rice in floodplain environments with low soil fertility and additionally differentiated responses to both pre- and post-rice strategies in different hydrological positions. A similar trend was observed but with a larger magnitude of up to 133% yield increase when recommended rates of mineral fertilizer N were applied at the same experimental sites and in the same years (Kwesiga et al., 2019). The large, and compared to organic amendment relatively higher rice yield responses to mineral N, even at the moderate application rate of 60 kg ha^{-1} could be related to the low N status of the alluvial floodplain soils (Daniel et al., 2017), where additionally small-scale farmers are not applying fertilizers and are hence mining the soil for nutrients (Senthilkumar et al., 2018). Such soil fertility considerations are likely to affect particularly organic amendments that have to undergo microbial decomposition before nutrients become plant available. On the other hand, mineral N sources are often not available and rarely affordable by small-scale farmers (Tsujimoto et al., 2019).

Reported benefits from green manures are mainly related to the legumes' ability to accumulate sufficient biomass and to fix atmospheric N_2 during a short growing period. In our study, the amount of atmospheric N fixed in the above-ground green manure legume biomass contributed 4–61 kg N ha^{-1}, depending on the species, the production system, and the fields' position within the floodplain (Table 7). These amounts are substantially less than those reported from some studies in favorable irrigated systems (Peoples et al., 2009) but within the range of works conducted in unfavorable rainfed lowlands in Cambodia (Ro et al., 2016) or North-East Thailand (Haefele et al., 2006). The share of N derived from the atmosphere (Ndfa) by biological N_2 fixation was assessed by the $\delta^{15}N$ method as suggested by other authors (Nyemba and Dakora, 2010) and ranged from 23% to 59%, depending on the species and the system (pre- vs. post-rice legumes). While the net N contributions from multi-purpose long-duration cowpea and from lablab were consistent with ranges reported from grain cowpea (Naab et al., 2009) or lablab in West Africa (Sanginga, 2003), the N contribution by stylosanthes grown as a post-rice forage species was much lower than that reported from rice-based systems in Madagascar (Zemek et al., 2018) or from maize-based systems in Kenya (Ojiem et al., 2007). Severe drought following the harvest of rice in 2015 combined with soil compaction after flood recession were likely to have affected legume establishment and stylosanthes growth during the dry season (Figure 10).

Also, the small seed size of stylosanthes compared to lablab or cowpea may have negatively affected germination and crop establishment and increased performance variability between years and positions, but also within plots. A poor stand establishment with small-seeded legumes is related to imperfect land preparation and seed deposition at variable depths, from which large seeded legumes can more easily recover than small-seeded ones (Madanzi et al., 2010). We conclude that long-duration multipurpose (forage and green manure) legumes will be required for the extended post-rice niche while short-duration and thus generally larger-seeded (grain and green manure) legumes may be preferred for the pre-rice niche in hydrologically variable floodplain environments.

3.4.3 Residual benefits of organic amendments in Kilombero

Irrespective of the legume species, the system or the study year, sole growth of green manure legumes resulted in largely negative partial N balances. Only with the addition of farmyard manure N balances of the legume-based systems were positive (Table 7). However, these balance calculations disregarded below-ground biomass and N accumulation, which may have severely under-estimated the legumes' contributions to N balances, particularly in the case of stylosanthes with its extensive and deep root system. On the other hand, the N balances may be even more negative when gaseous N losses are accounted for (Becker et al., 2007). Thus, some 15 kg N ha^{-1} are reportedly being lost by the process NH_3 volatilization in rice systems in Asia (Pathak et al., 2006; Zhang et al., 2018), while N losses by denitrification and nitrate leaching have been estimated at 32 kg ha^{-1} in non-amended rainfed rice in Nepal (Becker et al., 2007) and in Ghana (Asante et al., 2017). However, long-term experiments have shown that most of the N added by organic amendments is contained in various organic fractions (Hong et al., 2019) and becomes only gradually plant available after microbial decomposition. Thus gaseous N losses are minimized and residual effects on subsequent crops can reportedly occur (Becker et al., 1994), as also observed in the present study where yield increases in previously legume-amended plots could reach 4 t ha^{-1} in 2018. (Table 9). The slow mineralization of both farmyard and green manures compared to mineral N fertilizer (Naher et al., 2018). This may have contributed to the observed build-up of soil organic C and N during the two years of continuous organic treatment application as suggested before (Lal, 2015). Thus contributing to the observed residual benefits on soil C and N (Table 9), and presumably to higher water-holding capacity (Samal et al., 2017) and rice yield stability (Ladha et al., 2011). Similar residual benefits from sustained application of organic amendments have been reported from rainfed lowland rice systems in Asia, particularly on sandy soils with low inherent organic matter contents (Ladha et al., 2004b). Such effects are however not uniform, and in the present case, they differed not only between amendment types and systems but also by the hydrological position of the field plots within the floodplain (Table 9). Thus, largest residual mean rice gain from previously amended plots was observed in the middle positions, while gains were less evident in floodplain fringes. This observation further stresses that the effects of organic amendments strategies are transferable in both hydrological positions but higher in the middle position of the Kilombero floodplain.

In summary, we assessed legume performance as well as direct and residual yield benefits from different organic amendments. The reported effects of manures on increasing rice grain yields, and soil C and N contents were confirmed for a floodplain wetland in East Africa by our work. We believe that comparable benefits may be obtained in other hydrologically variable floodplain environments of the region and beyond. However, given the large variability in hydrological situations both between positions and years, the effects of building soil organic matter for buffering hydrological extremes as well as the phyto-sanitary and weed suppression aspects warrant further research attention in the future.

3.5 Conclusions

This study highlights the importance of green and farmyard manure application in resource-poor smallholder rice farming systems. Repeated application of organic amendments can enhance soil C and N with associated effects on direct and residual rice yield increase in the Kilombero floodplain. With the prevalence of rainfed lowland systems with one single crop per year, there are available cropping niches for both pre- and post-rice green manure growth. In addition, the widespread cattle rearing in the area ensures the availability of farmyard manure. These organic amendments provide small-scale rainfed rice farmers with a promising alternative to poorly-available and generally non-affordable mineral N fertilizers for soil fertility restoration and enhanced sustainable food production in hydrologically variable floodplain environments.

Chapter 4

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Rice yield gaps in smallholder systems of the Kilombero floodplain in Tanzania

Abstract

To meet the growing rice demand in Africa, gaps between actual and attainable yields have to be reduced. In Tanzania, this particularly concerns smallholder rain-fed production systems in the floodplains. After quantifying the existing yield gaps, key contributing factors need to be analyzed to improve site-specific management. Field experiments were conducted for three years and in three pedo-hydrological environments (fringe, middle, and center positions) of the Kilombero floodplain to evaluate: (1) The grain yield under farmers' management (actual yield), (2) yield with the best-recommended management (attainable yield), and (3) the non-limited yield simulated by the APSIM model (potential yield). In the field, we additionally assessed incremental effects of (1) field bunding and soil levelling, (2 and 3) additionally applying of 60 kg N ha^{-1}, as urea or as farmyard manure (FYM), and (4 and 5) incorporating in-situ-grown leguminous green manures. Attainable yields were determined with mineral N application at 120 kg ha^{-1}, additional PK fertilizer and supplemental irrigation. On average across years and positions, the potential, the attainable, and farmers' actual yields were 11.5, 8.5, and 2.8 t ha^{-1} indicating a high total yield gap. About 16–38%, 11–20%, and 28–42% of this gap could be attributed to non-controllable yield-reducing (i.e., pest and diseases), yield-limiting (i.e., water and nutrient deficiencies), and yield-defining factors (i.e., poor soil and crop management), respectively. Results indicate a closure of the exploitable yield gap (differences between attainable and farmers' actual yields) by up to 6.5 t ha^{-1} (nearly 60% of the potential yield). This exploitable yield gap was larger in 2016 than in 2017. Also, the gap was larger in the water-limited fringe and middle than in the frequently submerged center positions. Simple field bunds combined with land levelling could close 15–35% of the exploitable yield gap, depending on field positions and year. FYM or green manures were less effective than mineral N; however, in 2017 and in the wetter middle and center positions, they reduced the yield gap by >50%. We conclude that yield gaps in rainfed rice in Kilombero floodplain are large, but that a site- and system-specific adaptation of crop management can close much of the exploitable yield gap and increase grain yields by 0.7–4.8 t ha^{-1}. Similar benefits may be obtained in other hydrologically variable floodplain environments of the region and beyond.

4.1 Introduction

In many countries of sub-Saharan Africa, rice increasingly replaces traditional staple food crops such as maize and cassava in both daily diets and in dominant agro-production systems. However, with about 2 t ha^{-1}, grain yields of rain-fed lowland rice in Africa are far below the global average of 3.1 t ha^{-1} (Tanaka et al., 2017). Rice supply gaps in most countries are caused by low yields in combination with high demographic growth and are, in many instances, further exacerbated by land scarcity (Scoones et al., 2019). Meeting the growing future rice demand will require either an expansion of the rice-growing area (Tilman et al., 2011) or a substantial increase in rice yields from current farmland, without compromising the environment (Zabel et al., 2019). It has been suggested that yield gains can easily be achieved by applying existing knowledge and adopting available technologies for narrowing the existing large gaps between potential and farmers' actual yields (Neumann et al., 2010). The extent of the yield gaps and the effectiveness of technology options to close them largely differ by crop species, production environments and farmers' ability to adopt technologies (Fischer, 2015). Such yield gap analyses have been widely applied and are postulated to be useful tools for food security assessment (van Ittersum and Cassman, 2013), for priority-setting in research and development (van Oort et al., 2017), for policy framing both at local and at regional scales (Sumberg, 2012) and to evaluate the impacts of climate change (Lobell and Gourdji, 2012; van Oort and Zwart, 2018).

The term "yield gap" was first used in the 1970s by Herdt and Wickham (Herdt and Wickham), defining it as the difference between the maximum experimental station and the national on-farm average yields. Later, this definition was refined and expanded as yield gaps being the difference between biological potential or the water-limited potential and the actual yield in farmers' field (Fischer, 2015). Further, differentiation included the definition yield-defining, yield-limiting, and yield-reducing factors, which allowed better explanation of yield levels and differences (van Ittersum and Rabbinge, 1997). Since the 1990s, the genotype-specific "biological potential" of rice has been assessed initially under no-resource-limited conditions by the crop growth model ORYZA1 (Kropff et al., 1994). Later, water-limited potentials were simulated by ORYZA-W (Wopereis et al., 1996) and N-limited yields by ORYZA-N (Drenth et al., 1994). ORYZA2000 rice model integrates previous ORYZA models

(Bouman, 2001). The physiological part of ORYZA2000 was incorporated into the APSIM model for failure to simulate long-term flooded conditions (Gaydon et al., 2012). Further improvements and limitations of rice model have been discussed in (Gaydon et al., 2017) for APSIM but also in (Li et al., 2017) for ORYZA (v3). In 2019, a global sensitive analysis of the "Rice" module in APSIM (APSIM-Oryza) provided more comprehensive insights into the model and its parameters compared to existing studies (Liu et al., 2019). (Beza et al., 2017) suggested to include social and economic factors (beyond ecological and management factors). The resulting analyses are diverse and cross-comparisons are reportedly difficult because of lack consistency between various studies. Therefore, the general usefulness of yield gap analyses in the context of development-oriented agronomy still remains to be questioned (Beza et al., 2017). It is thus not surprising that the links between identified yield gaps and proposed technical solutions are still weak and non-specific (Lobell, 2013). However, within a specific and well-defined or homogenous environmental setting, yield gap analyses are capable of successfully shaping priority setting and assisting in technology targeting and influence policy formulations (Muller et al., 2017; Stuart et al., 2016).

In this study, the difference between simulated potential and farmers' actual yields has been termed the "total yield gap". It comprises yield-defining factors which are non-controllable or difficult to control, such as some pests, diseases, topography effects, crop submergence, or storm damage. The difference between the simulated potential and the yield attained under optimal conditions is termed "yield gap 1". The total yield gap further comprises the yield-limiting factors, which are mainly related to water shortages or nutrient deficiencies. These factors are manageable with supplemental irrigation and fertilizer applications and determine the "yield gap 2". Finally, there are yield-reducing factors that contribute to the total yield gap and these comprise several land and crop management practices that are often associated with poor management, such as the lack of land levelling or field bunding and the timely control of weeds or application of fertilizers and are termed "yield gap 3" (Tittonell and Giller, 2013). The combined effects of yield-defining, limiting and reducing factors determine the extent of the total yield gap.

For closing the yield gap, there is a need to (i) quantitatively and site-specifically evaluate key contributing factors. (ii) analyze the yield effectiveness of available technology options, and (iii) target interventions which are likely to have the strongest impact. Thus, the yield gap is decomposed into yield-effective contributing factors and their extent and usefulness in closing existing gaps. This approach has been successfully applied to quantify the role of weed management in upland rice systems (Becker and Johnson, 1999b), the effects of weed and fertilizer N management in irrigated rice systems (Becker and Johnson, 2001), and for the role of land management and genotype on rainfed rice yield in hydrologically variable valley bottoms (Touré et al., 2009). In rainfed rice production systems with varying soil properties and hydrology, there is a need for site-specific management options for smallholder farmers to benefit from such practices (Tsujimoto et al., 2019).

In the present research, the decomposed yield gap analysis was used to assess the productivity of rainfed lowland rice in the Kilombero floodplain of Tanzania. With some 800,000 ha, the floodplain is the largest rice-growing area of the country and is expected to contribute to national and regional self-sufficiency by 2030 (Buseth, 2017). Rice is mainly produced in smallholder systems that rely on traditional practices and low use of external inputs, resulting in low yields. Due to resource limitations, preferences for local genotypes, and poor access to modern technology, smallholder farmers are unable to benefit from recent innovations (Kwesiga et al., 2019). However, substantial yield increases of about 3 t ha^{-1} are reportedly possible when applying recommended crop, soil, and weed management practices (Senthilkumar et al., 2020), or by applying good agricultural practices in combination with improved genotypes (Senthilkumar et al., 2018). However, the benefits of such technologies are highly variable between years and production sites. The yield gap analysis for Kilombero floodplain must thus comprise an analysis over several years. It must further cover the diversity of the main biophysical land units prevailing in the floodplain considering those technology options that are available for the smallholders in the area. We hypothesized that applying this approach to Kilombero floodplain can site-specifically differentiate the benefits of specific agronomic interventions, and thus assist in formulating management recommendations for closing the existing large yield gap in this region. The main objectives of this research were; (1) to quantify actual and potential rice yields and their variability in space and time; and (2) to identify the causes of yield gaps by applying available land and fertilizer management options at different hydrological positions.

4.2 Materials and methods

4.2.1 Experiments

Field trials on private farms were conducted from 2015 to 2017 in the Kilombero floodplain, Ifakara, Tanzania. Fields were located at the fringe, middle and center positions, representing the typical hydrological production situations in rain-fed floodplain environments. The positions were selected based on inundation depth and flooding duration, plus their distance relative to the river (center) and the adjacent mountain ranges (fringe). The fringe position was located closest to the Udzungwa Mountains and furthest from Kilombero River. The fringe position has only short periods with ponded water during the main rainy season but has a relatively shallow groundwater due to subsurface interflow from the mountain slopes (Gabiri et al., 2018). The center position experiences extended periods of soil submergence by the overflowing Kilombero River, and soils tend to maintain high residual moisture contents after flood recession (Näschen et al., 2018). The middle position represents an interm-ediate situation with water contributions from both subsurface flow and river spill-over.

Daily solar radiation, maximum and minimum temperature, rainfall, relative humidity, and wind speed were obtained from an automated climate station at the Ifakara Health Institute, located 5 km away from the study areas. The experimental location has a sub-humid tropical climate with average annual temperatures between 22 and 23 °C with maximum and minimum peaks in December and July, respectively. The area receives binomial rainfall with about 90% of the annual rainfall between December and April. During the experimental period, the area received 846 mm, 787 mm, and 1252 mm of rainfall in 2015, 2016, and 2017, respectively. The mean maximum and maximum solar radiation varied from 16–25 MJ m^{-2} $year^{-1}$ day^{-1}. Soil attributes differed between positions with increasing clay content of 14.0% at the center to 36% in the fringe position. The reverse was true for the sand content increasing from 12% to 27% in the fringe and center positions respectively. The N content is generally low irrespective of the position of the floodplain with 1.0, 0.9, and 1.7 mg kg^{-1} in the fringe, middle, and center positions, respectively. Soil samples were taken from a depth of 20 cm before the first crop establishment to be analyzed for major physio-chemical attributes. Further details are provided in chapter 1.

4.2.2 Treatments and management

In each position, on-farm experiments were conducted with experimental plots of 30 m^2 (6 × 5 m), for each treatment. The experimental treatments were laid out in a randomized complete block design (RCBD) replicated four times. The treatments included: Farmers' practice, bunding and levelling, recommended practice, organic N (farmyard manure), pre-rice green manure, post rice green manure and best practice. All land and crop management was done by the researcher, following a standardized experimental protocol, including the following treatments:

(1) Farmers' practice: treatment plots were neither bunded nor levelled. No mineral or organic fertilizers other than the returned rice straw were applied, and plots received one-time hand weeding at 30 days after transplanting. Grain yields in this treatment are referred to as farmers' actual yield.

(2) Bunding and levelling: In contrast to farmers' practice, individual field plots were surrounded by 40 cm high and 20 cm wide bunds and the soil within the plot was manually levelled during puddling. No fertilizers but one additional weeding at 50 days after transplanting were applied. Yield gains obtained in this treatment were assigned to the effects of improved land management.

(3/4) Fertilizer N: In these treatments, plots were bunded and levelled and received the recommended rate of 60 kg N ha^{-1} either in the form of split-applied urea, with half applied basally and half at panicle initiation stage (treatment 3), or by one single basal application of fresh farmyard manure adjusted to an N rate of 60 kg ha^{-1} (treatment 4). Depending on the N content, farmyard manure application rates varied between 5.0 and 6.7 kg ha^{-1}.

(5/6) Two available green manure options including the in-situ growth of either lablab (*Lablab purpureus*) during the six-week period between the onset of the rain and the transplanting of rice (pre-rice green manure) (treatment 5) or of *Stylosanthes guianensis* established on residual soil moisture after rice harvest and occupying the plot for about six months until manual incorporation into the soil and the transplanting of rice (post-rice green manure) (treatment 6). The treatments 2–6 represent locally-available and/or recommended practices and are components of the "achievable yield".

(7) Best practice: The bunded and levelled regularly weeded plots received 120 kg urea-N ha^{-1} (split application), a basal application of 60 kg P (Single Super Phosphate) ha^{-1} and 60 kg K (KCl) ha^{-1} and supplementary irrigation as required to maintain constant water saturation. The management options are non-limiting under on-farm researcher managed conditions. Such practices are usually either not accessible or not affordable for smallholder farmers. This treatment represents the “attainable yield”.

All plots were homogenously transplanted at a 20 × 20 cm spacing with 28 day-old seedlings of the high-yielding genotype SARO5 (TXD 306) that is promoted by the Tanzania Agricultural Research Institute (TARI). Rice grain yield was determined from 6 m^2 area at the center of each plot, air dried, weighed, measured with a digital grain moisture meter (Satake Moistex SS7) and adjusted to 14% grain moisture content.

4.2.3 Yield gap concept and data analyses

The APSIM model combines biophysical and management modules within a central engine to simulate cropping systems. The APSIM-Oryza module simulates rice growth under potential production, water-limited and N-limited simulations (Gaydon et al., 2017). Using 2015 experimental data, the model was supplied with local input parameters which were directly measured, i.e., soil characteristics, water table dynamics, and recorded daily climate variables, i.e., solar radiation, maximum and minimum temperatures and rainfall. The parameters were used to parameterize soil water characteristics and soil organic matter decomposition rates. Variety-specific development parameters and partitioning coefficients for "SARO-5" were determined from observed key phenological stages and sequential biomass accumulation and partitioning data of treatment 7 while calibration performance was assessed against treatment 2 and 3 as well. The simulated outputs for rice phenology, biomass accumulation and partitioning, and grain yield were compared with observed values. The calibrated model was tested against data from 2016 and 2017 for model validation. The validated model was hence used to simulate potential yields by providing daily ample water and nitrogen for un-limited crop growth. In this study, the model’s capacity to provide potential yields from the different hydrological positions was the main aspect for evaluation. The middle was used as a proxy for the center due to complete crop failure resulting from prolonged submergence in 2015. Detail on model calibration and validation is given in our paper in prep (Grotelüschen et al., 2020 in press).

The actual farmers' yield (Y_{Fac}) was obtained from non-bunded and levelled and non-amended field plots (treatment 1), while the attainable yields (Y_{Att}) were determined from the "best practice" (treatment 7). The difference between the simulated potential yield (Y_{Pot}) and farmers' actual mean yield (Y_{Fac}) represents the total yield gap (YG_T). This gap comprises all yield-determining factors, including those that cannot be controlled by farmers. More appropriate for agronomic purposes is the difference between the yield that is attainable with best management practices (Y_{Att}) and farmers' actual mean yield (Y_{Fac}) indicating the exploitable yield gap (YG_E). For assessing the determinants of the exploitable yield gap the effects of sequentially super-imposed treatments of land management (bunding and levelling), of recommended fertilizer N, and of a combination of high NPK and supplemental irrigation were calculated based on data of treatments two to seven. The general conceptual framework and the different incremental levels of yield-limiting and yield-reducing factors in the yield gap analysis are illustrated in Figure 13. The modes of calculation are as follows:

Total gap:	$Y_{GT} = Y_{Pot} - Y_{Fac}$	(yield-defining, limiting, and reducing factors);
Yield gap 1:	$Y_{G1} = Y_{Pot} - Y_{Att}$	(yield-defining; non-controllable factors);
Yield gap 2:	$YG_2 = Y_{Att} - Y_{Ach}$	(only the yield-limiting factors);
Yield gap 3:	$YG_3 = Y_{Ach} - Y_{Fac}$	(only yield-reducing factors);
Exploitable gap:	$Y_{GE} = Y_{Att} - Y_{fac}$	(yield-limiting and reducing factors);

whereby Y_{Pot} is the simulated potential, Y_{Att} is the attainable, Y_{Ach} the achievable, and Y_{Fac} farmers actual rice grain yield.

We considered a new indicator focusing on the percentage share of individual sequentially applied management practices on the exploitable yield gap. This share was calculated as the ratio between the absolute increase of yield (Yai) above the farmers' practice and the exploitable yield gap (Y_{GE}), expressed as a percentage (Equation (5)). This indicator helps to quantify the relative importance of the specific measures for closing the exploitable yield gap.

$$\%Y \text{ share} = Yai/Y_{GE} * 100 \quad (5)$$

Descriptive statistics, including arithmetic means, standard errors of the mean, variances, and the percentage share on the exploitable yield gap, were calculated for the main effects of management practices (1) across years and (2) across hydrological positions. A linear mixed model fit by Restricted Maximum Likelihood (ReML), and Satterthwaite's method was used for the t-tests using R software version 3.5.0.

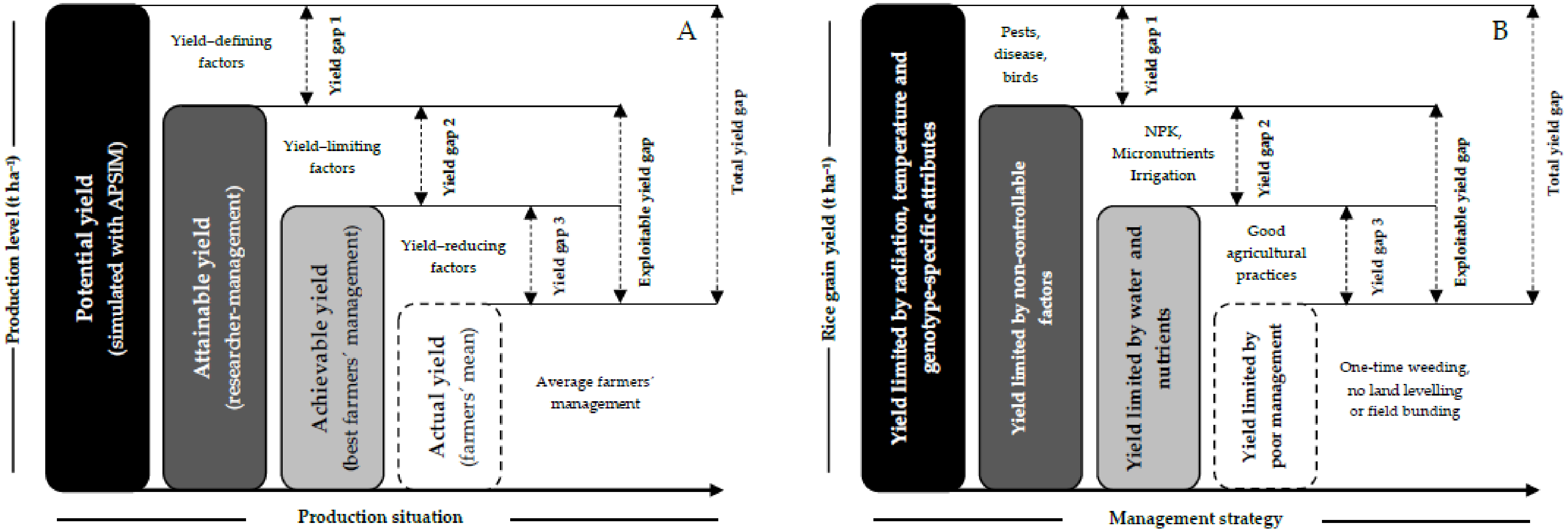

Figure 13. A conceptual framework for the analysis of yield gaps (A) and the concept applied to yield gaps in rain-fed lowland rice in the Kilombero floodplain (B).

4.3 Results

The farmers' actual and simulated potential yields, the yield attainable and those obtained by applying individual management practices, and the relative share of management interventions in closing the exploitable yield gap are presented for the different hydrological positions in Figure 14 and for the different study years in Figure 15.

4.3.1 Total and exploitable yield gaps

Rice grain yields from farmers' practice (actual yields) (Y_{Fac}) varied between 1.2 to 4.9 t ha$^{–1}$, depending on the year and the hydrological position. The yield variability within hydrological positions increased from the fringe with 3.3 ± 0.8 t ha^{-1} to the center position with 2.6 ± 1.3 t ha$^{–1}$ (Figure 14). While yields tended to be higher in 2017 than in 2016, such differences were not significant (Figure 15). The average potential grain yields (Y_{Pot}) were relatively stable, ranging from a low of 10.4 t ha$^{–1}$ in 2016 in the middle position to 12.3 t ha$^{–1}$ in 2017 in the middle and fringe position. The resulting total yield gap (Y_{GT}) (Y_{Pot}−Y_{Fac}) was accordingly very large, ranging between years from 8.2 t ha$^{–1}$ in 2015 to 9.5 t ha$^{–1}$ in 2017 and between positions from 8.3 t ha$^{–1}$ in the fringe to 9.0 t ha$^{–1}$ in the middle (Table 10). These gaps represent 72 to 77% of the potential yield. However, they contain yield-defining factors that cannot be controlled by management interventions. More realistic for assessing management interventions to effectively close the gap is thus the exploitable yield gap, which represents the difference between attainable and farmers' actual yields. The attainable rice yields, resulting from best management practices (Y_{Att}), varied between 6.4 and 11.3 t ha$^{–1}$, with the highest attainable mean yield of 9.8 t ha$^{–1}$ in the fringe, and the lowest with 7.1 t ha$^{–1}$ in the center position. Between years, the attainable yields varied relatively little with a maximal difference between 2015 (highest Y_{Att}) and 2016 (lowest Y_{Att}) of only 0.7 t ha$^{–1}$. Accordingly, the mean exploitable yield gap (YG_E) (Y_{Att}−Y_{Fac}) was 5.7 t ha^{-1} (3.1 t ha$^{–1}$ less than YG_T) across hydrological positions and years. The largest mean YG_E was observed in the fringe (6.5 t ha$^{–1}$), and the lowest was observed in the center (4.4 t ha$^{–1}$). The YG_E varied little between years, with a maximum of 5.9 t ha$^{–1}$ in 2017 and a minimum of 5.5 t ha$^{–1}$ in 2016.

Thus, the exploitable yield gap amounted only 39 to 56% of the potential yield across positions (Table 10).

4.3.2 Disentangling the total yield gap

Non-controllable factors accounted for 1.8–4.3 t ha^{-1} of grain yield and hence between 16% and 38% of the total yield gap cannot be closed by improved management (yield gap 1). This non-accountable yield gap was largest in the center position of the floodplain. Yield-limiting factors or application of cropping practices that are not at the reach of common smallholders define yield gap 2. This YG_2 was relatively small. While it varied little between years (1.2–2.3 t ha^{-1}), it was much larger in the drought-prone fringe. Here, it accounted for 20% of the yield gap compared to only 11% in the middle and center each. Finally, yield gains that can realistically be achieved by applying available technology options were in the range of 3.2 to 4.8 t ha^{-1}, closing 28–42% of the yield gap and contributing to the largest share of the yield gap overall (Table 10).

Table 10. Effect of hydrological position and seasonal variation on the total and the exploitable yield gaps (expressed as the percentage share of the simulated potential yield), and the share attributed to non-controllable factors (YG_1), to water and nutrient limitations (YG_2), and to good agricultural practices (YG_3) in closing the yield gap in the Kilombero floodplain.

Yield Gaps / Effects		**Reference Gaps**				**Component Gaps**					
		Total Yield Gap (YG_T)		Exploitable Gap (YG_E)		Yield-Defining Factors (YG_1)		Yield-Limiting Factors (YG_2)		Yield-Reducing Factors (YG_3)	
		t ha^{-1}	%	t ha^{-1}	%	t ha^{-1}	%	t ha^{-1}	%	t ha^{-1}	%
Position effects	Fringe	8.3	72	6.5	56	1.8	16	2.3	20	4.2	36
	Middle	9.0	80	6.0	53	3.0	26	1.2	11	4.8	42
	Center *	8.8	76	4.4	39	4.3	38	1.3	11	3.2	28
Time effects	2015 **	8.2	72	5.7	50	2.5	22	1.1	10	4.6	40
	2016	8.6	76	5.5	49	3.1	27	1.4	12	4.1	36
	2017	9.5	77	5.9	48	3.6	29	2.0	16	3.9	32

YG_T: difference between potential and farmers' actual yield; YG_E: difference between attainable and farmers' actual yield; YG_1: share of the yield gap attributed to non-controllable yield-defining factors); YG_2: share of the yield gap attributed to yield-limiting factors; YG_3: share of the yield gap attributed to yield-reducing factors. * only two year evaluation, ** center position excluded.

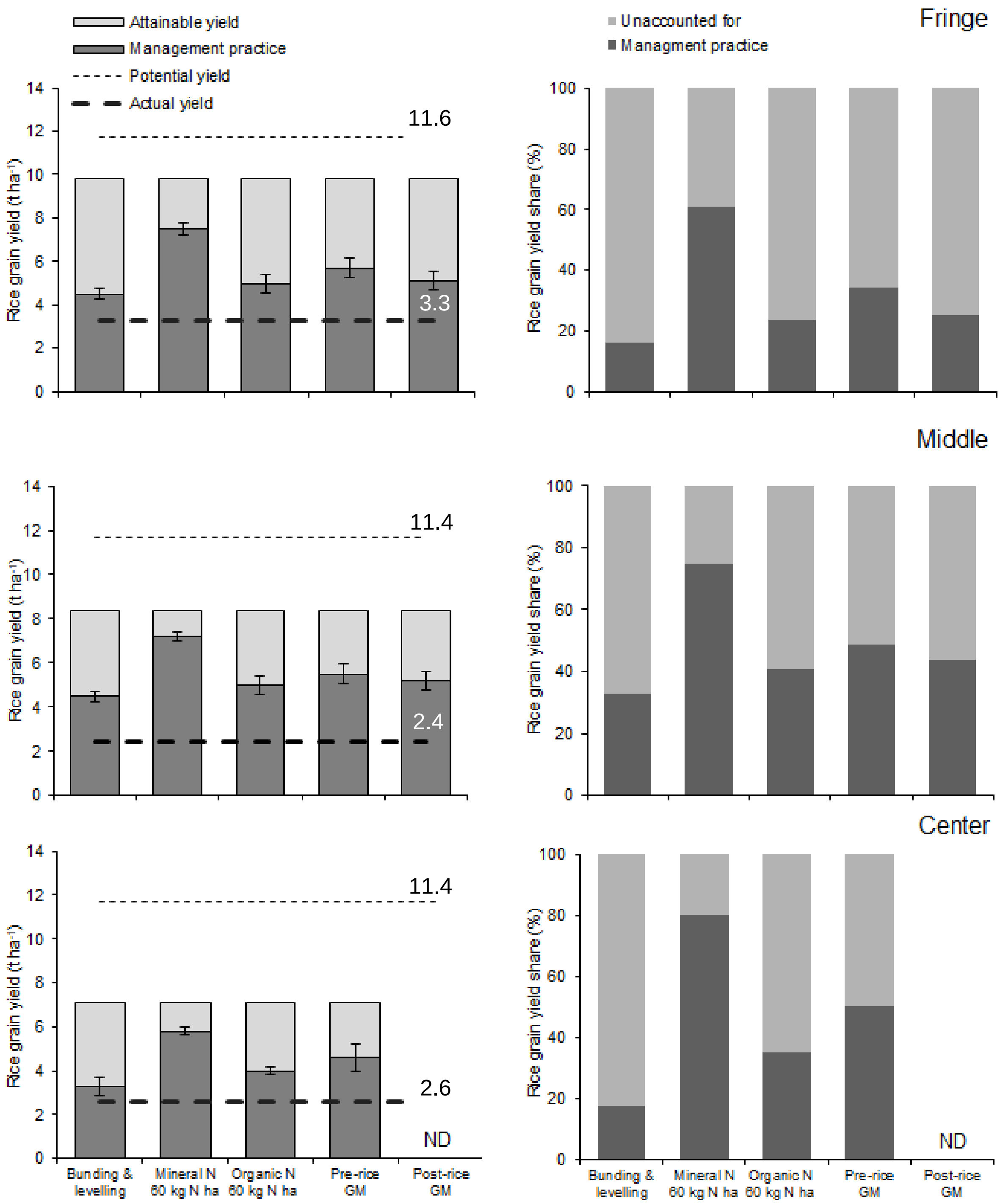

Figure 14. Rice grain yields in Kilombero floodplain attainable with a package of recommended management practices (light grey columns = attainable yield) and grain yields obtained under farmers' management or by applying individual practices (dark grey columns = actual yield) at the fringe, middle and center. The left and right graphs represent mean rice yields of individual practices and the percentage share of the exploitable yield, respectively. Data are means of 3 years (2015, 2016, 2017). Bars present standard error of the mean (n = 12). Dotted lines indicate the potential simulated yield (upper) and farmers' actual yields (lower). Mineral N = Urea, organic N = farmyard manure ND = not determined; GM = green manure.

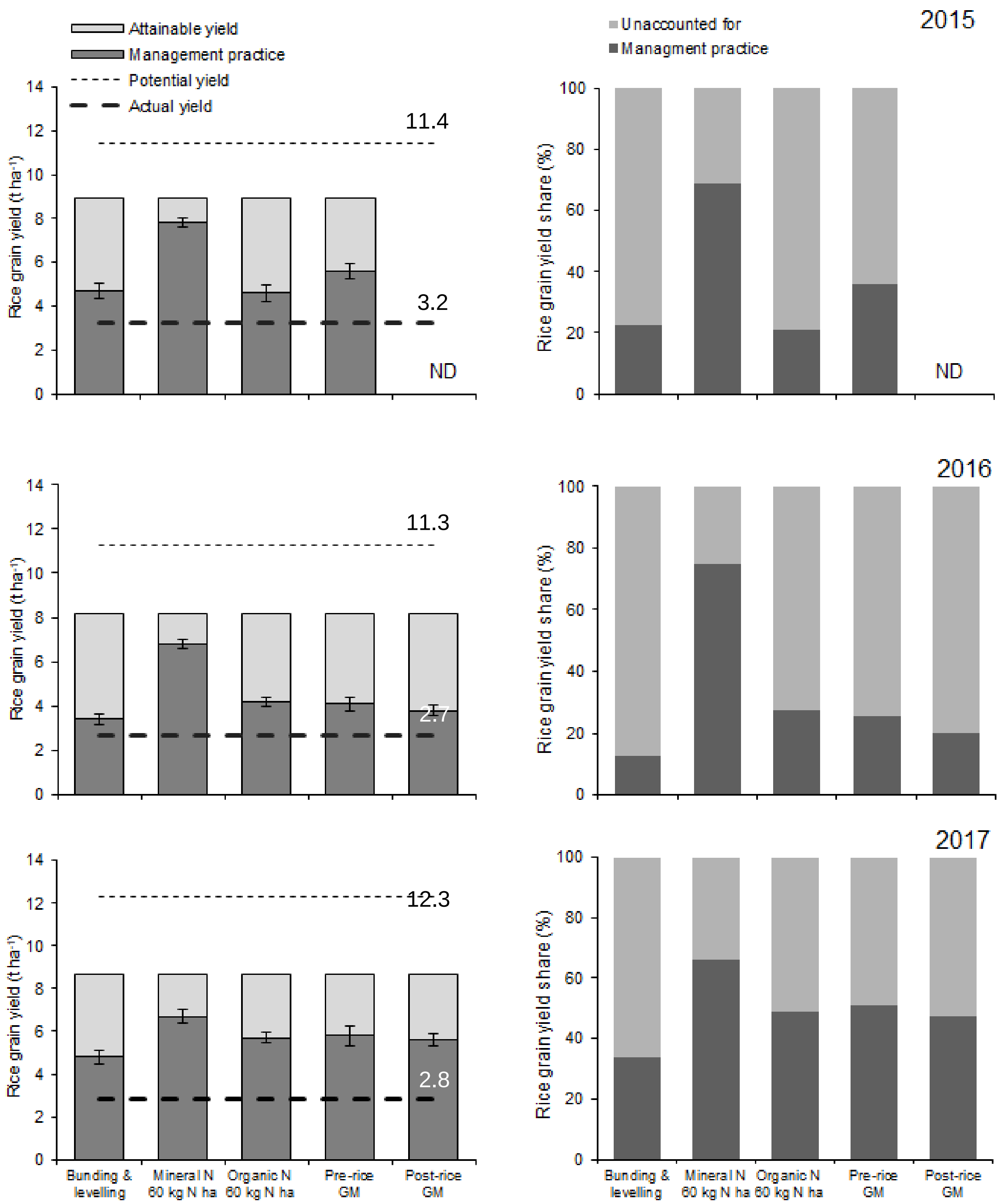

Figure 15. Rice grain yields in Kilombero floodplain attainable with a package of recommended management practices (light grey columns = attainable yield) and grain yields obtained under farmers' management or by applying individual practices (dark grey columns = actual yield) during three consecutive years (2015, 2016, 2017). The left and right graphs represent mean rice yields of individual practices and the percentage share of the exploitable yield, respectively. Data are means of three positions (fringe, middle, center). Bars present standard error of the mean (n = 12). Dotted lines indicate the potential simulated yield (APSIM-Oryza). Mineral N = Urea, organic N = farmyard manure ND = not determined; GM = green manure.

4.3.3 Disentangling the exploitable yield gap

Simple land management was associated with mean rice yields ranging from 3.3 t ha^{-1} to 4.5 t ha^{-1} across hydrological positions. This corresponds to yield increases over farmers' management by 0.7 t ha^{-1} in the submergence-prone center position and reaching 2.1 t ha^{-1} in the middle position. The effect was much higher in 2017 compared to 2016 and 2015. Thus, recommended land management closed >30% of the yield gap in 2017 and in the middle position and <20% in 2016 and the center and fringe positions (Figures 2 and 3).

Combining improved land management with the application of the locally-recommended rate of 60 kg urea-N ha^{-1} produced rice grain yields of 5.8–7.8 t ha^{-1}, corresponding to yield increases above farmers' management by 3.2 to 4.8 t ha^{-1}. This implies that, depending on the year, mineral N could close 66–75% of the exploitable yield gap. This yield gap closing effect was less in the drought-prone fringe (61%) than in the wetter middle (75%) and center positions (80%). Beneficial effects of comparable amounts of organic N (farmyard manure) were much lower, irrespective of the hydrological position. However, the share in closing the yield gap increased over time from 21% in 2015, over 27% in 2016 to 49% in 2017.

In the absence of mineral N or farmyard manure, farmers rely on biological nitrogen fixation by different green manure legumes. Depending on farmers' preference or on available soil moisture for crop establishment, farmers may opt for short-duration legumes during the pre-rice cropping niche, or for forage legumes established on residual soil moisture during the post-rice niche. Both types of green manure were comparable but generally more yield-effective than applying farmyard manure. In the drought-prone fringe, they closed only 30%, in the wetter positions nearly 50% of the exploitable yield gap. Similar to the trend observed in farmyard manure, this effect increased over time with repeated application from initially >20% in 2016 to nearly 50% of the exploitable yield gap in 2017.

4.4 Discussion

This study set out with the aim of quantifying the actual and potential rice yields and their variability in space and time while identifying the causes of yield gaps by applying and modifying available management practices. The findings are valuable indicators for guiding research, extension, and policy formulations in hydrologically variable rain-fed floodplains. In the following paragraphs, we discuss the implications for disentangling the different gaps.

4.4.1 The extent of total and exploitable yield gaps

From our study, actual rice grain yields from farmers' practice were generally low, varying between 1.2 and 4.9 t ha^{-1}, which is similar to findings by (Senthilkumar et al., 2018), who reported grain yields in Kilombero ranging from 0.7 to 4.3 t ha^{-1} in farmers' fields. Yield potentials, on the other hand, were very high and can reach up to 12 t ha^{-1}. The resulting total yield gap was equally very high and actually much higher than the total yield gaps reported from rice-growing areas of South East Asia (Laborte et al., 2012) and West Africa (Saito et al., 2015). However, in these areas, the actual yields in farmers' fields were much higher than those observed in the present study. The amounts of mineral fertilizers used and the general knowledge level of farmers are much higher in those areas where rice is a traditional crop cultivated since centuries or even millennia (Boling et al., 2008; Saito et al., 2019) and where consequently, the exploitable yield gaps (differences between actual and attainable yields) were much lower (1.3–3.8 t ha^{-1}) than in the Kilombero case (5.7 t ha^{-1}). Finally, low and highly variable actual yields in farmers' fields in Kilombero are related to fluctuating and unpredictable hydrological regimes, differing greatly between years and positions causing high risks for rice production.

4.4.2 Disentangling the total yield gap

The yield gains obtained by applying improved or recommended management practices suggest large opportunities for further increases in rice yields beyond the current levels. Our data indicate a closure of the exploitable yield gap by up to 6.5 t ha^{-1} or by nearly 60% of the potential yield (Table 10). In the Kilombero case, non-controllable factors (YG1) were responsible for up to 38% of the total yield gap, which is a much larger share than that reported from yield gaps in the Philippines (<18%, (Laborte et al., 2012)) or in West Africa (<20%, (Saito et al., 2013)). The extent of YG_1 in the present study depended on positions and differed between years, and was mainly related to unfavorable hydrology, here mainly the duration of crop submergence. Similarly, large unexplained shares in the total yield gap reported from Indonesia were associated to unfavorable hydrology (Boling et al., 2010), particularly to differences in groundwater depths between the top and the bottom positions of rice fields along a toposequence. Consequently, the depth and the duration of ponded water may explain the large observed YG1 which was largest in the submergence-prone center positions, particularly during the submergence-sensitive early reproductive growth stage of rice.

Yield gap 2 resulting from yield-limiting factors was relatively small (11–20% of the potential yield) in the middle and center positions, but much larger in the fringe position. This share of the total yield gap is related mainly to nutrient management and particularly the use efficiency of applied N. The extent of this share to the total yield gap in irrigated rice in the Philippines has been related to sub-optimal rates of macro-nutrient fertilizers (Silva et al., 2017). Tsujimoto et al. (2019) highlighted, that hydrology was a major factor influencing N use efficiency and affecting fertilizer application and yield. In the case of Kilombero this share in the yield gap is much larger, which may be linked to the low recommended N application rate of 60 kg urea-N ha^{-1} compared to the Philippines (120 kg N ha^{-1}) or West Africa (100 kg N ha^{-1}). Thus, both fertilizer application rates and the use efficiency of the applied N are likely to explain the extent and the variations in YG_2 between different positions.

Yield gap 3 accounted to the largest share in the total yield gap with values ranging from 28% to 42%. This share of yield gap 3 is much larger than reported values from other yield gap analyses in Asia (Laborte et al., 2012) and West Africa (Becker et al; Niang et al., 2018) or of those reported from irrigated systems (Saito et al., 2019) and it varies strongly between positions. This part of the yield gap is related to soil fertility attributes, to soil and land management and to varietal choice. Rice genotypes did not differ and can thus be discounted for in this study. The large yield gap could also be attributed to low (less than 22 kg ha^{-1}) application rates or no N at all in farmers' fields in Tanzania compared to 37–147 kg ha^{-1} in Mauritania, Burkina Faso, Mali or Senegal (Tsujimoto et al., 2019). Hence, these large N-related gaps create an opportunity to increase rice yields in Tanzania more than in most areas in West Africa. On the other hand, soil attributes such as texture, soil organic matter, and total soil N differ between positions in the floodplain (Daniel et al., 2017) and may thus explain part of the large YG3 and the observed differences between positions (Table 10), and reinforces the recommendation for site and system-specific soil management in alleviating soil constraints and increasing grain yields (Anderson et al., 2016).

4.4.3 Disentangling the exploitable yield gap

Land management was associated with yield gains between 0.7 and 2.0 t ha^{-1}, representing about 16–33% of the exploitable yield gap depending on the hydrological position. Field bunding retained rainwater for extended periods of time, thus reducing water stress at least in the middle position. Enhanced soil water retention has been shown previously to increase rice yields in Tanzania (Raes et al., 2007) and in West Africa (Worou et al., 2013). Also, field bunding reduced the weed biomass compared to open plots and increased the use efficiency of applied mineral N (Touré et al., 2009). In the present study, the benefits of bunding were largest in the potentially drought-prone fringe and middle position of the floodplain. However, adoption of such simple but highly effective land management at farm-level is very low in Tanzania in general and in floodplain environments in particular (Nhamo et al., 2014), with missing awareness by farmers and labor shortages having been pinpointed as key reasons.

A combination of improved land management and the application of mineral N (60 kg ha^{-1}) increased rice grain yields substantially to 5.8 and 7.8 t ha^{-1}, thus closing 61–80% of the exploitable yield gap. Despite N having been stressed as the most yield-limiting nutrient element, yield increases of 1–3 t ha^{-1} due to N application were much less in the rain-fed lowland systems of West Africa (Niang et al., 2017). In that region the building of field bunds is common practice and applied fertilizer N is reportedly used much more efficiently (Becker and Johnson, 2001). In our study, the combination of field bunding and N application reduced the exploitable yield gap by up to 80%. A particularly higher percentage in the center position is however, linked to the relatively low attainable yield in this submergence-prone environment, and hence to a much lower yield gap compared to fringe and middle positions. However, up to date, smallholder farmers do rarely benefit from such dramatic effects of technology adoption, key reasons being the untimely availability and non-affordability of mineral N fertilizers in the Kilombero region (Nhamo et al., 2014). Another disincentive for adopting the use of fertilizers is the high production risk or uncertainty in the outcome of such investments due to complete crop failure related to unreliable hydrology in floodplain environments (Näschen et al., 2018).

On the other hand, organic N sources may reduce such risks and have been shown to increase yields and reduce the exploitable yield gap in upland systems of Northern Tanzania (Saidia and Mrema, 2017), in water-limited rain-fed lowland rice in South-

East Asia (Haefele et al., 2006), as well as in the Kilombero floodplain (Kwesiga et al., 2020). The benefits of these organic N sources were largest in the wetter middle and center positions of the floodplain. However, while reducing the variability and hence the risk for farmers, organic amendments have been shown in the present study to be less effective than mineral fertilizers. Green manure legumes closed only between 20 and 50% of the exploitable yield gap. In addition, both the ecological and the social niches for farmers adopting green manure technologies in sub-Sahara Africa are limited and widely constrain their adoption (Nandwa et al., 2011). In chapter 2 we highlighted the suitability of both the pre- and the post-rice niches for growing leguminous green manures in Kilombero floodplain. Thus, short-duration pre-rice legumes can establish with the short rains in November–January in the floodplain fringes, while post-rice forage legumes can benefit from residual soil moisture after flood recession in the center position. The drought-tolerant post-rice forages could be grown under moisture regimes that are unfavorable for a cash crop. In the present study, the contribution of both legumes towards yield increase and gap closure was comparable irrespective of hydrological position. Thus, based on the year and the position of the rice field in the floodplain, and based on on-farm labor availability, smallholder farmers can decide to seed legumes either before rice establishment (pre-rice green manure) or after rice harvest (post-rice green manure) with comparable effects on yields and on closing the exploitable yield gap in the rainfed systems of Kilombero floodplain.

4.5 Conclusions

Our research has confirmed considerable exploitable yield gaps in the Kilombero flood plain. The rice production potential in the region is high since the gap between potential and attainable yields was low. Different hydrological positions strongly affect the attainable yields within a rainfed lowland system and require site-specific management. The tested management options closed between 25 and 80% of the exploitable yield gap. Other factors besides fertilizer N management may prevent farmers from closing the exploitable yield gap. Joint efforts of all stakeholders including research, policy and extension efforts are needed to guide smallholder rice farmers in implementing site-specific locally available management options towards increasing rice production in floodplains.

Chapter 5

This chapter presents the general concluding remarks referring to each of the initially stated research objectives, implications for future research and policy recommendations.

General conclusions and recommendations

5.1 Introduction

In Tanzania, rice production is of significant national importance as a source of employment, income and food security for most rural households. The Kilombero floodplain, one of the largest rice-producing areas, was the focus of the BMBF-funded project "GlobE Wetlands". The focal interest in developing and using the floodplain for large-scale rice production dates back to colonial times. These have recently been revived in the frame of the "Kilimo kwanza" initiative of the Tanzanian government and later by the growth corridor initiative "SAGCOT" that aimed at boosting regional (rice) production by fostering private-public partnerships. However, none of the colonial, post-colonial and recent international endeavours has led to substantial production increases, and neither have any productivity gains materialized ever since. Lacking investments in infrastructures for irrigation and crop production but also for linking the area to national and global input and output markets have slowed development efforts from the beginning. In addition, the high risk of investments in crop production in a highly submergence-prone and hydrologically unpredictable environment further limited farmers' and developers' willingness to invest in more capital-intensive production strategies.

Chapter 1 of this thesis highlights that a poor understanding of floodplain environments' attributes and functioning is a key contributing factor to low and variable rice yields. We further hypothesized that new production strategies must consider farmers' resource endowment and technical capabilities, the availability of use of local production resources, but also the large spatio-temporal variability in soil quality and water availability. Such scientific guidelines are meant to site-specifically target a range of locally-adoptable technical options targeted in view of minimizing production risks and for attaining sustainable rice yield increases in floodplain environments. In this context, the "Wetlands project" has generated substantial knowledge on the Kilombero floodplain. Among knowledge gains that are of relevance to this thesis is the; i) characterization of the growing conditions and physical dimensions that support sustainable land management, ii) quantification of upland-wetland interactions and their impact on the occurrence of hydrological extremes, iii) establishment of the spatio-temporal dynamics of flooding as a key determinant of agricultural risk, iv) recognition that groundwater is recharged not through flooding but by water originating from adjacent mountain ranges and reaching the floodplain after infiltration of precipitation via sub-surface interflow, v) recognition that soil moisture dynamics are controlled by overbank flow from the central river in the center and by lateral subsurface flow in the fringes of the wetland, and vi) categorization of farmers into (1) sole rice-growers, (2) those growing rice in addition to maize and high-value vegetable, and (3) those growing rice and keeping cattle. A fourth category refers to “white collar” absentee farmers with high-input and purely market-oriented cash crop production systems. All these knowledge gains obtained by different project groups within the GlobE-Wetlands project have shaped the design of the agronomic experiments and guided the choice of treatments and their application in the present thesis.

Thus, this thesis evaluated the actual and potential rice yields while quantifying the main limiting factors necessary to guide intervention strategies and assess the floodplain’s future contribution to food security. Different recommended management strategies and those based on low-cost locally-available resources were comparatively evaluated in researcher-managed on-farm field trials. The technical options' focus was always to counteract key production constraints, increase yield, and minimize outcome variability and production risks. Strategies assessed and approaches compared included simple water and soil management techniques, mineral N fertilizer application, and the use of farmyard manure, different leguminous green manures and crop residues and their effect on resource base quality, grain yield and yield variability. Key findings of the options compared, and the results discussed are presented in chapters 2, 3, and 4, all of which have been published in international journals. A summary of the highlights is provided in the following section.

5.2 Main research findings

As laid out in Chapter 2, simple soil and water management such as land levelling and the building of water-retaining field bunds significantly increased rice grain yields, beyond farmers’ practice in the fringe and middle positions, where grain yields were generally higher than in the submergence-prone center position of the floodplain. Also, yield variability and the production risk were highest in center and lowest in the fringe positions. These high yields were attributed to high soil P, favourable soil texture, and a relatively high soil N supplying capacity. The low yields in the center position were linked to prolonged crop submergence, particularly detrimental when occurring during the reproductive and grain filling stages of rice. Thus, improved land and fertilizer management options are most beneficial in the drought-prone fringe and middle positions where they contributed to enhanced N use efficiency, increased grain yield and reduced production risks.

Chapter 3 describes pre-rice and post rice green manure cropping strategies as well as the use of locally-available farmyard manure as promising alternatives to expensive and often unaffordable mineral fertilizer options for soil fertility restoration. Depending on the position of the floodplain, organic amendments increased rice grain yields by >60%. This yield increase was linked to legumes' ability to fix atmospheric N_2 and to accumulate it in biomass that can be restituted to the soil upon incorporation and soil tillage. In addition, the relatively slow mineralisation of organic amendments and hence a (compared to mineral sources) slow release of nitrogen explained the observed build-up in soil organic C and N, which contributed to the residual benefits in a non-amended succeeding crop. The extent of such effects varied by amendment types and hydrological positions. Therefore, with the prevalence of one single crop of rainfed rice per year, repeated application of organic amendments can enhance soil C and N with associated positive effects on direct and indirect increases in rice grain yield and a reduction in yield variability.

Chapter 4 assessed the simulated potential and farmers' actual yields and evaluated the yield gaps between years and in different hydrological positions. Most management options tested in this study contributed substantially to closing the large prevailing yield gaps. Thus, simple field bunds combined with land levelling closed up to 35% of the exploitable yield gap. Mineral N and organic amendment options contributed up to 60% of the potential yield. A combination of land management and mineral N closed up to 80% of the exploitable yield gap. Overall, mineral N was more effective in closing the yield gap than green and farmyard manure. However, the latter options are at the reach of most small-scale farmers. Simultaneously, mineral N sources' availability and affordability are largely restricted to better-off farmers, and its use efficiency is limited to years and physical positions with favourable hydrological conditions. While both mineral N and organic amendments improve soil fertility and reduce yield gaps, the relative benefits of such rice production strategies are highly site-and system-specific in highly variable floodplain environments.

5.3 Policy recommendations

In Tanzania, the idea to intensify rice production, although not very salient during the pre-and the early post-colonial era, has always been an explicit government policy aim. More recent agricultural policies have increasingly included the private-sector and supported larger-scale commercial farming to attract more private and public investments in agriculture. Most of these policies tended to ignore smallholder farmers' diversity, needs, aspirations, and constraints. They also tended to ignore the highly variable nature of floodplain hydrology and the associated uncertainties and production risks. Consequently, many of the recommended production technologies resulting from such policies have rarely been adopted by smallholder farmers. Also, they are hardly suitable for diverse hydro-edaphic situations with large spatio-temporal dynamics. The absence of supportive policies to mediate the full strength of changing market forces in smallholder systems and strengthen value chains that link rice production to national, regional, and international markets constrain increased food production. Therefore, technology recommendations derived from this thesis are as follows:

- Construction of field bunds should be encouraged by extension services, particularly to farmers in the floodplain's fringe positions. There the resulting retention of water is a prerequisite for crop intensification by use of external inputs.
- The findings on varying N use efficiencies in different hydrological positions could form a basis for refining existing blanket recommendations for mineral fertilizer N application.
- Farmers should be encouraged to use existing and on-farm available resources such as using the pre-rice and post-rice niches for growing legumes for forage, food and soil fertility restoration. Beyond these plots and field scale-level technology recommendations, which were the focus of the present thesis, there are broader needs that require policy changes.
- As the potential for rice intensification in the Kilombero floodplain is largely limited to the fringe and some favourable middle positions, the submergence-prone and hence highly risky center positions may be taken out of production. This would contribute to Kilombero’s character as a Ramsar site by delineating protection zones for biodiversity conservation and reducing classical user conflicts by setting aside dry season grazing grounds for semi-nomadic and agro-pastoralist.

- As Kilombero and the town of Ifakara are poorly linked to urban centers such as Morogoro or international harbours such as Dar-es-Salaam, value chains are poorly organized, and the missing access to both input and output markets act as a deterrent for agricultural intensification. Conducive policies for establishing infrastructure and strengthening value chains are urgently required.

5.4 Implication and future research

- The results provide insights on the rice yield performance at different hydrological positions within the floodplain and the overall potential for sustainable rice intensification. Even with the current set aside of the SAGCOT initiative as a political priority area, there is a need to save foreign exchange currently spent on rice imports. In addition, the investment in rice research, development and production in Kilombero is promising.
- Soil N limitations in floodplain environments are a common feature of the prevailing Fluvisols. They can be addressed by N addition in mineral or organic forms and by better management of native soil N, i.e., minimizing nitrate N losses. This latter aspect requires research efforts to improve our understanding of soil N mineralization dynamics and of technical options that contribute to minimize gaseous and leaching losses of (nitrate)-N.
- The different environments require the introduction of niche-specific rice farming systems. These need to be visualized in GIS-based maps for future land use planning and fostering spatially explicit targeting of interventions.
- New cropping strategies that expand the cropping portfolio and spread production risks may be envisioned in the face of hydrological risks and farmers' general attitude of risk-averseness. Besides the development and distribution of submergence- and drought-tolerant rice genotypes, cropping diversification by including short-cycled high-value vegetables in the pre-rice niche of peri-urban sites and a range of adapted flood recession crops for the post rice niche in rural areas may contribute to increasing food production and diversity, while reducing production risks.
- Finally, Kilombero floodplain is one of many large floodplains along the eastern coast of the African continent. In areas with similar climatic, edaphic and socio-economic environments, an extrapolation of the findings presented in this thesis may be envisioned.

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Appendix

Plate 1. Prof. M. Becker (supervisor) inspecting the rice nursery bed site and green manure multiplication plots

Plate 2. Farmers after participating in field preparation involving bunding, puddling and levelling of the experimental field

Plate 3. Rice transplanting

Plate 4. Data collection during the flooding period at the middle position of the floodplain

Plate 5. Field inspection at complete rice crop submergence in the center position.

Plate 6. Rice inspection in a farmers field after flood recession in the middle position

Plate 7. Field experiment at the fringe position

Plate 8. Field experiment at the middle position

Plate 9. Field experiment at the center position

Plate 10. Farmers' management practice treatment plot

Plate 11. Field bunding, paddling and levelling treatment plot

Plate 12. Maximum mineral N at 120 kg N, 60 P and 60 K ha^{-1} fertilizer management treatment plot

Plate 13. Recommended fertilizer management of 60 kg ha^{-1} treatment plot.

Plate 14. Pre- rice green manure (*Lablab purpureus* L.) treatment plot.

Plate 15. Post-rice green manure (*Stylosanthes guianensis* L.) treatment plot.

Plate 16. Farmyard at 60kg N ha^{-1} manure treatment plot

Plate 17. Combination of cowpea (Vigna unguiculata) and farmyard manure treatment plot.

Plate 18. Pre-rice green manure (*Lablab purpureus* L.) stand.

Plate 19. Post-rice green manure (*Stylosanthes guianensis* L. in the foreground and *Vigna unguiculata* in the background) stands.

Plate 21. Rice harvest from pre-rice green manure treatment plot.

Plate 20. Farmer field day at the experimental site

Plate 21. Team