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IMPROVEMENT OF FERTILIZATION STRATEGIES IN MOZAMBICAN RICE PRODUCTION: RECONCILING ENVIRONMENTAL SUSTAINABILITY AND EQUITABLE SOCIO-ECONOMIC DEVELOPMENT

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A dissertation carried out on the Tropical Knowledge and Management, under the supervision of Professor David Fangueiro and co-supervision of Professor Alexis Ndayiragije, Marina Temudo and Pedro Vicente.

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Errata

In page 103: Total rainfall was equivalent 3371 mm change to "… 337.1 mm"

In page 103:

Table 3.1: Average temperature, relative humidity and total rainfall registered during the field experiment (2018–2019)

Year (2018)	**Maximum Temperature (°C)**	**Minimum Temperature (°C)**	**Relative Humidity (%)**	**Rainfall (mm)**
November	32.7	22.1	62.5	370
December	32.8	28.2	60.8	74.1
Year (2019)				
January	32.5	20.5	74.0	900
February	32.3	27.3	53.8	780
March	33.4	31.0	54.7	760
April	31.2	20.0	66.7	190
May	29.8	16.6	60.6	270

Should be:

Year (2018)	**Maximum Temperature (°C)**	**Minimum Temperature (°C)**	**Relative Humidity (%)**	**Rainfall (mm)**
November	32.7	22.1	62.5	37.0
December	32.8	28.2	60.8	74.1
Year (2019)				
January	32.5	20.5	74.0	90.0
February	32.3	27.3	53.8	78.0
March	33.4	31.0	54.7	76.0
April	31.2	20.0	66.7	19.0
May	29.8	16.6	60.6	27.0

In page 104:

Table 3.2: Properties of the soil and organic fertilizer used in the experiment

Soil Parameters	**Soil**	**Beef Cattle Manure**	**Poultry Litter**
pH	7	8.2	8.5
EC (μS.cm^{-1})	640	7.2	4.4
Dry matter (%)	NA	84	80
Total N (g.kg^{-1})	1.1	21	27.1
NH_4^+ -N (g.kg^{-1})	0.01	12	11
NO_3^--N (g.kg^{-1})	0.02	7.7	15
CEC (cmolc.kg^{-1})	31.63	30.2	32.1
C/N ratio	11.55	12	10
Organic matter (g.kg^{-1})	21.9	31.8	30.7
P (mg.kg^{-1})	33.69	12.1	12.3
K (mg.kg^{-1})	660	NA	NA
Exchangeable cations (cmol.kg^{-1})			
Ca	17.5	NA	NA
Mg	9.94	NA	NA
K	1.26	NA	NA
Na	1.88	NA	NA

(Mean of three replicates; values presented on a dry matter basis); NA- not available.

Should be:

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CEC (cmolc.kg^{-1})	31.63	30.2	32.1
C/N ratio	11.55	12	10
Organic matter (g.kg^{-1})	219	318	307
P (g.kg^{-1})	33.69	12.1	12.3
K (g.kg^{-1})	660	NA	NA
Exchangeable cations (cmol.kg^{-1})			
Ca	17.5	NA	NA
Mg	9.94	NA	NA
K	1.26	NA	NA
Na	1.88	NA	NA

(Mean of three replicates; values presented on a dry matter basis); NA- not available.

List of Abbreviations

GHG- greenhouse gases emissions

CIS- Chókwè Irrigation Scheme

RFSs- Rice Farming Systems

GDP-Gross Domestic Product

MLM- Multinomial Logit Model

MLR- Multiple Linear Regression

ANOVA- Analysis of Variance

KW- Kruskal- Wallis

AIC- Akaike information criterion

RSE- Residual Standard Error

NGO- Non-Governmental Organization

RCBD- Randomized Complete Block Design

N- Nitrogen

CEC- Cation Exchange Capacity

EC- Electrical Conductivity

KCl- Potassium chloride

NH_4^+-N- Ammonium

NO_3^-N- Nitrate

TGW- Thousand Grain Weight

Mg- Magnesium

Fe- Iron

P- Phosphorus

K- Potassium

Mn- Manganese

Na- Sodium

Ca- Calcium

OM- Organic Matter

pH- Potential of Hydrogen

GWP- Global Warming Potential

Abstract

The overall importance of rice production has been increasing over the last few years. It is one of the main cereals consumed, ensuring world food security. Rice is the staple food in Africa which represents the most consumed crop compared to others, such as sorghum, maize, and cassava crops. In addition, rice is one of the main sources of energy in West Africa. According to the Food and Agriculture Organization of the United Nations, rice production in Africa has increased by 74% against the prospects and by 2018 the eventual target will be 28 million metric tons, with Nigeria and Tanzania as the major producers. Rice production is one of the main sources of agricultural greenhouse gases emissions (GHG), such as methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2) and contributes concretely to more than 10% of global methane emission.

In Mozambique, rice production remains at a subsistence level, which is characterized by low production and low productivity levels despite a long production practice of more than 500 years. Mozambique has 900.000 ha of land for rice production but only 34% are being used, Mozambique has potential to become rice exporter to regional scale. National demand for consumption of this cereal fluctuates at around 621.000 tonnes, with over 350.000 tonnes supplied by imports with an underlying cost of over 140 million dollars. The national sector rice is still subject to several constraints. Most of rice production in Mozambique is done by small farmers in rain-fed conditions, with low financial resources, poor technical support regarding soil fertility with average productivity of 1.0-1.2 tons per hectare in rainfed systems and 2.8-3.5 tons per hectare in irrigated systems and relying on the use of practices such as burning of cultural waste as well as the use of fire to open new areas for production. Nevertheless, most of fertilizers are used without any knowledge about soil, needs with negative consequences in terms of rice production, farmers' economy, and the environment. Thus, it is extremely important to develop agricultural practices of rice production that are environmentally sustainable, economically viable and that can respond to social needs, mainly those related to the population growth consequently increasing demand of imported rice. With an increase in rice prices on the world market and the effects of climate change, it is of the utmost importance to design national strategies and to respond to the requirements of the national rice sector development. Considering the high percentage of smallholders who still use rudimentary farming practices, it is necessary to encourage the optimal use of inputs (optimal fertilizer and water) to be developed that ensure high yields with low GHG.

The main goal of this PhD research was to provide technical and scientific information to improve fertilization strategies on rice production addressed to small-holder’s rice producers. Chókwè Irrigation Scheme (CIS) is the major irrigation scheme area in Mozambique. Using CIS as a case study, we aim to explore which typologies of Rice Farming Systems (RFS) are predominant in the CIS; which factors affect the production and productivity of smallholder farmers in the CIS; and what kind of policies/incentives can be proposed to enhance the production and the productivity of rice in the CIS. Based on the main constraints that affect smallholders’ rice production, we evaluated the agronomic results and the economic benefits of using mineral fertilizers and organic nitrogen sources. Finally, we evaluated the effect of fallow time, organic and inorganic fertilization on GHG emissions in the soils. The results showed four different kinds of rice farming systems: the subsistence FS, specialised rice FS, mixed crops FS, and rice–livestock FS. At the same time, the combination of different three source of nitrogen such as, urea, beef cattle manure and poultry litter at a rate of (40%:30%:30%) produced good results and is thus recommended to smallholder farmers for better optimum crop production on Chókwè Irrigation Scheme. Finally, the results observed demonstrate that the period of fallow can be an important source of GHG emissions with relative importance on CH_4 and N_2O. This study contributes to fight a knowledge gap about GHG emissions by rice paddies in Mozambique.

Keywords: Rice Farming Systems, Fertilization Strategies, Greenhouse Gases Emission, Sustainability.

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Chapter I

General overview

1. Introduction

1.1. Global rice production and consumption worldwide

Given the rapid population growth projections of 9.7 billion in 2050 and nearly 11 billion around 2100 (United Nations 2019), one of the main challenges is how to feed and provide food security to millions of people worldwide, especially in developing countries. Hence, new agriculture strategies and pathways are needed to solve future challenges. (Liu et al. 2009). So, to meet the food demand, more knowledge regarding soil management and sustainability is fundamental.

Soil management and agricultural sustainability can play a fundamental role in the population's food security, which is in its turn threatened by population growth, urbanization and ever-changing consumer behaviour, which are considered the main drivers of growing cereal demand (CARI 2018a). For instance, according to UN projections, between 2000 and 2025, food production will need to increase by 70% of cereals and 40% rice (Fahad et al. 2018). Furthermore, rice, wheat and maize are among the most widely used cereals, and also the three primary food crops in the world, that directly supply more than 42% of all calories consumed by the entire human population (GRiSP 2013).

Globally, rice production occupies nearly 158 million hectares (M.ha), achieving 470 million tons (Mts) of milled rice in 2009 (IRRI 2010). Nearly 90% of the world rice is produced in Asia (nearly 640 million tons), with China and India as the major contributors. Rice production and consumption are among the highest in Asian populations, with about 84% of the total rice consumption (Becker et al. 2019; CARI 2018). More than two billion people in Asia and hundreds of millions in Africa and Latin America rely on rice consumption (Ladha et al. 1997). More than 3.5 billion inhabitants depend on rice for obtaining 20% of their daily calorie intake (GRiS 2013; IRRI 2018; Muthayya et al. 2014). Rice consumption is more than 100 kg per person annually in some African (e.g., Madagascar, Liberia) and many Asian countries, (Fahad et al. 2018). In Africa, rice is one of the main cereals consumed, followed by sorghum, maize and cassava. Nevertheless, rice is one of the main sources of energy in West African countries (CARI 2018; FAO 2017a). Data from the United Nations Food and Agriculture Organization (2018) indicate an increase in rice production in African countries to 74% above expectations, with Nigeria and Tanzania taking a prominent position within African rice-producing countries.

Rice production on the African continent only accounts for 4.8% of world production, despite its potential and the average rice yield of 2 tons per hectare, well below the Asian averages of 7 tons per hectare. Among the African continent, the main producers are: Egypt, Nigeria, Madagascar, Tanzania and Mali (Adjao et al. 2015; FAOSTAT 2019).

Worldwide, *Oryza glaberrima* (Steudel) and *Oryza sativa* (L.) are commonly cultivated species of rice (Lu 1999). These are adapted to diverse climatic conditions and can be cultivated both in dry and wetland environments at high and low altitudes. Rice (*Oryza sativa* L.) belongs to the genus *Oryza* and family *Poaceae*, has 22 known species and has great economic importance (Bajaj et al. 2005).

The rice plant can grow in different types of ecosystems, characterized according to the primary water source: rainfed upland, rainfed lowland, irrigated upland, irrigated lowland, mangrove and deep-water (Bishwajit et al. 2013). Approximately 94% of the rice is produced in irrigated and rainfed lowland environments, considered commonly as paddy rice field (Chivenge et al. 2020).

In Mozambique, much of the population lives below the poverty line and human development rates are low in rural areas (Monjane et al. 2018). A significant number of the Mozambican population (70%) lives in rural areas and their income comes from agriculture (Mosca 2017). Agriculture plays a key role for the country's economy contributing to approximately 40% of GDP and employs about 80% of the country's labour force (JICA 2014; INE 2018).

Rice has been produced in Mozambique for over five centuries and in the past five years, the rice planted area represent 204.000 ha/year with a production of 120.000 ton/year (average yield of paddy is 0.8 - 1.6 ton/ha), significantly lower than the average 7 ton/ha observed in Asian countries (NRDSM 2013). Data from FAO (2018) revealed that in recent years Mozambique observed an increase in rice production (Figure 1), accompanied by the expansion of the cultivated area. However, productivity rate remained low in the last three agricultural seasons. With the increase in rice demand (25 kg/capita/year) the rice self-sufficiency percentage dropped drastically (24.7% in 2004) and more than 300.000 tons of rice were imported to compensate such deficit. From the food security standpoint, self-sufficiency should be achieved immediately .

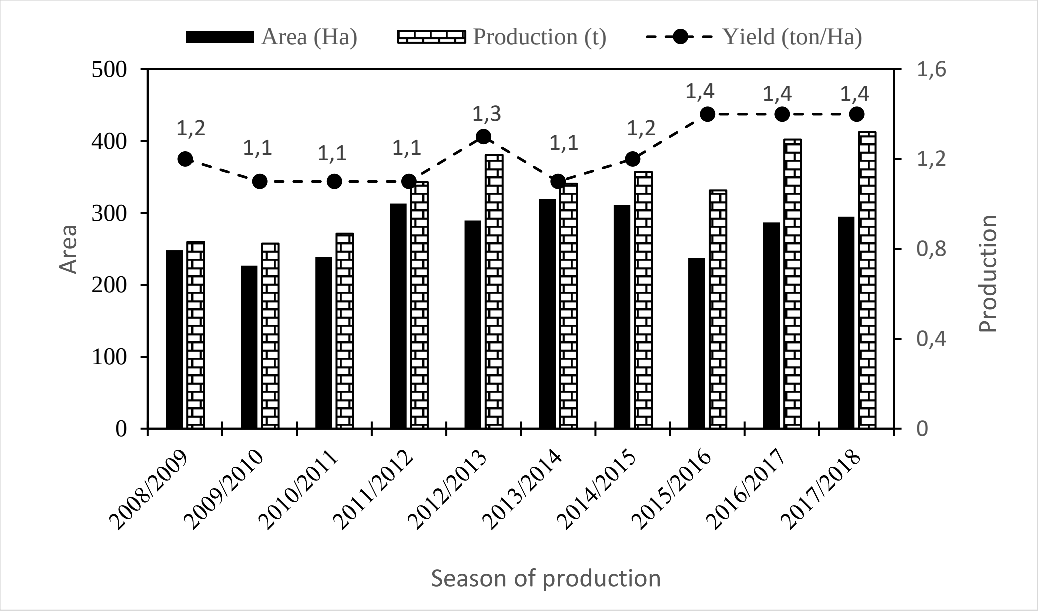

Figure 1.1: Rice Production in Mozambique Source: MASA, 2019

1.2. Problems related with rice production in Mozambique.

Mozambique is considered one of the most vulnerable countries to the negative impacts of climate change. In recent years, it has been facing increasing temperatures, adverse droughts, reduced precipitation levels, and simultaneously flooding, which consequently and strongly affect its agricultural production (FAO 2017b;Araneda-Cabrera et al. 2021). According to CGAP (2016), there are 3 types of farms (small, medium, and large). It is estimated that around 4.2 million small farms practice subsistence rainfed agriculture and less than 1% of the producers are market-oriented. This group is incapable of ensuring a continuous supply in line with national rice consumption thus the country is forced to import in response to the existing demand.

The agricultural potential for rice production in Mozambique is estimated at around 900.000 hectares, of which only 320.000 hectares are cultivated, only 36% are currently under cultivation. About 90% of the cultivated area lies in Zambézia and Sofala provinces, 7% in Nampula and Cabo Delgado provinces, and the remaining 3% in Gaza province (Regadio do Chókwè and Baixo Limpopo). Part of this production is also made by commercial (16.1%) producers located in the Chókwè, Baixo Limpopo, Búzi and Matutuíne (MASA 2015).

Several factors contribute to the low productivity for smallholders, such as low use of production technologies (fertilizers, certified seeds and pesticides), low access to infrastructure and marketing support services (access roads, warehouses, electrification), insufficient and inadequate financial services, poor water management capacity in fields due to poor land/soil levelling, poor capacity for proper soil preparation, high level of post-harvest losses and wastes, the country`s vulnerability to climate change and natural hazards (cyclones, floods, and drought) (Cunguara et al. 2018). The lack of up-to-date and accessible information on profitable technological options for different producer groups and a poor provision of an effective agricultural extension service should not be ignored as main constrains affecting rice productivity in the country (FAO 2017b).

Smallholder farmers in Mozambique engage mostly in rudimentary subsistence agriculture, dependent on rain, use of traditional varieties, low technical support for soil fertility, minimal use of pesticides and fertilizers, burning crop residues, as well as the use of fire to open new areas. Agriculture is mostly non-mechanized and land productivity is typically low (CGAP 2016). Many of these practices described above contribute to rise environmental and economic consequences such as increased gas emission rates and reduced soil fertility (Nhamo et al. 2014).

Therefore, fertilization production strategies will have to be developed and tested for increasing production, as well as for productivity with low environmental impacts and high acceptance by producers. The priority and strategic actions defined by the Government of Mozambique for the different types of farmers, especially for small farmers, include technical assistance in low-cost technology, including the availability of inputs, technical support in the supply chain, fertilizer production, availability and monitoring, irrigation and water availability, market, post-harvest management, infrastructure extension and investment, agro-processing and agricultural mechanization (Zavale et al. 2020).

1.2.1. Soil fertilization and its management for rice production

Fertilizers are a diverse group of artificial or natural products that should contain nitrogen, phosphorus, potassium, and other trace minerals in various chemical forms (Cope 2017). Their use provides essential mineral elements for positive crop growth and flourishing harvests. The continuing population growth implies an increase of the agricultural production supported by the use of fertilizers (Khan et al. 2017).

Agricultural intensification along the lines presented by the Green Revolution in 1960 led to the massive use of improved seeds combined with increased use of fertilizers and irrigation, although production tripled the cost of ecosystem services increased. Overuse of fertilizers is a cause of soil quality deterioration and ecosystem and biodiversity change (Naher et al. 2019).

The intensification of fertilizer application to soil has dramatic and predictable effects on soil microbial flora; it alters the soil’s physical, chemical, and biological properties leading to increased nutrient losses (Dornbush et al. 2017). It should be noted that the process of natural replacement of soil nutrients is slow, leading to the need of expansion of agricultural areas. Balanced fertilizer application is not only crucial for crop yield but also for environmental sustainability (Yousaf et al. 2017).

One of the major challenges associated with the rice production is related with soil management, specifically nutrients requirements. Soil degradation is a major threat to food security and could become a major obstacle to future food production, globally. At least 8.3 million hectares of rice are grown on marginal soils, including saline, alkaline/sodium, acid sulfate and organic soils around the worldwide (Zeigler 2016a).

According to Haefele et al. (2014) , Asia has the highest percentage of good soil rice production (47%), while the percentage is much lower in the Americas (28%) and in Africa (18%).

The use of fertilizers can achieve for 20–25 % of the total rice production costs. Hence, the intensification of rice production per unit area through the use of appropriate nutrient management practices has become an indispensable component of sustainable rice production (Chauhan et al. 2017). Given the importance of fertilization on the grain yield, it is essential to know the best dosage for each variety as well as its influence on components of yield and other agronomic parameters such as the cycle, plant height, lodging and moisture content of the grain. FAO alerts to ecosystems degradation as a consequence to conventional modes of production. That said, food must be produced using less resources, namely water and nutrients.

Farming in today's intensive modes with excessive or inappropriate use of chemical fertilizers can contribute to climate change and pollution, while the expansion of agricultural areas is undesirable. Therefore, it is imperative to find ways to achieve global food security without expanding crops or pastures and without increasing greenhouse gas emissions (Bajželj et al. 2014).

The negative environmental impact of chemical fertilizers implies its substitution by organic fertilizers, but farmers usually attribute greater effectiveness to inorganic chemical fertilizers. Hence, policymakers need to find strategies to stimulate the use of organic fertilizers rather than inorganic fertilizers, or at least mixing them at effective rates to achieve desirable yields (Wang et al. 2018).

Excessive use and transportation of chemical fertilizers for cereal production is causing soil pollution and greenhouse gas (GHG) emissions. Global rice cultivation accounts for at least 10% of agricultural emissions and by about 1.3% and 1.8% of anthropogenic GHG emissions (Maraseni et al. 2018). Greenhouse gas emissions remain a challenge under rice farming, particularly methane, contributing in 11% to global methane emission. There is a need for management alternatives that mitigate both methane and nitrous oxide emission (Chivenge et al. 2020). Few or no studies have addressed this problem in rice production in Mozambique.

Given the importance of rice production fertilizers, an integration of nutrient management practices through the incorporation of chemical, organic / biofertilizer nutrient sources will be the best strategy for restoring soil health and soil carbon storage. Therefore, the future rice production strategy should combine the use of mineral and organic fertilizers, rather than the single use of mineral fertilizers (FAO and Statista 2019) (Naher et al. 2018).

Technological innovation is vital for economic growth and food security. Extension services and peer learning are two common approaches to facilitate the diffusion of new technologies, but little is known about their relative effectiveness (Takahashi et al. 2019). Bearing in mind that the country has not been able to be self-sufficient in its consumption so far, soil fertility and its maintenance were considered factors in consideration and justification for subsequent studies.

New fertilization strategies were developed using alternative sources of organic fertilizers in combination with the main inorganic source (urea) of nitrogen used in rice production in Mozambique. However, it is extremely important to develop agricultural practices of rice production that are environmentally sustainable, economically viable and that can respond to social challenges, mainly those related to the population growth.

The main goal of the PhD research was to evaluate soil management aspects related to rice production, namely the influence of the fertilization strategies of rice production in Mozambique, on rice yield, nutritional soil quality and environmental impact with special emphasis on GHG (methane, nitrous oxide, and carbon dioxide) from the soil.

This overall objective was addressed through specific analyses and discussions that compose the five chapters of this thesis. The first chapter gives a brief overview of the Rice sector globally, following to the specific case of Mozambique. The second chapter gives a brief overview Rice Farming Systems (RFS) existent in Chókwè Irrigation Scheme (CIS). We aim to answer which typologies of RFS are predominant in CIS. Which factors affect the production and productivity for smallholder farmers in the CIS, and what kind of policies/incentives can be proposed to enhance production and productivity of rice in the CIS. Based on the main constrains that affect rice production in CIS at smallholders' producers such as management of soil, in a third chapter we discuss an alternative way to fertilizer the rice production namely integrated fertilization. To our knowledge we evaluate the agronomic effect and economic benefits of combined fertilization of rice production using mineral fertilizers and organic materials such as nitrogen sources in Mozambican conditions. In the fourth chapter, as far as we know, in Mozambique there is no information available on GHG emissions from rice paddies, so in this chapter it will be the first of its kind in which it is intended to evaluate the effect of fallow time, organic and inorganic fertilization on methane, nitrous oxide and carbon dioxide gas emissions in the soils of Umbeluzi, Maputo Province in Mozambique. Finally in the fifth chapter, the last one is a briefly recommendation based in our findings and conclusion related with our study to answer and enhance the rice production in Chokwe Irrigation Scheme.

1.3. General and specific goals of the thesis

The present thesis aims to provide technical and scientific information to improve fertilization strategies on rice production in Chókwè Irrigation Scheme (Mozambique), addressed to smallholder's rice producers. To achieve this goal, the following specific objectives were set:

i. to assess rice farming system typologies in the Chókwè Irrigation Scheme (CIS) the drivers and constraints for smallholder rice farmers are better understood, and to propose alternative policies for decision-makers to improve production and productivity.

ii. to evaluate the agronomic effect and economic benefits of combined fertilization of rice production using mineral fertilizers and organic materials as N sources in Chókwè conditions.

iii. to evaluate the effect of soil management and organic and inorganic fertilization on methane, nitrous oxide, and carbon dioxide gas emissions in Umbeluzi paddy field soils.

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Chapter II

Understanding the Dynamic of Rice Farming Systems in Southern Mozambique to Improve Production and Benefits to Smallholders

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Understanding the Dynamic of Rice Farming Systems in Southern Mozambique to Improve Production and Benefits to Smallholders

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Abstract

Rice farming systems (RFSs) in southern Mozambique are very heterogeneous and diversified, which has implications for smallholders’ adoption of each RFS, as well as on rice production and productivity in the region. In this regard, it is important to understand: (i) which RFS typologies can be leveraged to improve rice production and productivity; (ii) the drivers for smallholder farmers’ decisions to adopt an RFS; and (iii) which policies/incentives could enhance existing RFSs. The present study was based on surveys of 341 smallholder rice farmers in the Chókwè Irrigation Scheme (CIS), southern Mozambique. Data on the productivity of rice, size of the herd, and total other crop types were used to frame the RFS typologies. A multinomial logit model (MLM) and multiple linear regression (MLR) were applied to determine the driver for each RFS and predict the constraints for production and yield. Based on cluster analysis, four typologies of RFSs were identified: the subsistence farming system (FS), specialised rice FS, mixed crops FS, and rice–livestock FS. Farms with longer experience reported applying more fertiliser and seedlings per unit hectare. The availability of labour increased the likelihood of adopting the mixed crops FS and rice–livestock FS. Older households were more likely to adopt the subsistence FS, and live closer to the farming fields. Yield of rice was positively associated with inputs such as fertilizers, pesticides, and seedlings, as well as years of experience of the household. Our results suggest that smallholder farmers need more assistance and technical support to identify and adopt more productive and less costly RFSs in this region.

Keywords: crop–livestock; farming systems; production and productivity of rice; fertilization; smallholder farmers

2.1. Introduction

Global rice production reached 0.5 billion tonnes (on a milled basis) in 2018, which represents an increase of 1.4% (FAO 2018a), and it will continue to grow, especially in Africa, where production is far behind the global average (Karimov et al. 2019). This significant growth was driven by market demand, prices, and state subsidies (FAO 2013). The Asian region accounted for almost 80% of the increased production (Fahad et al. 2019), while Sub-Saharan Africa is the only region in the world where food production per capita, including of staple cereals, has been growing slowly, leaving many people more vulnerable to food insecurity (Sanchez 2002; Meijer et al. 2015). By 2050, the African population is predicted to reach 2.5 billion, more than double the current population (Goldstone 2019). Feeding this growing population will remain a great challenge for most of the African governments', requiring rapid changes to policies and agricultural technology (Karingi et al. 2018).

Global cereal production is increasing dramatically, providing a platform for rural and urban economic growth (Pretty et al. 2011). In Africa, as in many other parts of the developing world, cereals such as maize, rice, and wheat are essential for the daily diet of most rural and urban households, preventing them from falling into acute food insecurity (Ranum et al. 2014; FAO 2018a; Mutsvangwa-Sammie et al. 2018). Indeed, these three staple cereals together account for 94% of all cereal consumption in Africa (Ranum et al. 2014), which also helps to frame the prevailing narrative that African agriculture has lagged behind the rest of the world (Pretty et al. 2011).

Even in the context of lower staple cereal production, there is a widespread agreement that the agriculture sector will remain pivotal for the development of the sub-Saharan region (Pretty et al. 2011), employing many rural people; up to 80% are smallholder farmers who produce most of their regional food (Mutsvangwa-Sammie et al. 2018; Adenle et al. 2019). Rural smallholder farms grow a wide variety of food grains, root crops, cash crops, and livestock that support diverse food and livelihood systems in different agricultural zones, and traditionally produce modest surpluses for local or distant trade (Dixon 2019).

Despite the availability of lowland and wetland suitable for sustainable rice-based cropping (Fagnombo et al. 2018), rice production and productivity in sub-Saharan Africa is hindered by low soil fertility (Sanchez 2002; Kwesiga et al. 2003; Sileshi et al. 2007), a lack of technology (Mills et al. 2017; Mutsvangwa-Sammie et al. 2018), poor agricultural polices (Balasubramanian et al. 2007), and a lack of adequate infrastructure (Meijer et al. 2015) and skilled workers (GRiSP 2013). As in most sub-Saharan countries, agriculture is a key sector in Mozambique, employing 80% of the labour force and contributing approximately 20% of the GDP (Cunguara et al. 2018). Rice is the main cereal, second to maize, and its production area encompasses 204,000 ha, with an average paddy yield of 1.27 t/ha (JICA 2014)). This figure is remarkably low compared to the average paddy yields of 4.2 t ha^{-1} in Asia (Zeigler 2016a). Most of the farming plots are located in lowlands, which are seasonally rain-fed and account for 90% of the total rice area (MASA 2009), and contribute about 10–15% of the cereal caloric supply at the national level (Alasia et al. 2003).

The growing human population and increase in middle-class consumers have exacerbated the demand for rice in Mozambique (Alasia et al. 2003). This increasing demand has created 300.000 t $year^{-1}$ of rice deficit, which has been covered by importation from Asian countries (INE 2018). The production deficit is likely related to (i) a lack of technology (agricultural mechanization, use of chemical and organic fertilizers, herbicides, and improved rice varieties); (ii) insufficient support for smallholder farmers, who are the main rice producer in the country (Silici et al. 2015); (iii) a lack of extension services to smallholders (Benfica et al. 2018); and (iv) high heterogeneity and diversity of farming systems (FS), which hampers the implementation of agriculture policies. The construction of specific typologies of FSs, and understanding of drivers that motivate smallholder farms to adopt each specific FS, will be a useful step forward to frame the aforementioned problems (Dixon et al. 2001; Dixon 2019).

Although the country has a potential to reach 900,000 hectares of rice production, it is estimated that only 35% of this area is under cultivation, mostly in Gaza province (south Mozambique), Zambézia and Sofala provinces, in the centre of the country, and Nampula and Cabo Delgado provinces, in the north (MASA 2009; MASA 2019). The majority of rice farming fields in the south and centre of the country are located in the Chókwè and Baixo Limpopo irrigation schemes, respectively (Alasia et al. 2003). The Chókwè Irrigation Scheme (CIS) is the largest irrigated area in Mozambique, and it has a vigorous agricultural community (including rice cultivation, horticulture, and sheep farming) in intensive and mixed FSs. However, the production volume has been remarkably low, with a lengthy stagnation since 1988, due to internal warfare, floods of the Limpopo River (JICA 2014), and a lack of policies, especially around the difficulty of accessing credit (Kajisa et al. 2011). Most rice producers are smallholders (< 5 ha) and medium holders (5–20 ha), who also need to diversify their production to improve their livelihood and income generation. The spatial predominance of mixed FSs is dependent on the drivers and constraints. Thus, it is important to propose incentives to effectively improve the production of rice in the CIS. This will require an in-depth understanding of the existing FSs and other alternative livelihood options available in the region. The present study aimed to answer the following questions: (i) Which typologies of rice Farming Systems (RFSs) are predominant in the CIS? (ii) What are the drivers for each RFS in the area? (iii) Do different demographic patterns affect household decisions to embrace different FSs? (iv) What factors affect production and productivity for smallholder farmers in the CIS? (v) What policies/incentives can be proposed to enhance production and productivity of rice in the CIS?

To answer the above questions, a survey was carried out with smallholder rice farmers who were based adjacent to the CIS. Answering these questions was important in order to underpin development strategies, assess production constraints, prioritise research, and identify scaling potentials, which in turn will improve local food production and nutrition security, and the rice value scheme.

2.2. Materials and Methods

2.2.1. Study Area: Chókwè Irrigation Scheme (CIS)

The Chókwè Irrigation Scheme (CIS) is located in southern Mozambique, in the Chókwè District, adjacent to the Limpopo River (Abbas 2018a; de Sousa et al. 2019) (Figure 2.1). It is the largest irrigation scheme in the country (Alasia et al. 2003; Agriculture 2009), covering 33.000 ha of land (JICA 2014). Its production potential has not yet been achieved, and is hindered by an insufficient supply of irrigation water, excessively expensive chemical fertiliser, and moderately costly labour (Kajisa and Payongayong 2011). The total population living in Chókwè district is about 212.071 people, with 56% living in rural areas (INE 2017). The climate of the region is semi-arid (MAE 2012), with an average annual temperature of 22–26 °C, and rainfall averaging between 500 and 700 mm/year (Kajisa et al. 2011; De Sousa et al. 2019). The CIS is composed of three main hydraulic sectors: montante (upstream), sul (midstream), and rio (downstream) (Figure 1). The hydraulic structures in the irrigation scheme include the Massingir dam, Macarretane weir, and the main, secondary, and tertiary canals, as well as the drainage network (de Sousa et al. 2019).

The predominant FS in the area is agropastoral (Dixon 2019), with approximately 3500 farm households, extension workers, and technical staff. Small-scale farms hold on average less than 5 ha per plot of land for rice production (JICA 2014). Most of the agricultural activities in the area include mixed crops and livestock production, in which most of the vegetables are produced on wetlands in the dry season (MAE 2012). Rice yield is on average low in small scale FSs, but has slightly increased in the last few years (JICA 2014). Few commercial rice farmers use farm machinery, fertilisers, pesticides, and improved seeds varieties (Kajisa and Payongayong 2011).

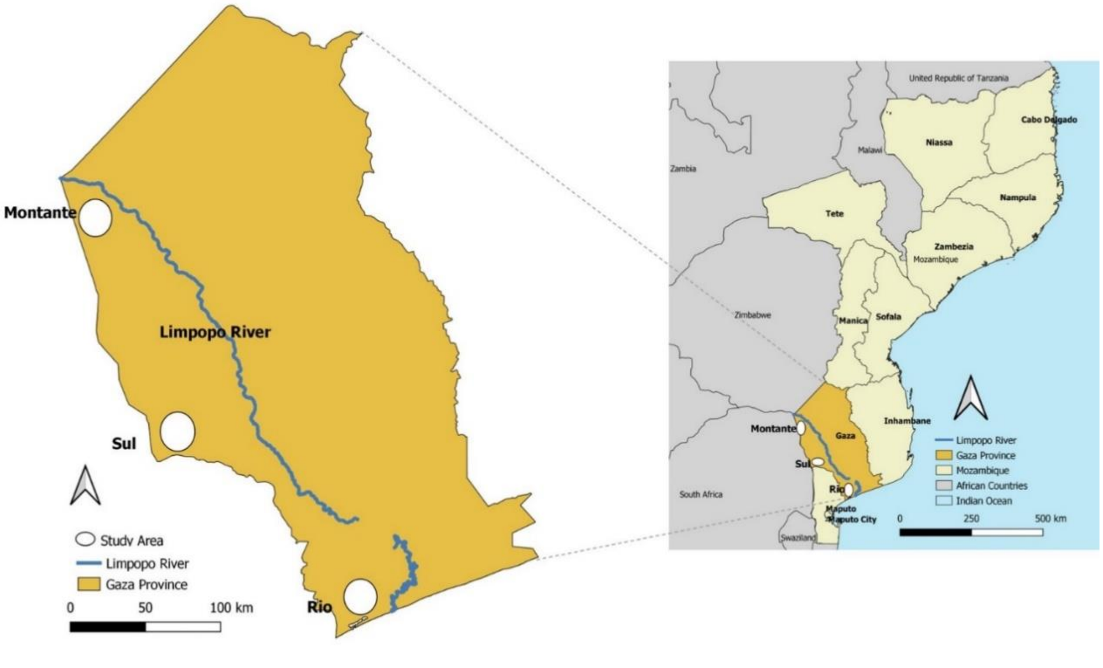

Figure 2.1: The location of the Chókwè Irrigation Scheme (CIS)

2.2.2. Data Collection

The survey was conducted in 25 villages, selected to cover the three main regions of the CIS: upstream/montante, midstream/sul, and downstream/rio (Figure 1). The villages were selected after an exploratory field visit and consultation with key informants (government entities and the village chairperson). Most of the households in the villages were essentially rice farmers, who also practiced other activities to sustain their daily livelihoods and generate income, such as cattle herding, fishing, and small-scale informal business, and who also cultivated fresh vegetables. Upstream, we surveyed eight villages representing a total of 93 farms (27.19%), while in the midstream and downstream a total of 5 and 12 villages were sampled, covering a total of 110 farms (32.16%) and 138 farms (40.35%), respectively (Table 1). The number of households sampled was more than 10% of the total in all of the sampled villages. According to Bartlett at al. (2001) and Landry et al, a 5% sampling intensity is sufficient for social studies.

Table 1.1: Total number of smallholder rice farmers in the three main zones of the irrigation scheme, sample size and number of village samples per zone

Chókwè Scheme	**Number of Villages Sampled**	**Total Small Rice Farms**	**Nº and (%) of Household Sampled**
Upstream/Montante	8	782	93 (11.9)
Midstream/Sul	12	1137	138 (12.1)
Downstream/Rio	5	994	110 (11.1)
Total	25	2913	341 (11.7)

The survey was conducted from February to June 2019. During this period, a total of 346 smallholder farmers were surveyed; of these, 5 surveys were not validated. The criteria used to select the 341 surveyed households was: (i) living in a village adjacent to the CIS for more than two years; and (ii) having a rice farming plot of less than 5 ha in size in the CIS.

Household Survey

The first section of the survey obtained the socio-economic characteristics of the surveyed households, and a description of their agriculture production system: (i) socio-demographic and socio-economic information of the household (gender, age, the composition of the family, and education); (ii) different sources of income; (iii) if the household held a permanent labour force or hired labour workers; and (iv) agricultural and livestock production. The second section obtained the characterisation of the RFS, including (i) type of land access; (ii) soil fertilisation; (iii) weed control; (iv) types of seeds and yield; and (v) the destination of the production, including market access. All questions included in the survey were based on a literature review, field visits, and meetings with key informants, and part of the questionnaire was from a similar study conducted in Angola, with some adjustments (Temudo and Talhinhas 2019). The survey was conducted in close collaboration with two field workers, who were native to the area and able to speak Changana, the native language, because most of the respondents either did not understand Portuguese or preferred to be interviewed in Changana. To control for potential mistranslation, the survey was translated to Changana and reverse translated to Portuguese, until a similar meaning was consistently achieved. The questionnaire was pre-tested with five respondents from upstream and was later adjusted based on their observations.

2.2.3. Data Analysis

Data were coded and analysed using R software. Exploratory analysis and descriptive statistics were performed. A table of frequencies and percentages was used to represent the socio-demographic and socio-economic characteristics of the households in the CIS. The information included gender of the household head, education, the main and secondary activities, accessibility of land, the number of households who hire or have permanent workers, average distance to the farming field, the use of fertiliser and types, livestock husbandry, and destination of production output.

2.3.4. Typology of Rice Farming Systems

The prevailing RFSs were developed based on three main variables: yield of rice, expressed in ton ha^{-1}; livestock breeding; and total other types of crops (vegetables (cabbage, lettuce, tomato, etc.), maize (*Zea mays*), cowpea (*Vigna unguiculata*), common bean (*Phaseolus vulgaris*), and sweet potato (*Ipomoea batatas*), that households reported growing. Three livestock categories (cattle, swine, and goats) were considered. We used only these categories because: (i) these are the livestock categories that most households declared; (ii) households devote a considerable amount of time and effort to these activities; (iii) depending on the size of the herd, the household may need an additional labour force and it may impact resource allocation; (iv) a trade-off between livestock production and agricultural activities is also common, as suggested by (Mota et al. 2019; Temudo and Talhinhas 2019). Because the survey was focused only on rice, the yield of other crops was not assessed. Nevertheless, the annual yield of each crop was needed for construction of the FS typology (García-Pérez and Núñez-Antón 2003; Legendre and Legendre 2003a; Sileshi et al. 2007); an artefact was thus used to derive a proxy variable, which consisted of summing the number of all other crops the household reported growing, besides rice. Although we recognise the limitations of this approach, it was the most appropriate, in the sense that it best captured the main purpose of the work, which was to understand the basis of household decision making with regards to enterprise diversification, with an emphasis on rice. In future research, a more flexible approach to the typology of FS construction might provide further context and insight into the causes, consequences, and negotiations of farm diversity (Kuivanen et al. 2016).

The classification of the RFS was assessed through cluster analysis of the household data on rice yield, total number of other types of crop the household reported growing, and household herd size (Kuivanen et al. 2016; Ribeiro et al. 2018). We used the Minkoskwi distance as a measure of dissimilarity and ran Ward’s method because our variables were mixed between continuous and discrete. A Z transformation was also used to standardise the different scales of variables, minimising the object function error (Legendre and Legendre 2003b). To understand to what extent each variable described the FS, an analysis of variance (ANOVA) was also conducted. If a significant difference between each variable that described the RFS was detected, the post hoc test of Tukey was used to test for statistical differences of means between pairs of clusters of the RFS.

2.3.5. Crop Patterns across Farming Systems

To characterise the distribution patterns of other crops at the FS level, a cross-tabulation between the FS and each crop type was assembled and tested to verify whether the null hypothesis of similar patterns of crop distribution across the FS could be rejected. Post hoc cell-wise tests were performed to find out which crop types were above/below what would be expected by chance in each FS (García-Pérez and Núñez-Antón 2003; Sharpe 2015). The same procedure was also used to characterise the proportion of literate households across each FS. The ANOVA and a non-parametric Kruskal–Wallis (KW) test were required to test for statistical differences of average distances households travel to reach the farming field.

Table 2.2: Drivers for rice farming systems (RFSs), and predictors of production and productivity of rice, in the Chókwè Irrigation Scheme

Variable Name/Cod	**Type**	**Unity of Measuring/Class**	**Min-Max**	**Mean (SE)**
Age of the household	Numerical	NA	25–79	53.30 (±0.59)
Education	Ordinal	4 Classes	Illiterate (0)–high School (3)	1.01 (±0.35)
Distance to the farming field	Ordinal	4 Classes	<30 min (1)–>60 min (4)	2.47 (±0.58)
Labour force in the family	Numerical	NA	1–28	10.23 (±0.25)
Permanent workers	Categorical	Dummy	0–1	NA
Seeding	Numerical	Kg/ha	20–300	50.98 (±1.47)
Application of fertiliser	Categorical	dummy	0–1	NA
Quantity of fertiliser	Numerical	Kg/ha	0–200	22.58 (±2.35)
Use of pesticides	Categorical	Dummy	0–1	NA
Total rice activities	Numerical	NA	0–3	1.3 (±0.04)
Region	Categorical	Dummy	0–1	NA

Socio-economic drivers and predictors were: (i) age and education of the household. Age was a numerical variable, while education was ordinal, they were coded in the following categories: (0 = illiterate, 1 = primary school, 2 = secondary school and 3 = high school); (ii) the distance to the farming field. This was the average time that the household spent travelling to the farming area; thus, this time represents how far the field was from the place where the family lived and was coded in four categories (1 for <30 min; 2 = 30–45 min; 3 = 46–60 min; and 4 for ≥60 min); (iii) the availability of labour in the family. This was the number of family members of active working age, including men, women, and youth; (iv) whether the household had permanent paid workers, and whether the household used fertilisers or not, were both coded as dummy variables (yes = 1 or no = 0); v) the amount of seedlings and fertiliser that households use per hectare of rice; (vi) The total number of activities involved in rice production. The biophysical variable only considered the region in which the farming field was located. This variable was coded as a dummy (0 = if the household farm was in the upstream and 1 = if it was in the midstream or downstream).

2.3.6. Rice Farming Systems

A multinomial logistic model (MLM) was applied to investigate the importance of each driver of the RFSs. The importance of the variables in the fitted model was detected based on the log-likelihood, likelihood ratio, and Nagelkerke and Cox and Snell pseudo R-square. Predictors were selected based on their significance in the model, and possible meaningful interpretations. The importance of each predictor included in the model was assessed at the $p \leq 0.05$ level of significance.

2.3.7. Predicting Factors Affecting Production and Yield

A multiple linear regression (MLR) was also applied to investigate the factors affecting the production and yield of rice in the CIS. The rice yield (tonnes ha^{-1}) was used as a response variable to predict the factor constraint productivity, while the extension of rice farming (ha) was used as a response variable to predict the factors that positively or negatively affect the expansion of the rice area. The importance of each predictor in the model was assessed through the significance of each coefficient. A stepwise procedure was used to select the most parsimonious sub-model, based on the Akaike information criterion (AIC). All models were selected based on the significance of the p-value, residual standard error (RSE), multiple R-squared, and Adjusted R-square.

2.3. Results

2.3.1. Socio-Economic and Demographic Characteristics

The socio-economic and demographic characteristics of the respondents are presented in Table 2.3 and Table S1 (Supplementary Materials). More than half of the respondent farmers were men (210, 62%), while the remaining 131 (38%) were women. The predominant age group ranged from 35 to 64 years old, comprising 80% of all sample households. Only 19 (5.6%) respondents were in a younger (25–34) age group. The smallest group was the older population (65–79 years old, at 47, or 14%). Most of the households were either illiterate (55, 17.3%) or had a primary school level of education (230, 67.4%). Most respondents (256, 75.1%) reported they do not use fertiliser for their rice crop. Urea and Urea + NPK (84, 24.2%) were the most widely used fertilisers (Appendix A).

Table 2.3: Socio-economic and demographic characteristics of surveyed households in the CIS

Variables	Frequency	Percentage %
Gender		
Male	210	62
Female	131	38
Total	341	100
Age		
25–34	19	5.6
35–49	103	30
50–64	172	50
65–79	47	14
Total	341	100
Level of education		
Illiterate	59	17.3
Primary	230	67.4
Secondary	42	12.3
High School	10	2.9
Total	341	100
Use of fertilisers		
No	256	75.1
Yes	85	24.9
Total	341	100

Most of the households (294, 86%) reported paying for extra labour; only 13 (3.8%) farmers had permanent workers. Livestock rearing was also common among the farmers (246, 72%). Most of the farmers (224, 66%) reported that the largest proportion of production was for both consumption and sale (Appendix A).

2.3.2. Typologies of Different Rice Farming Systems in the CIS

Four FSs of rice were identified in the CIS (Table 2.4): (i) the subsistence farming system, where the outputs of rice and livestock are relatively lower, but only two other crops (maize and common bean) beside rice are produced; (ii) the specialised rice FS, where rice production is on average higher and dominant. The average size of the livestock herd in this system is four animals, and the number of other crops besides rice that the household grows was slightly different from subsistence farming. The common bean is the most evident secondary crop; (iii) mixed crops, in which the rice yield is lower and statistically similar to the subsistence FS. In this system, the size of the herd of each household is relatively lower, but similar to the previous two systems, and on average each household grows more crops besides rice (vegetables, maize, cowpeas, and sweet potatoes); and (iv) crop-livestock, where livestock is clearly predominant compared to the rest of the systems, followed by rice. On average, each household reported growing four other crops besides rice; specifically, the same crops as in the previous FS.

Table 2.4: Farming systems in the Chókwè Irrigation Scheme, and some of their socio-economic determinants

	Farming System						
	Subsistence	**Specialised Rice**	**Mixed Crops**	**Rice–Livestock**			
Variables	**N = 105|30.8%**	**N = 85|24.9%**	**N = 61|17.9%**	**N = 90|26.4%**	**Mean**	***p*-Value**	**Eta^2**
Rice (ton/ha)	1.64 c	3.24 a	1.88 c	2.49 b	2.31	0.000 ***	0.374
Livestock	2.95 b	3.59 b	3.61 b	18.46 a	7.32	0.000 ***	0.478
Other Crops	1.61 c	1.94 b	3.59 a	3.56 a	2.56	0.000 ***	0.729
Proportion of Households Growing Each Type of Other Crop (%)							
Vegetables	6.7	15.3	60.7	61.1	31.8(112)	0.000 ***	0.54
Adjusted residual	---	--	+++	+++			
Maize	92.4	89.4	100	97.8	94.4(322)	0.015 *	0.175
Adjusted residual		-	+				
Cowpeas	26.7	37.6	100	100	61.9(211)	0.000 ***	0.705
Adjusted residual	---	--	+++	+++			
Common beans	35.2	35.3	0.0	1.1	19.9(68)	0.000 ***	0.430
Adjusted residual	+++	++	---	--			
Sweet potatoes	0.0	16.5	98.4	95.6	46.9(160)	0.000 ***	0.898
Adjusted residual	---	---	+++	+++			
Other Characteristics of the Farming System							
Distance to the farming field # (min)	1.06 b	1.05 b	1.98 a	1.99 a	1.47	0.000 ***	0.190
Proportion of literate households	81.0	74.1	91.8	86.7	82.7	0.028 *	0.164
Adjusted residual		-	+				

Note: α = ***; ** and * denote significance at 0.1%, 1%, and 5%, respectively. Lowercase letters in the line indicate the difference between farming systems for each variable. Similar letters in the line are not statistically different. Proportions of households who reported growing other types of crops in each RFS were determined based on the adjusted residual: the symbols plus (+) and minus (–) indicate the existence of a relationship or no relationship between farming systems and the proportion of households who are literate, or grow each type of other crop. +|-; ++|-- and +++|--- denote significance at 5%, 1%, and 0.1%, respectively. Values within brackets represent the total number of households in all RFSs who reported growing each crop. The value of the ETA is the proportion of variance between FS for the variables, (yield of rice, herd size, and other crops) that characterise each FS. The variance is higher when the Eta is close to one.

Most smallholders (30.8%) in the CIS are subsistence farmers, followed by crop–livestock 26.4%, and 24.9% are specialised rice farmers. Mixed crops are the least adopted FS (17.9%). The proportion of literate farmers is on average higher in the mixed crops (91.8%), and lower in the specialised rice. Households who practice subsistence and specialised rice travel less distance from home to the field than those who have adopted mixed crop and crop–livestock FS.

All of the main variables that characterise the FSs (yield of rice, herd size, and other crops) are significantly ($p < 0.001$) different across FSs. The proportion of variance across the FSs is higher than in other crops; it represents more than half of the total variance ($ETA^2 = 0.73$) and is moderate for livestock and rice ($ETA^2 = 0.478$ and 0.374, respectively). All other crops, except maize ($p = 0.015$ and $ETA^2 = 0.175$) and common beans, vary considerably across FSs. Maize is the only crop which has been adopted by almost all households in all RFSs.

2.3.3. Farmer Choices Regarding Different Rice Farming Systems in the CIS

The estimated multinomial logistic model of choice for different FSs is represented in Table 2.5. The model shows that the location of a smallholder farmer in the upstream increases the likelihood of choice of subsistence and specialised rice FSs, in opposition to mixed and crop–livestock FSs, which are more likely to be located in the midstream and downstream. Meanwhile, increases in the household age reduce the likelihood of adopting the mixed crop FS and crop–livestock FS, as opposed to the subsistence and specialised FSs.

Table 2.5: Multinomial logistic model of farming system choice and its drivers/determinants

Farming System	Drivers	Coefficient	Std. Error	Z-Value	Alf (α)	Exp(B)
Specialised Rice	Intercept	–1.492	1.126	1.756	0.185	
	Region = mid + downstream	–0.262	0.245	1.148	0.284	0.769
	Age	–0.022	0.016	1.803	0.179	0.978
	Total rice activities	0.114	0.326	0.123	0.726	1.121
	Distance to the farming field	–0.221	0.205	1.160	0.281	0.802
	Household labour force	0.044	0.043	1.073	0.300	1.045
	Permanent labour force = Yes	0.951	1.271	0.559	0.455	2.587
	Seeding (kg/ha)	0.027	0.008	10.515	0.001 ***	1.028
	Fertiliser application = No	–0.966	0.404	5.735	0.017 **	0.380
Mixed Crops	Intercept	–5.206	1.629	10.213	0.001 **	
	Region = mid + downstream	0.884	0.297	8.882	0.003 **	2.421
	Age	–0.073	0.022	11.028	0.001 **	0.929
	Total rice activities	1.480	0.436	11.533	0.001 **	4.392
	Distance to the farming field	0.406	0.222	3.344	0.067	1.501
	Household labour force	0.091	0.057	2.521	0.112	1.096
	Permanent labour force = Yes	3.584	1.456	6.056	0.014 **	36.010
	Seeding (kg/ha)	–0.007	0.013	0.269	0.604	0.993
	Fertiliser application = No	0.712	0.610	1.364	0.243	2.038
Rice–livestock	Intercept	–7.030	1.565	20.170	0.000 ***	
	Region = mid + downstream	0.879	0.287	9.404	0.002 **	2.408
	Age	–0.070	0.022	10.344	0.001**	0.933
	Total rice activities	0.952	0.408	5.440	0.020*	2.590
	Distance to the farming field	0.455	0.217	4.370	0.037*	1.576
	Household labour force	0.201	0.054	13.878	0.000***	1.223
	Permanent labour force = Yes	2.461	1.436	2.936	0.087	11.718
	Seeding (kg/ha)	0.022	0.010	4.687	0.030*	1.022
	Fertiliser application = No	–0.123	0.525	0.055	0.815	0.884

Note: Subsistence farming system is a reference category; α = *** is significant at 0.1%, ** = 1%, * = 5%, NS = not significant. Model fit (log-likelihood = 650.61); likelihood ratio test (Chi-square = 282.67, α = 0.000). Number of observations = 341; Pseudo R-squared (Nagelkerke = 0.60, Cox and Snell = 0.56).

Having more activities related to rice production increases the likelihood of choice of a mixed and crop–livestock FS, as opposed to a subsistence FS. Increasing the distance to the farming field increases the likelihood of a choice for crop–livestock, as opposed to a subsistence FS. The availability of permanent labour, either from the family or by hire, significantly increases the likelihood of adopting a mixed crop ($\alpha = 0.014$) and crop–livestock ($\alpha = 0.000$) FS, rather than subsistence farming. Increasing the seedling rate per hectares increases the likelihood of the choice to adopt a specialised rice FS ($\alpha = 0.001$) and crop–livestock FS ($\alpha = 0.030$), as opposed to the subsistence FS. Likewise, the use of fertiliser significantly increases the likelihood of choosing specialised rice over subsistence farming.

2.3.4. Production and Yield of Rice in the CIS

Table 2.6 presents the results of the multiple linear regression that predicts the factors that constrain or stimulate the yield of rice in the CIS. The four variables (fertiliser, seeds, pesticides, and age of the household) selected through the AIC algorithm explained 51% of the variance ($p = 0.000$). All variables selected positively affected the yield of rice in the CIS, although they were not equally significant.

Table 2.6: Multiple linear regression to predict rice yield in the Chókwè Irrigation Scheme

Variables	Coefficient	Std. Error	T-Value	Alf(α)
Intercept	0.227	0.473	0.479	0.633
Fertiliser (Kg/ha)	0.007	0.003	1.938	0.056 *
Seeds (Kg/ha)	0.016	0.003	5.813	0.000 ****
Pesticide (yes/no)	0.531	0.335	1.583	0.117
Age of the household	0.021	0.009	2.338	0.022 **
R^2			0.5101	
p-value			0.000 ****	
Start AIC			–4.92	
End AIC			–12.83	

Note: Model was plotted based on the Akaike information criterion (AIC). α = ****, ** and * is significant at 0.001; 0.05 and 0.1, respectively.

Increasing the amount of fertiliser and seeds per hectare slightly increases the yield per hectare, with $p = 0.056$ and $p = 0.000$ significance, respectively. The application of pesticides has a positive effect on the rice yield, although the effect is not statistically significant. Increasing age of the household also has a positive effect on rice yield.

Table 2.7 presents the Multiple Linear Regression that describes the increase in production in the CIS. Only four variables (years of experience, total rice activities, and the amount of money invested in paying casual and permanent labour) were selected by the stepwise algorithm. Total rice activities were the only variable with a negative effect on production. The expansion of land for growing rice is positively affected by the years of household experience, the amount of money that the household spends to hire labour, and the availability of permanent labour for farming activities.

Table 2.7: Multiple linear regression to predict rice production in the Chókwè Irrigation Scheme

Variables	**Coefficient**	**Std. Error**	**T-value**	**Alf(α)**
Intercept	0.317	0.150	2.119	0.035 **
Years of experience	0.022	0.005	4.576	0.000 ****
Total rice activities	–0.330	0.087	–3.784	0.000 ****
Amount of money paid for labour	0.009	0.002	4.890	0.000 ****
Permanent labour force	2.669	0.259	10.302	0.000 ****
R^2		0.3501		
R^2 Adjusted		0.3423		
p-value		0.000 ****		
Start AIC		–73.34		
End AIC		–82.15		

Note: Model was plotted based on the AIC criterion. α = ****, and ** is significant at 0.001; and 0.05, respectively.

More years of experience also increases the likelihood of increased production (p = 0.035), while hiring permanent labour and increasing the amount of money that the household spends to hire labour also significantly increase the likelihood of expanding the farming area (p = 0.000). Both models, the MLM of yield and production, showed no significant effect of any interaction between factors (e.g., gender, education, hiring permanent labour, and application of pesticides) or covariates (e.g., amount of fertiliser and seeds per hectare, age of the household, distance to the farming field, and the amount of money paid for labour, etc.)

2.4. Discussion

2.4.1. Drivers of Rice Farming Systems

Livestock and other crop types, including vegetables, maize, cowpeas, common beans, and sweet potatoes, appear to be indispensable components of all RFSs in the CIS. Even in specialised rice FSs, most households grow other crops and raise livestock (e.g., cattle, swine, and goats). There are several reasons for households to diversify their FSs; most importantly, it can secure their livelihood, and protect against food scarcity (Ayoola et al. al 2011; Landry et al. 2011; Sharpe,2015) For instance, Mota et al. (2019) (Mota et al. 2019) reported less income generation and more food insecurity for farmers with no livestock, compared to those who owned livestock. Based on the average plot size allocated to rice in the surveyed households (min = 0.25 ha, max = 5.3 ha; mean = 0.94 ha and, mode = 1 ha), one can easily infer that only a few farmers can survive by specialising in rice production. This allocation of a small rice plot is also related to the fact that most households also grow maize, which is a rice substitute, as well as the existing land restrictions. The optimal allocation of substitute crops, such as maize and cassava, has also been reported in other FSs in north Mozambique (Mbanze et al. 2020). The use of a small amount of land for subsistence agriculture is a widespread practice in the rural areas of developing countries, such as Mozambique (Landry and Chirwa 2011) and the sub-Saharan region (Afolami et al. 2012; Sharpe 2015; Sraïri et al. 2017; Ribeiro et al. 2018), due to the lack of technology and capital to hire a labour force (Chukwu et al. 2016). Even in the specialised rice system, the average rice output of 3.24 ton/ha is still very low when compared to other regions (Zeigler 2016b). The adoption of livestock rearing is a traditional practice in south Mozambique (Dixon 2019), as it confers a comparative advantage due to the availability of lower lands and favourable climate conditions (Ducrot et al. 2018). To underline the above hypothesis, moving from upstream to downstream increases the likelihood of adoption of the rice–livestock FS, as opposed to other FSs. Rice is, on average, grown over a single rainy season from October to March (Menete et al. 2008), and other crops, such as sweet potatoes, vegetables, and cowpeas, are grown after harvesting the rice.

Increasing age of the household is associated with increased likelihood of adopting specialised rice and subsistence farming, as opposed to mixed and crop–livestock FSs; this is likely because either experience is important for specialised rice adoption, or because older households only grow a few other crops for subsistence (e.g., maize and common beans). Other studies conducted in Africa have also highlighted the importance of experience in rice production (Afolami et al. 2012). In contrast, Kajisa (2014) argued that, for rice production, technology is more important than years of experience. However, technology is still very expensive for smallholder farmers in this region, hence it was not yet being used by the surveyed households.

A study conducted in the same region found that younger people are more willing to move closer to bigger cities, such as Maputo and Xai-Xai, seeking employment opportunities and better living conditions (Ibraimo 2017). Thus, they are less likely to embrace farming. It is also important to highlight that the Chókwé district headquarters is in the upstream region, so most of the households in this region are formally employed in the government and in NGO institutions; they practice subsistence agriculture as a second occupation.

Labour availability significantly increases the likelihood of adoption of the mixed crops and rice–livestock FSs as opposed to the subsistence FS, which is probably related to the fact that, in rural areas of developing countries, farmers need to hire more workers or have a large family to overcome labour scarcity, especially when there are other off-farming activities such as animal rearing to consider (Kuivanen et al. 2016). A study conducted by Sraïri and Ghabiyel. (2017), in the Gharb Irrigation Scheme in rural Morocco, found that crop–livestock farms devote, on average, 56.41% of their annual working time to livestock raising, and the remaining time to crop-related necessities. Increasing the labour force also increases the likelihood of choosing the specialised rice FS, although not as significantly as the crop–livestock FS, which is likely because an increase in the productivity of rice requires more rice-related activities (e.g., ploughing, harrowing, fertiliser and pesticide application, and weed control), hence requiring additional labour.

2.4.2. Promoting Factors and Constraints for Rice Productivity in the CIS

Based on the MLR, we have demonstrated that only four variables—seeds, fertilisers, pesticides, and age of the household—predict 51% of the variability in the rice yields in the CIS. Thus, optimising these inputs could greatly improve the productivity of rice in the CIS. Fertiliser and seeds appear to be the most important production inputs to improve the yield of rice (see, for instance, Afolami et al. 2012). However, in this study, only 24.5% of farmers reported applying fertiliser. This relatively low number of farmers is probably related to the following factors: (i) the lack of financial incentives, such as bank loans and low import tariffs, for rice inputs such as fertiliser and improved seeds, so that smallholder farmers can afford to purchase them, and (ii) lack of information and capacity-building required to take advantage of the available animal manure (Ismael et al. 2021).

Based on the MLR (see Table 2.7), a lack of experience and lower labour availability (either permanent or hired) also hinder farmers' decisions to expand their production area. Again, we might therefore infer that a lack of financial support constrains famers in terms of intensification and expansion of rice production in the CIS, which is also in line with conclusions from Chukwu et al. (2016). The number of activities that farmers carry out prior to harvesting the rice is negatively correlated with land expansion; this is likely because intensification requires more inputs (activities), such as weed and pest control, which in turn requires more labour and inputs, and these are out of reach for smallholder farms in the CIS. Thus, within the existing constraints that farmers are exposed to, they must choose to optimise scarce resources either by intensifying or diversifying their production. According to Ayoola et al. (2011), increasing the use of land and inputs such as fertilisers, herbicides, and labour could also increase the production and productivity of rice.

2.4.3. Policy Recommendations to Improve Production and Productivity for Smallholder Farmers in the CIS

The main constraints for productivity and production in the CIS are (i) land restriction; ii) lack of inputs (e.g., fertilisers, herbicides, and labour); and (iii) poor training and lack of rural extension services. The expansion of farming areas appears to be hampered by a lack of capital for the acquisition of more land, since most households (70.4%) in our survey reported inheriting land from relatives (Appendix A). To overcome this restriction, smallholder farmers need to strengthen corporativisms and intensify productivity in small plots by using more inputs (Afolami et al. 2012). However, to facilitate intensification, the government and NGOs operating in the CIS need to create incentives, such as providing loans and cheaper agrarian credits, so that farmers can better access market inputs (e.g., fertilisers, herbicides, and labour). Providing more extension services and training to smallholder farmers in the CIS should be the top priority to improve production and productivity in this area (Benfica et al. 2018). For instance, we noted that limited chemical fertiliser could be replaced by adopting animal manure, which has a great potential to contribute to the development of green agriculture in the area (Ismael et al. 2021). However, we also acknowledge the crop yield gap between organic and conventional agriculture (De Ponti et al. 2012). Nevertheless, training households to adopt animal ploughing could minimise scarcity, without being constrained by the unaffordable price of human labour.

Despite the efforts towards fitting the destination of the rice output (e.g., for sale locally or for household consumption) as an FS driver, no meaningful explanation was captured. All FSs in the CIS appear to be more consumption-oriented than market-oriented (Appendix A). Most of the FSs appear to have evolved towards mixed crop and rice–livestock production, which is typical of subsistence agriculture, even though the CIS was primarily designed for rice production. This remarkable dynamic is likely because there is a market opportunity for other crops and products, such as vegetables and meat, that can be sold at nearby towns such as Maputo and Xai-Xai. According to Glover and Jones (2019), farms are highly selective in their locations, preferring areas close to existing infrastructure and markets. This hypothesis was highlighted by the fact that educated households are more likely to focus production on more cattle and vegetables, since they are also in a better position to see market opportunities and assess the viability of other commodities which do not demand higher production inputs. Second, rice appears not to be a profitable business for the smallholder farmer, since Asian rice (from China, Thailand, and Vietnam) is sold at a very competitive price in Mozambique. To make matters worse, maize is a competing product, and a substitute for rice that requires less water and production inputs, especially in the context of climate change.

To better advise decision-makers in this area, the hypotheses explored above need to be tested with comprehensive data on production, yield, value chain, and gross margin analysis of each crop and livestock type, in comparison to large and middle-sized farmers, since some authors have reported possible economic spillovers from commercial activities to local smallholders (Glover et al. 2019). However, due to time and resource restrictions, this will be a focus for future research.

2.5. Conclusions

This study aimed to assess rice farming system typologies in the CIS to better understand the drivers and constraints for smallholder rice farmers and proposes alternative policies for decision-makers to improve production and productivity. The results demonstrated that the use of different RFS typologies, rather than one FS for all farmers, can better capture the specific drivers for each FS in the region.

Four RFSs were identified: the subsistence FS, specialised rice FS, mixed crops FS, and rice–livestock FS. Subsistence and specialised rice are predominant in the upstream region of the CIS, while mixed crops and crop–livestock are predominant in the midstream and downstream. The households who adopted subsistence FS were on average older and had fewer resources. Specialized rice farmers had access to more resources and were driven by the household power for purchasing production inputs. Mixed crops and rice–livestock were driven by the availability of labour and possession of lower lands. In general, increased production inputs (e.g., fertiliser, pesticides, weed control, and the number of seeds per hectare) might greatly improve productivity, whilst household experience and labour availability could greatly improve production.

This research suggests that rice farmers in the region require more training opportunities to optimise the available resources, such as animal manure and animal traction, as well as to explore other more valuable trade-offs, such as potential market opportunities and the production cost of other crops and livestock in the region.

Supplementary Materials: The following are available online at www.mdpi.com/xxx/S1, Table S1: Socio-economic and demographic characteristics of the surveyed households in the CIS.

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__Chapter II__

Appendix A
Supplementary Materials Final

Survey to households head

Date: ___________

Village: _________

SECTION A

CHARACTERISATION OF THE AGGREGATE AND THE PRODUCTION SYSTEM

1. Household name (optional): _____________

2. Age of the household: ____________

3. Education status:

(a) Did not attend___ (b) Primary school ___ (c) High school ___(d) Degree ____ (f) Other (specify)

4. Aggregate composition:

(a) Male _(b) Bigamy __ (c) Female ___ (d) Youth ___ (e) Children (<10) __ (f) Elderly people__ (g) Disabled__

5. Income Sources

Income Sources	**Gender**		
	Male	**Female**	**Relative Importance**
Agriculture			
Chore			
Hunting			
Charcoal			
Firewood			
Small Business			
Other			

6. Workers

6.1. Do you hire people during the work peak/occasionally? No __ Yes __

6.2. For what kind of activities? ___________ How much do you pay per day/activity? ___________

6.3. Do you have permanent workers? No ____ Yes __ Wage _______

6.4. Are you enrolled in any association of self-help at work? No _________ Yes_________

7. What other crops do you grow in addition to rice cultivation? (a) Vegetables ____; (b) Maize; (c) Cowpeas ____; (d) Common Beans ____; (e) Sweet Potatoes ____; (f) Millet ____; (g) Peanuts ___; (h) Potatoes _____; (i) Yams_____; (h) Other _____

8. Livestock and Poultry

Livestock Production	Number of Animals
Cattle	
Goat	
Pigs	
Poultry	
Others	

SECTION B

CHARACTERISATION OF RICE PRODUCTION

9. What is the distance between your house and the field where your rice is produced:

(**a)** 15 min ___; (b) 30 min ___**;** (c) 45 min; (d) an hour __ and (e) >1 h __

10. How many years have you been producing rice for? _____ (years)

11. How did you obtain access to the land for the rice field?

(a) Inherited/Offer __; (b) Loan __; (c) Purchased __; (d) Partnership __; (e) Associations ____ (f) Other ______

12. Do you consider fallow on the rice field? No __; Yes __;

12.1. If yes, how many years in average do you fallow the plot? _________

12.2. Why do you consider this number of years? _________________

13. Mobilisation of the land:

(a) Soil hand preparation? __ (b) Mechanical tillage (nº)__ (c) Mechanical harrowing (nº)__

13.1. (a) Tillage price/hectare ________; (b) Price harrowing/hectare __________

14. Fertilisation

(a) Type of fertiliser_____; (b) Amount of fertiliser_________; (c) Cost of acquisition _________ (d) How many times do you apply each fertiliser in one season?; (e) Type of application (basal/dressing) _______

15. Pesticides

(a) Pre-emergent _________; (b) Post- emergent ________;

15.1. How many times do you weed your plot in one season?

16. Type of sowing:

(a) Throw _____; (b) Located___; (c) Sowing direct __; (d) Transplant__; (e) Pre-germination__

16.1. Quantity of seeds (kg/hectare) _____

16.2. Method acquisition

(a) Purchase in the local market _____ (b) Family or friend offer _______; (c) Acquisition from the cooperative;___________________; (d) Other __________

16.3. If you declared buy, what price do you pay per kg _________________________________

17. Productivity:

(a) Sacks of 50 kg*hectare^{-1} paddy bases _________; (b) Dimension of the plot (hectare) _______

18. Destination of production:

(a) Domestic consumption _____; (b) Sold in the local market _____; (c) Both___________

End

Chapter II_____

Supplementary Materials

Table S1. Socio-economic and demographic characteristics of the surveyed households in the CIS.

Variables	Frequency	Percentage %
First occupation		
Farming Rice	332	97.4
Farming + Other activities	9	4.2
Total	341	100
Land access		
Heritage	210	70.4
Lending	60	17.6
Associative	41	12
Total	341	100
Distance to farming field (minutes)		
<30 minutes	52	15.2
30–45 minutes	177	5.9
46–60 minutes	13	3.8
>60 minutes	99	29
Total	341	100
Type of fertiliser		
No	256	74
NPK	1	0.3
Urea	42	12.1
Urea/NPK	42	12.1
Total	341	100
Eventual hired labour		
No	47	13.8
Yes	294	86.2
Total	341	100
Permanent hired worker		
No	328	96.2
Yes	13	3,8
Total	341	100
Livestock production		
No	95	28
Yes	246	72
Total	341	100
Destination of the output		
Consumption	117	34
Consumption and sale	224	66
Total	341	100

Chapter III

New Fertilizer Strategies Combining Manure and Urea for Improved Rice Growth in Mozambique

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New Fertilizer Strategies Combining Manure and Urea for Improved Rice Growth in Mozambique

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Abstract

The cost of chemical fertilizers is increasing and becoming unaffordable for smallholders in Africa. The present study aimed to assess the impact of combined fertilization strategies using urea and animal manure (beef cattle manure and poultry litter manure) on rice yield and nutrient uptake. For this, a field experiment was carried out on a loam sandy soil in the Chókwè Irrigation Scheme. We set seven treatments in a Randomised Complete Block Design (RCBD), namely: T0- no fertilizer, T1- 100% urea, T2- 100% beef cattle manure, T3- 100% poultry litter, T4- 50% urea + 50% beef cattle manure, T5- 50% urea + 50% poultry litter and T6- 40% urea + 30% beef cattle manure + 30% poultry litter, replicated four times each. All treatments, except T0, received an amount of nitrogen (N) equivalent to 100 kg N.ha^{-1}. Results revealed that the highest yield grain (425 g.m^{-2}), plant height (115 cm), number of tillers (18) and thousand-grain weight (34g) were observed in treatments combining urea with manure (T4, T5 and T6) indicating that

N supply in the mixture (urea + manure) is more efficient than in isolated applications of N (T1, T2 and T3). The data obtained in this study suggest that a combination of fertilizers (T6) lead to competitive yields and is thus recommended for best soil management practices.

Keywords: organic fertilizer; chemical fertilizer; Rice (*Oryza sativa* L.), nutrient uptake

3.1. Introduction

Rice plays a major role in global food security and is becoming the staple food of more than half of the world population, providing principal nutrients in the different continents, particularly in Asia, Latin America, and Africa (Chauhan et al. 2017). In Africa, rice production is below growing consumer demand coupled to increases in population, rapid urbanization and changing consumer behaviour (CARI 2018b). The African continent accounts for only 4.8% of the world rice production, and despite its potential with 130 million hectares of arable soil, only 8% are currently under cultivation (IRRI 2018). The average rice yield in Africa (2 $Mg.ha^{-1}$) is much lower than in Asian countries, e.g., Indonesia, Bangladesh, Vietnam and Myanmar which produce 7 $Mg.ha^{-1}$ (MINAG 2013).

In Mozambique, rice is cultivated over a total area of 320,000 hectares, thus representing the second most important source of cereal production. The average productivity, however, is low (about 1.04 $Mg.ha^{-1}$) (MASA 2019), partly due to inappropriate or poor land preparation (burning crop residues, as well as the use of fire for opening new areas) and inadequate fertilizer management such as rate and timing of fertilizer application. This occurs mainly because most of this production is carried out by smallholder farmers who are engaged in rudimentary subsistence agriculture, depending mostly on rain as water source, use of local rice varieties, low technical support in management of soil fertility and minimal use of pesticides and fertilizers (CGAP 2016).

It is estimated that around 4.2 million small farms consist of subsistence-level rainfed agriculture and less than 1% of producers are commercial (MASA 2019). The majority of smallholders cannot be competitive by ensuring continuous supply in line with national rice consumption, so the country relies on imports to respond to the existing demand and low supply (FAO 2019). The lack of up-to-date and accessible information on profitable technology options for different producer groups in combination with poor provision of an effective agricultural extension service, have been pointed out as other potential factors affecting rice productivity in the country (FAO 2016). Inadequate fertilizer input is one of the most limiting factors to rice production. Furthermore, water is another vital factor that constrains rice production, namely water access, and additionally, weak water management capacity in the fields to guarantee timely adequate supply (Zavale et al. 2020). The fertilizer application rate in Mozambique has remained at less than 5.7 $kg.ha^{-1}$ (Zavale et al. 2020), a cause for the consistently low production.

Intensive rice production and future rice demand will require intensive knowledge-based farming strategies for the efficient use of all inputs, including fertilizer nutrients. Increase in rice production requires an adequate amount of essential nutrients (Moro Buri and Nuhu Issaka 2020). The use of integrated fertilization combining mineral and organic fertilizers has a strong potential and could be available and affordable for smallholder rice producers. An advantage of the application of organic wastes as fertilizer is that they usually provide nutritive elements to crops at little added cost along with the addition of organic matter to enrich the soil (Myint et al. 2010). Compared with chemical fertilizers, nutrient availability is dependent on the mineralization rate of the organic material, which is generally low due to the high C/N ratio of these products leading to low crop growth and yield (Moe et al. 2019b). According to Iqbal et al. (Iqbal et al. 2019) organic fertilizers with lower nutrient releasing ability limit uptake of nutrients and fail to meet short-term crop requirements.

Nitrogen is a macronutrient with an important role in rice production, compared to other nutrients (Jahan et al. 2020) since it is fundamental to promote rapid plant growth and it improves grain yield and quality (Fageria et al. 2009). Therefore, better N management is essential, namely the use of adequate 1) amounts of fertilizers, 2) N forms and formulations and 3) application time and method (Tamele et al. 2020).

The continued increase in rice demand should be supported by increased production using adequate techniques, particularly in the developing countries (Druilhe and Barreiro-Hurlé 2012). Reducing dependence on imports, optimising the use of existing resources in rice cultivation, with direct consequences for food security, generating wealth sources and economic growth of the Mozambican population are all a priority. Due to the high cost of chemical fertilizers in African countries, including Mozambique, it is necessary to guarantee an optimal and alternative way of rice production. However, few studies provide technical support related to crop productivity, and simultaneously, N use efficiency, which are important parameters to evaluate nutrient management in farms producing rice. Therefore, fertilization strategies will have to be developed and tested to increase rice production with low environmental impact and high acceptance from the producers. The main objective of the present study was to evaluate the agronomic effect and economic benefits of combined fertilization of rice production using mineral fertilizers and organic materials as N sources in Mozambican conditions.

3.2. Materials and Methods

3.2.1. Study Site

The study was conducted at the Chókwè Irrigation Scheme (CIS), located in Chókwè District, Gaza Province, adjacent to Limpopo River, southern Mozambique (24°52′ S, 33°00’ E, 33 m above sea level) (Druilhe and Barreiro-Hurlé 2012). The area is the major irrigation scheme in Mozambique (Abbas 2018b) and covers 33,000 ha extension of land possible for irrigation (Ducrot et al. 2018). The climate is predominantly semi-arid (JICA 2014) with a mean annual temperature ranging from 22 to 26°C and a total annual precipitation ranging from 500 to 700 mm. Yearly evapotranspiration ranges from 99.6 to 167.4 mm.

Variation of precipitation, temperature and relative humidity measured during the experimental period (December-April) are presented in Table 1. Total rainfall was equivalent to 337.1 mm. Precipitation mainly fell during January to February contributing 54% of the total rain during the experimental period. The average minimum and maximum temperatures are 20.0 °C (in April) and 33.4 °C (in March) respectively. The annual interval of relative humidity is 60.6 to 74.0%.

Table 3.1: Average temperature, relative humidity and total rainfall registered during the field experiment (2018–2019)

Year (2018)	**Maximum Temperature (°C)**	**Minimum Temperature (°C)**	**Relative Humidity (%)**	**Rainfall (mm)**
November	32.7	22.1	62.5	37.0
December	32.8	28.2	60.8	74.1
Year (2019)				
January	32.5	20.5	74.0	90.0
February	32.3	27.3	53.8	78.0
March	33.4	31.0	54.7	76.0
April	31.2	20.0	66.7	19.0
May	29.8	16.6	60.6	27.0

Rice is a primary crop cultivated during the rainy season (October to April) followed by fresh vegetables like tomatoes, onions, and green pepper cultivated during the dry season (May to September) (MAE 2012). Soil type was classified as loam sandy soil. The texture of the top (0–20 cm) soil layer was classified as sandy loam (sand = 59%, silt = 30%, clay = 7%). Soil pH and total N concentrations in the top soil layer were 7.0 and 1.1 g.kg^{-1}, respectively. Cation exchange capacity and soil organic matter were 31.6 cmolc.kg^{-1} and 21.9 g.kg^{-1}, respectively. Before the experiment, beef cattle manure and poultry litter samples were collected from the local farmers and analysed to determine their physical and chemical properties. Detailed initial soil, beef cattle manure and poultry litter properties are presented in Table 3.2. Air temperature and precipitation data were collected from the weather station in the Chókwè meteorological office.

Table 3.2: Properties of the soil and organic fertilizer used in the experiment

Soil Parameters	**Soil**	**Beef Cattle Manure**	**Poultry Litter**
pH	7	8.2	8.5
EC (µS.cm^{-1})	640	7.2	4.4
Dry matter (%)	NA	84	80
Total N (g.kg^{-1})	1.1	21	27.1
$NH_4{}^+$-N (g.kg^{-1})	0.01	12	11
$NO_3{}^-$-N (g.kg^{-1})	0.02	7.7	15
CEC (cmolc.kg^{-1})	31.63	30.2	32.1
C/N ratio	11.55	12	10
Organic matter (g.kg^{-1})	219	318	307
P (mg.kg^{-1})	33.69	12.1	12.3
K (mg.kg^{-1})	660	NA	NA
Exchangeable cations (cmol.kg^{-1})			
Ca	17.5	NA	NA
Mg	9.94	NA	NA
K	1.26	NA	NA
Na	1.88	NA	NA

(Mean of three replicates; values presented on a dry matter basis); NA- not available.

3.2.2. Treatments and Experimental Field Design

From December 2018 to April 2019, seven treatments (four replicates) were set up in terms of N source: T0-no fertilizer, T1-100% urea, T2-100% beef cattle manure, T3-100% poultry litter, T4-50% urea + 50% beef cattle manure, T5-50% urea + 50% poultry litter and T6-40% urea + 30% beef cattle manure + 30% poultry litter. Details of each treatment are presented in Table 3. Twenty-eight plots of 2m x 3m were used for the present experiment. All plots were separated by 50 cm ridges to avoid the mixing of water and nutrients from adjacent treatments. All treatments were managed following the same practices (irrigation, weeding pest and disease control) usually adopted by farmers during the rice growing season. Different amounts of fertilizers were applied to supply a total amount of N, equivalent to 100 kg.ha^{-1}, except T0 which received no fertilizer. Fertilizers were applied in two distinct time periods: half was applied two weeks before transplanting (applied as basal fertilization) and the remaining/other half was applied before panicle maturity stage. Irrigation water was separately applied to each treatment from a water channel. The irrigation requirements were conducted based on rice plants needs and weather conditions. Rice seeds (cv Makassane) were sown in a nursery on 18 December 2018 and seedlings were transplanted on 10 January 2019.

Table 3.3: Amounts of natural and synthetic organic N-fertilizers applied in each treatment

Treatment	**Amount of Fertilizer Applied (kg.ha^{-1})**			**Total N Applied (kg.ha^{-1})**
	Urea	**Beef Cattle Manure**	**Poultry Litter**	
T0	0	0	0	0
T1	1.3	0	0	100
T2	0	3.0	0	100
T3	0	0	2.2	100
T4	0.7	1.5	0	100
T5	0.7	0	1.1	100
T6	0.5	9	6.6	100

3.2.3. Soil Analysis

Soil samples were collected from the 0–20 cm topsoil layer at harvesting time. Soil pH and electrical conductivity (EC) were determined in a soil:water (1:2.5 w/v) suspension. Soil samples were extracted with 2M potassium chloride (KCl) solution and the extract was analysed for ammonium N (NH_4^+ -N) and nitrate N (NO_3-N) concentration by continuous flow analysis as described by (Fangueiro et al. 2015c). The N total was measured by Kjeldahl method (Nelson and Sommers 1973). The organic matter was quantified by loss-on-ignition after incineration at 500–550 °C of dry sample. Potassium (K) and phosphorus (P) content were determined according to Egner-Riehm method (Grigg and Grigg 1965). Available Cu, Zn, Fe and Mn were extracted based on the procedure described by Lakanen and Ervio (1971) (Prado et al. 2020) and quantified by atomic absorption spectrophotometer. Exchangeable cations were extracted by 1M ammonium acetate at pH 7 and measured by atomic absorption spectrophotometry (Motsara and Roy 2008).

3.2.4. Growth Indicators, Plant Yield and Nutrient Uptake

From the day of transplanting up to harvesting time on May 17, 2019, plant growth parameters such as plant height, and number of panicles in the same plants were collected every two weeks throughout the experiment. Ten plants were randomly selected in each plot and identified to allow the monitoring of these two growth parameters. At harvest time, the plant height, thousand-grain weight (TGW), the number of spikelets per panicle, and the maximum panicle length (cm) were measured in these same ten plants.

At the end of the experiment, aboveground (straw and grain) and belowground (roots) samples were harvested manually in an area of 1 m^2 (1m × 1m) randomly selected in each plot. In this sampling area, panicles of each plant were counted, and all samples were air dried for almost one week. Grains were separated from straw and the total number of grains was counted and weighed. Rice straw was also weighed to evaluate the total dry matter (grain + straw).

Subsamples of each plant component (grain, straw and roots) were ground and analysed for N content by micro-Kjeldahl method (Nelson and Sommers 1973) and for K and P content by hydrochloric acid digestion followed by quantification by the ammonium vanadomolybdate method for P and molecular absorption spectrophotometry for K (Fangueiro et al. 2009). Crop nutrient uptake was calculated from dry biomass weight and percentage of nutrient content (grain and straw) (Fixen et al. 2015).

3.2.5. Statistical Analysis

Data were subjected to analysis of variance (ANOVA) (Asai 1991) and means between treatments were compared using the Tukey`s honest significance difference test (HSD) at 5% level of significance. The analyses were carried out using “R” Software (version 3.3.2).

3.3. Results

3.3.1. Plant Growth Parameters

Plant growth parameters are important tools to assess rice productivity and yield. At harvest time, the main parameters related to rice growth assessed here were plant height, tillers per hill, number of spikelets per panicle, and the yield components. The number of tillers also indicate the number of panicles, so these parameters give one idea about yield potential. Likewise, number of spikelets per panicle is one tool used to estimate rice yield in experiments. Some parameters such as number of tillers per hill and rice plant height were assessed also across the experiments. This information allows to estimate the performance that the plant can have to achieve yield attributes since excellent vegetative growth and development resulted in maximum height.

Variation of plant height and number of tillers during the experiment are presented in Figures 1 and 2, respectively. Plant height throughout the experiment followed a similar trend: T1 > T6 > T5 > T4 > T3 > T2 > T0 (Figure 1), with no significant differences. Maximum plant height was observed in T1 and T6, at 114.5 and 113.25 cm, respectively, whereas minimum plant height was observed in T0 at 100.25 cm. Similar plant heights were observed by Moe et al. where rice was fertilized with urea alone and manure plus urea. Maximum tillering was observed in T6 and T4, with 18 and 16 tillers, respectively. Minimum tillering was observed in T0 with 8 tillers (Figure 2). The values obtained here were similar to those obtained by John Hunter et al. (John Hunter et al. 2016).

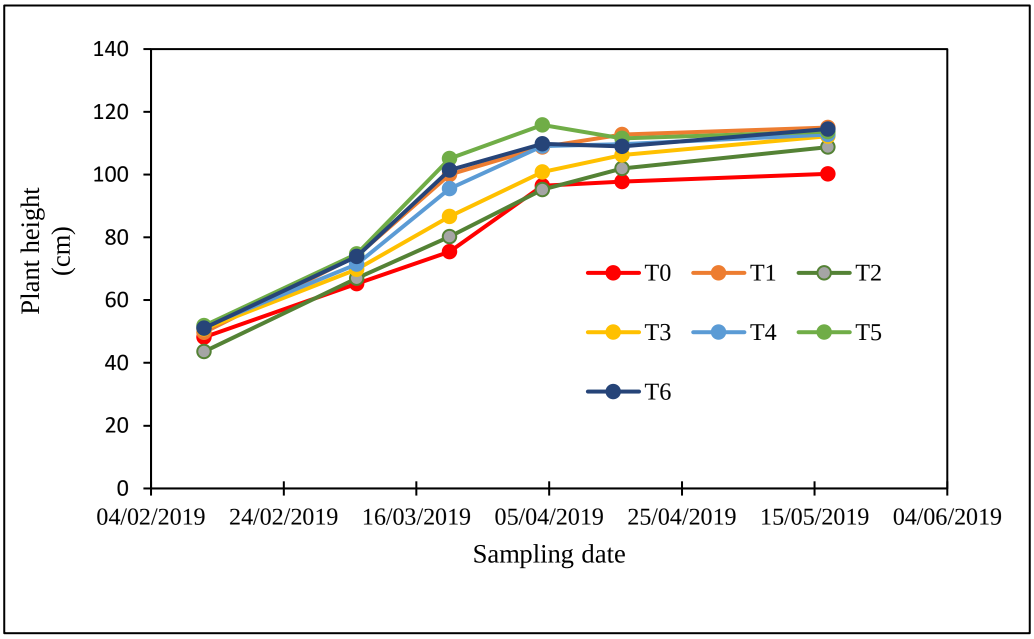

Figure 3.1: Effect of the different treatments on rice plant height; mean of 4 replicates; error bars were removed for clarity, T0: no fertilizer, T1: 100% urea, T2: 100% beef cattle manure, T3: 100% poultry litter, T4: 50% urea + 50% beef cattle manure, T5: 50% and and T6: 40% urea + 30% beef cattle manure + 30% poultry litter

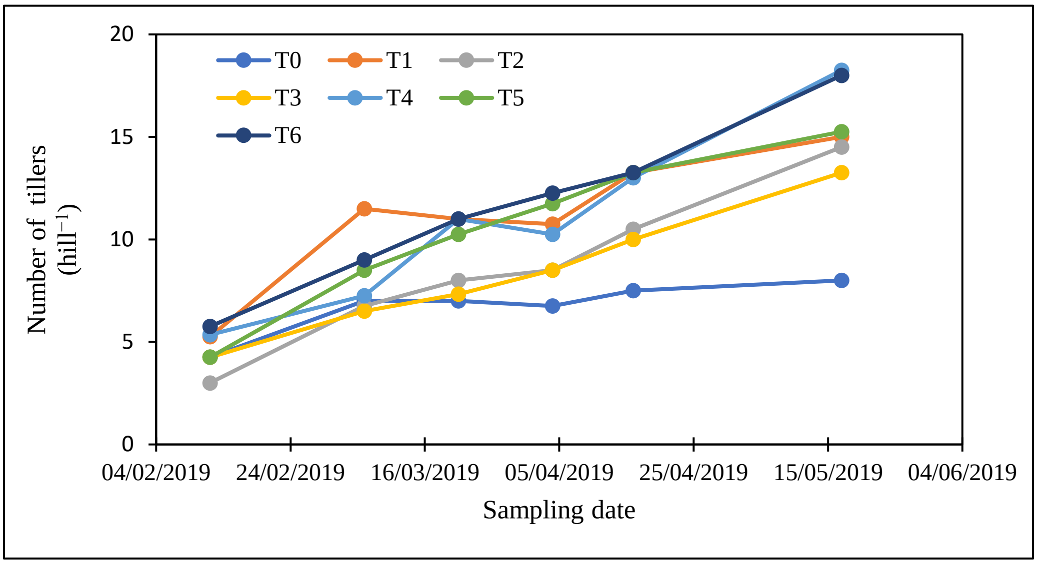

Figure 3.2: 1Effect of the different treatments on rice plant tillering; mean of 4 replicates; error bars were removed for clarity, T0: no fertilizer, T1: 100% urea, T2: 100% beef cattle manure, T3: 100% poultry litter, T4: 50% urea + 50% beef cattle manure, T5: 50% urea + 50% poultry litter and T6: 40% urea + 30% beef cattle manure + 30% poultry litter.

The 1000-grain weight was also affected by the treatments (Figure 3.3) and was significantly ($p < 0.05$) greater in all the fertilized treatments compared to the control. The highest 1000-grain weight was obtained in T2 and T6 with a significantly higher value compared to the remaining treatments. The lowest values in fertilized treatments were observed in T3 and T4.

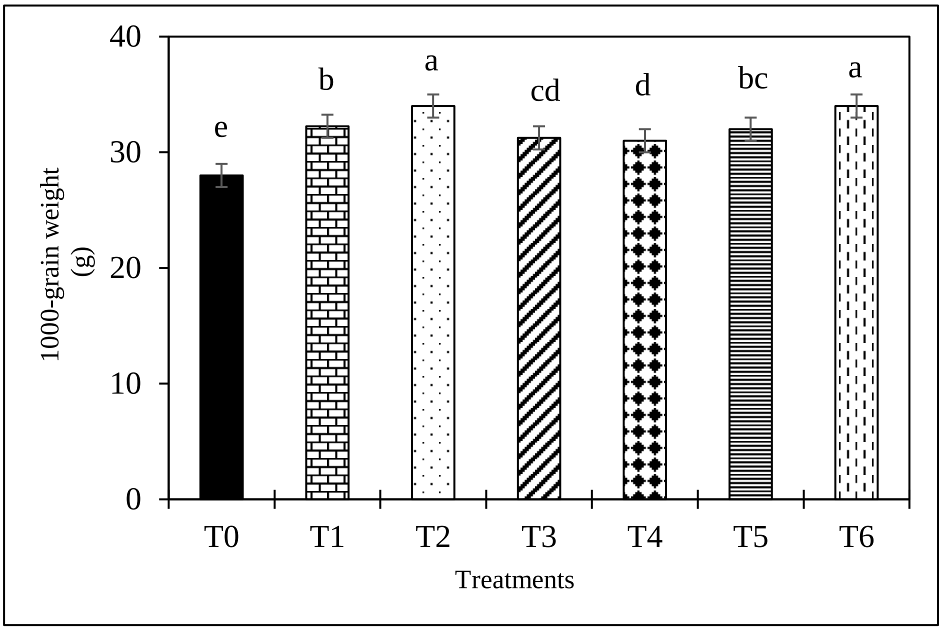

Figure 3.3: 1Effect of different N fertilizer and their combinations on one thousand grain weight; mean of 4 replicates. Different letters indicate statistical differences ($p < 0.05$), T0: no fertilizer, T1: 100% urea, T2: 100% beef cattle manure, T3: 100% poultry litter, T4: 50% urea + 50% beef cattle manure, T5: 50% urea + 50% poultry litter and T6: 40% urea + 30% beef cattle manure + 30% poultry litter.

The number of spikelets were significantly influenced by the different N sources among treatments (Figure 4). The highest number of spikelets (96) was observed in T6, even if no significant differences were observed between T6, T5, T4 and T3. Significant differences were observed between T0, T1 and T2 where the lowest number of spikelets was observed (72) (Figure 3.4). A high number of spikelets observed in the integrated treatments indicates that the combined application of fertilizers caused increased growth.

This may have been due to enhanced mineralization of the organic N from the manure indicating that the combination with chemical fertilizers is efficient (Kakar et al. 2020).

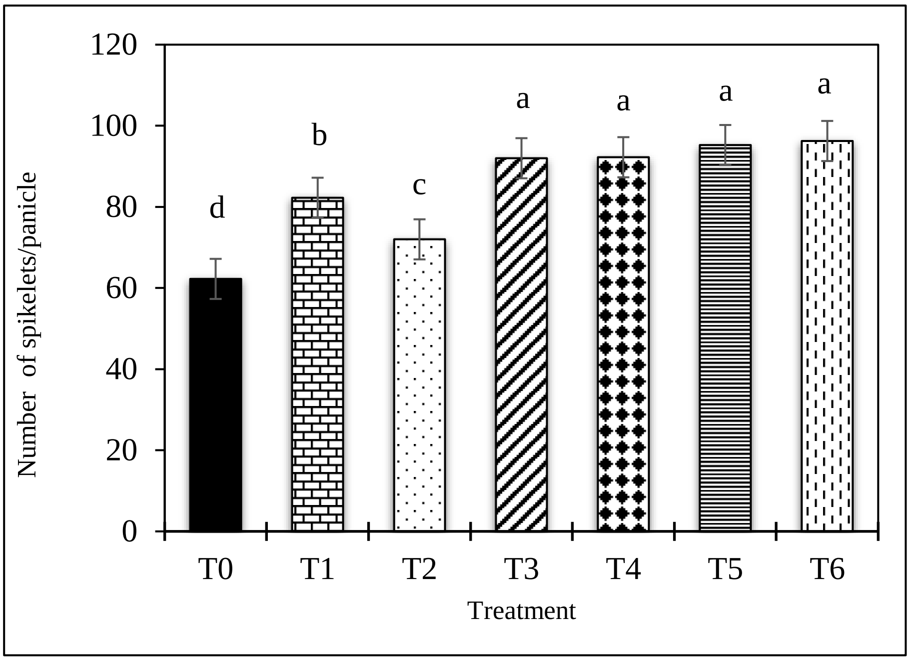

Figure 3.4: 1Effect of the different treatment combinations of N source on number of spikelets per panicle; mean of 4 replicates. Different letters indicate statistical differences ($p < 0.05$), T0: no fertilizer, T1: 100% urea, T2: 100% beef cattle manure, T3: 100% poultry litter, T4: 50% urea + 50% beef cattle manure, T5: 50% urea + 50% poultry litter and T6: 40% urea + 30% beef cattle manure + 30% poultry litter

3.3.2. Rice Yield and Yield Components

Our results demonstrate that grain yield was significantly affected by fertilizer application compared to plants which received no fertilizer. However, there was no significant statistical difference between T1, T4, T5 and T6. The highest grain yields were observed in T6, followed by T5 > T4 > T1 > T2> T3 > T0. The lowest grain yield of 200 g.m^{-2} was recorded in plants treated with no fertilizer while a yield of 425 g.m^{-2} was observed in T6 (Figure 3.5).

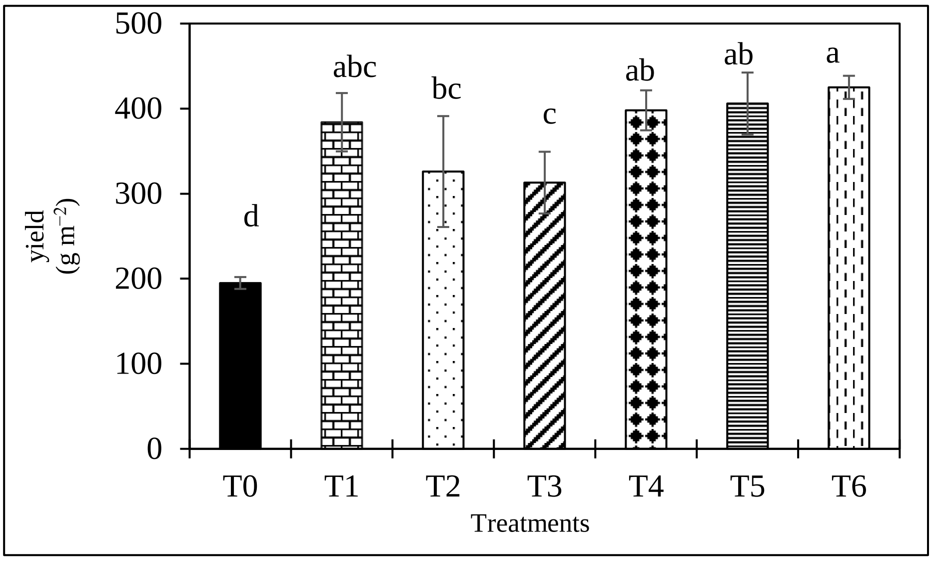

Figure 3.5: 1The effect of different N fertilizers and their combinations on rice grain yield; mean of 4 replicates. Different letters indicate statistical differences ($p < 0.05$), T0: no fertilizer, T1: 100% urea, T2: 100% beef cattle manure, T3: 100% poultry litter, T4: 50% urea + 50% beef cattle manure, T5: 50% urea + 50% poultry litter and T6: 40% urea + 30% beef cattle manure + 30% poultry litter

An overview of the effects of treatments T2 to T6 on rice experimental parameters compared with urea alone (T1) is given in (Table 3.4). As can be seen, some parameters such as number of tillers and spikelets and yield were positively affected by the integrated treatment compared to urea alone. Application of integrated fertilizers (T4 and T6) increased number of tillers by 20%. There was no increase in plant height in any treatment compared with T1. The sole use of poultry litter (T3) and combined use of urea and manure fertilizers (T4, T5 and T6) increased the number of spikelets by 12, 12, 16 and 17% relative to T1, respectively. Application of beef cattle manure (T2) and integrated fertilization (T6) showed an increase of 6% in 1000-grain weight. Application of integrated fertilizers (T4, T5 and T6) increased yield by 3, 6, and 11%, respectively. Plants treated with T4, T5 and T6 also had a positive response in numbers of tillers and spikelets and yield compared with the plants treat with only urea.

Table 3.4: Effect of applied treatments (T2: 100% beef cattle manure, T3: 100% poultry litter, T4: 50% urea + 50% beef cattle manure, T5: 50% urea + 50% poultry litter and T6: 40% urea + 30% beef cattle manure + 30% poultry litter) on different parameters compared

Treatments	**Plant Height**	**Number of Tillers**	**Number of Spikelets**	**1000-Grain Weight**	**Yield**
T2	⇨	⇨	⇨	⇗	⇨
T3	⇨	⇨	⇧	⇨	⇨
T4	⇨	⇧	⇧	⇨	⇧
T5	⇨	⇗	⇧	⇨	⇧
T6	⇨	⇧	⇧	⇧	⇧

no effect; ⇧ : an increase. ⇨

3.3.3. Nutrient Content

The effects of the six treatments on the nutrient content of the rice plants (root, grain and straw samples) are shown in (Table 5). For root nutrient content, highest level of root Mg was observed in T5 at 3956.09 mg.kg^{-1} which was not statistically different from all the treatments. The lowest amount of Mg content in root was found in the control (T0).

The treatments T0 to T3 produced levels of Fe in roots that were up to 7-fold higher than in treatments T4 to T6.

For grain nutrient content, although there were no significant differences between the treatments, highest levels of grain N were observed in T5 and T6, while the lowest was observed in T1. P accumulation was lowest in T5 and highest in T1. K accumulation was highest in T6 and lowest in T2.

Table 3.5: Effects of fertilization treatments on nutrient concentration accumulation in the rice plants; mean of 4 replicates

Treatments	**Mineral Content in Rice Straw (mg.kg^{-1})**									
	N	**P**	**K**	**Ca**	**Mg**	**Na**	**Fe**	**Cu**	**Zn**	**Mn**
T0	7204.25 ^{c}	1557.66 ^{b}	5125.13	5709.3	1189.59	7204.25 ^{c}	2378.26	42.32	55.4	817.43 ^{c}
T1	9148.58 ^{ab}	1895.21 ^{ab}	5095.28	6238.14	2661.3	9148.59 ^{ab}	3734.54	54.33	57.94	837.49 ^{b}
T2	8855.76 ^{abc}	2016.21 ^{a}	5309.3	5955.49	199.24	8855.77 ^{abc}	3137.8	54.74	56.85	773.49 ^{e}
T3	8881.07 ^{abc}	1949.49 ^{ab}	5486.29	6552.12	4981.6	8881.08 ^{abc}	3129.38	55.64	56.66	790.34 ^{d}
T4	8052.95 ^{bc}	1804.18 ^{ab}	5433.73	6349.82	232.15	8052.95 ^{bc}	2323.57	54.74	62.27	870.35 ^{a}
T5	9559.71 ^{ab}	1917.69 ^{ab}	5515.91	6436.95	2578.82	9559.71 ^{ab}	3414.07	55.24	58.09	775.51 ^{de}
T6	10155.7 ^{a}	1887.56 ^{ab}	5146.55	6204.23	2197.62	10155.79 ^{a}	2282.46	54.14	56.66	822.55 ^{bc}

Treatments	Mineral content in rice grain (mg.kg^{-1})									
	N	P	K	Ca	Mg	Na	Fe	Cu	Zn	Mn
T0	8569.73	20.54	5.25	1.26	8.42	0.61 ^{a}	0.31	0.18	2.24	0.25
T1	8542.61	24.78	5.52	1.26	10.39	0.34 ^{a}	0.45	0.16	2.2	0.29
T2	9279.55	21.2	5.16	1.16	8.61	0.29 ^{a}	0.4	0.14	2.37	0.24
T3	9005.85	22.81	5.59	1.24	9.23	0.42 ^{a}	0.25	0.16	2.33	0.26
T4	8991.96	21.38	5.27	1.13	8.16	0.29 ^{a}	0.39	0.14	2.28	0.26
T5	9532.9	19.55	5.04	1.08	7.23	0.04 ^{a}	0.37	0.15	2.34	0.21
T6	9354.42	20.94	5.29	1.15	8.06	0.17 ^{a}	0.31	0.13	2.37	0.25

Treatments	Mineral content in rice root (mg.kg^{-1})									
	N	P	K	Ca	Mg	Na	Fe	Cu	Zn	Mn
T0	5093.6	5412.94	6878.22	3952.77	2773.8 ^{b}	3400.83	20781.45 ^{a}	40.99	55.57	509.82
T1	3589.01	5936.93	8919.15	3792.8	3258.7 ^{ab}	4292.52	20310.99 ^{a}	58.02	54.63	545.29
T2	4326.9	5578.15	8242.13	3890.35	2860.8 ^{ab}	3881.94	23101.07 ^{a}	34.76	96.04	525.37
T3	5060.25	5496.22	8012.77	4077.31	3393.85 ^{ab}	3387.57	19275.17 ^{a}	46.48	58.42	567.86
T4	4423.99	5758.9	6982.94	4244.45	3322.39 ^{ab}	3813.65	7429.72 ^{b}	44.41	75.04	525.56
T5	4867.76	6183.64	6939.77	4422.64	3956.09 ^{ab}	2735.8	3095.58 ^{b}	38.15	47.46	686.52
T6	5409.26	6161.38	8182.94	3726.39	3291.11 ^{ab}	3428.45	3530.92 ^{b}	31.72	86.24	590.05

Means followed by the same letter in a column do not differ from each treatment by Tuckey´s test at ($p < 0.05$); T0: no fertilizer, T1: 100% urea, T2: 100% beef cattle manure, T3: 100% poultry litter, T4: 50% urea + 50% beef cattle manure, T5: 50% urea + 50% poultry litter and T6: 40% urea + 30% beef cattle manure + 30% poultry litter.

As shown in (Table 3.5) nutrient contents in straw were significantly influenced by the treatments for some macro and micronutrients namely N, P, Na and Mn. The highest amount of N in straw was observed in T6 at 10155.7 mg.kg^{-1} which was statistically different from all other treatments. As expected, the lowest amount of N content in straw was observed in the control (T0). With respect to P concentration in straw, the values ranged from 1557 mg.kg^{-1} in T0 to 2016 mg.kg^{-1} in T2, statistically different from all other treatments. Additionally, the next highest P level was observed in T3 at 1949 mg.kg^{-1} which was statistically similar to all other treatments. Considering Na in straw, the highest level was observed in T6 which was statistically different from all other treatments. The next highest result was observed in T5.

Finally, the highest amount of Mn in straw was observed in T4 which was statistically different from all the other treatments while the lowest result was observed in T2 at 773 mg.kg^{-1}.

3.3.4. Nutrient Uptake by Rice

Total nutrient uptake (N, P and K) by the rice plants as well as specific uptake in root, grain and straw are detailed in Table 6. Our data indicate that there are significant differences ($p < 0.05$) in the total N uptake ranging from 31.56 to 68.87 kg.ha^{-1}. Highest total N uptake was observed in T5 and T6 which was statistically different from the other treatments. Lowest total N uptake was observed in T0, the control, as expected.

Regarding the specific components of the rice plant, results showed a wide variation in N uptake by straw and grain but with the same trend observed in total N uptake. Regarding the root, higher total N uptake was observed in T5 and T6, although not statistically significant.

Total P uptake ranged from 10.99 to 20.27 kg.ha^{-1} over the treatments with the lowest level in T0 (control). The average total P uptake was 20.27 kg.ha^{-1} for T5 which was similar to 19.9 kg.ha^{-1} for T1. Phosphorus uptake by roots ranged from 6.55 to 12.47 kg.ha^{-1} with the highest level in T5. The lowest P uptake in root (6.55 kg.ha^{-1}) was observed in T0 (control). P uptake in grain ranged from 2.54 to 4.80 kg.ha^{-1}. Highest was found in T1 even if not statistically different from T4, T5 and T6. Regarding P uptake in straw, values varied from 1.89 to 3.90 kg.ha^{-1} with the highest level observed in T5.

The highest values of total K uptake by the rice plants were achieved with combined fertilizers (17.28 kg.ha^{-1} which was statistically similar to T4, T5 and T6). Lowest mean value was 8.30 kg.ha^{-1} in the control. K uptake in root ranged from 8.30 to 17.29 kg.ha^{-1} with the highest value in T1 (not statistically different from the other fertilized treatments). K uptake in grain ranged from 5.56 to 11.75 kg.ha^{-1}. Regarding K uptake in straw, values ranged from 6.23 to 11.21 kg.ha^{-1}.

Table 3.6: 1Effect of fertilizer on N, P and K uptake (kg.ha−1) in rice plants

Treatment	**N uptake (kg.ha^{-1})**			**Total**
	Root	**Grain**	**Straw**	
T0	5.23 a	17.58 b	8.75 d	31.56 c
T1	6.98 a	28.94 a	17.64 ab	53.56 ab
T2	6.59 a	29.47 a	13.07 bcd	49.12 b
T3	6.97 a	27.71 ab	12.15 cd	46.83 b
T4	8.50 a	34.79 a	15.44 abc	58.73 ab
T5	9.85 a	38.08 a	18.93 a	66.87 a
T6	10.16 a	37.67 a	18.98 a	66.81 a
Treatment	**P uptake (kg.ha^{-1})**			**Total**
	Root	**Grain**	**Straw**	
T0	6.55 c	2.54 c	1.89 b	10.99 c
T1	11.52 ab	4.80 a	3.67 a	19.98 a
T2	8.07 bc	2.98 bc	2.96 ab	14.01 bc
T3	7.54 bc	3.13 bc	2.68 ab	13.35 bc
T4	11.01 ab	4.07 ab	3.43 a	18.52 ab
T5	12.47 a	3.90 abc	3.90 a	20.27 a
T6	11.41 ab	3.82 abc	3.54 a	18.77 ab
Treatment	**K uptake (kg.ha^{-1})**			**Total**
	Root	**Grain**	**Straw**	
T0	8.30 b	5.66 b	6.23 c	20.19 b
T1	17.29 a	10.22 ab	9.86 abc	37.36 a
T2	12.23 ab	8.43 ab	7.86 abc	28.52 ab
T3	11.01 ab	9.63 ab	7.52 bc	28.16 ab
T4	13.33 ab	10.75 a	10.38 ab	34.46 a
T5	14.39 ab	10.15 ab	11.21 a	35.75 a
T6	15.22 ab	11.43 a	9.65 abc	36.30 a

Means followed by the same letter in a column do not differ from each other using Tuckey´s test at ($p < 0.05$) significance. T0: no fertilizer, T1: 100% urea, T2: 100% beef cattle manure, T3: 100% poultry litter, T4: 50% urea + 50% beef cattle manure, T5: 50% urea + 50% poultry litter and T6: 40% urea + 30% beef cattle manure + 30% poultry litter.

3.3.5. Soil Properties after Harvest

Significant differences were observed between treatments in terms of N-NH_4^+, available P and available K while pH, EC, N-NO_3^-, OM, CEC presented similar values in all treatments at the end of the experiment (Table 7). The maximum N-NH_4^+ content of 9.9 mg.kg^{-1} was obtained in the treatment receiving three sources of N (T6), followed by T2 and T3 with 8.9 and 8.8 mg.kg^{-1}, respectively.

Table 3.7: Properties of the soil after harvesting in the experiment

Treatment	pH	EC	N-NH$_4$	N-NO$_3$	P available	K available	OM	CEC	Na	K	Ca	Mg
		(µS.cm^{-1})	(mg.kg^{-1})				(mg.kg^{-1})	cmol(+)/kg	cmol(+)/kg			
T0	7.4	620	7.3 e	1.52	21.1e	24.6 c	2.6	36.3	1.09	0.47	2.43 b	0.39
T1	7.5	640	9.6 ab	0.76	23.4d	26.5 ab	2.7	36.9	0.79	0.23	1.89 b	0.45
T2	7.6	620	8.8 bc	1.16	21.1e	25.8 b	2.8	36.3	0.69	0.22	1.60 b	0.37
T3	7.7	640	8.9 bc	1.49	26.1c	24.8 c	2.6	35.8	0.54	0.24	2.37 b	0.47
T4	7.8	620	7.5 de	1.08	23.7d	24.1 c	2.8	35.8	0.71	0.39	4.51 a	0.89
T5	7.6	660	8.4 cd	1.45	33.7b	24.4 c	2.8	37.6	0.69	0.31	4.68 a	0.93
T6	7.7	650	9.9 a	0.89	35.7a	27.2 a	2.8	39.1	0.61	0.45	3.93 a	0.91

Means followed by the same letter in a column do not differ from each treatment using Tuckey´s test at ($p < 0.05$) significance. T0: no fertilizer, T1: 100% urea, T2: 100% beef cattle manure, T3: 100% poultry litter, T4: 50% urea + 50% beef cattle manure, T5: 50% urea + 50% poultry litter and T6: 40% urea + 30% beef cattle manure + 30% poultry litter.

Organic matter content showed no significant differences between the treatments, despite the application of combined N sources which should favour a long-term increase in soil organic matter. Application of different N sources had no significant impact on the exchangeable cations (Mg, Na and K) even if Ca was significantly higher in T4, T5 and T6. pH tended to increase in all treatments even if no significant differences were observed. The combined application of manures (beef cattle and poultry litter) plus urea tended to increase the available P content compared with the control. Similarly, the highest content of available K was observed in T6. It can be concluded that a combination of several N sources tended to improve soil chemical properties.

3.3.6. Economic Evaluation

Table 3.8 presents the estimated costs (per hectare) of the implementation of the treatments in our study. Considering that both poultry and cattle manure are not marketed in the studied region, the amount that would be spent on transport to cultivation areas was considered for financial evaluation purposes, according to the data obtained by the authors during the study period. The unit price transport costs were 0.002 €.kg^{-1} for poultry manure and 0.001 €.kg^{-1} for cattle manure. The unit cost of synthetic urea was 0.58 €.kg^{-1} (MASA 2019). To calculate the monetary yield for each treatment, the values of the rice weight per hectare were used. These values were then multiplied by the sale price (0.20 €.kg^{-1}). The difference between monetary income and the cost of production was considered profit.

Other production costs were not included e.g., labour, seed price, ploughing land preparation, irrigation water tax, scaring of birds, weed control and herbicide application. These costs were similar across all the treatments and independent of the type of fertilizer applied.

Table 3.8: Economic evaluation

Treatment	**Cost of Fertilizers Application (€.ha^{-1})**	**Cost per Ton of Rice Produced**	**Monetary Income (€.ha^{-1})**	**Profit (€.ha^{-1})**
T0	0	0	0	0
T1	125.86	37.6	768	642.14
T2	5	1.59	650	645
T3	7.4	2.41	626	618.6
T4	65.43	16.89	794	728.57
T5	66.63	16.66	810	743.37
T6	54.06	13.43	850	795.94

The highest cost per hectare was for T1 (urea only) at 125.86 €.ha^{-1}. The results showed that the similar yields found in T5 and T6 had different costs. Cost for T5 (66.63 €.ha^{-1})

was higher than that for T6 (54.06 €.ha^{-1}), indicating that combining cattle, poultry and urea was more profitable. The use of combined fertilizers (T4, T5 and T6) produced higher income than the use of sole fertilizers (T1, T2 and T6).

The highest profit of 795.94 €.ha^{-1} was obtained in the treatment receiving three sources of N, followed by T5 and T4 with 743.37 €.ha^{-1} and 728.57 €.ha^{-1}, respectively.

3.4. Discussion

3.4.1. Effect of the Fertilizer Treatments on Rice Growth Parameters

Our results indicate that single applications of urea or manure as well as their combined application had a positive influence on the vegetative growth of the crop. Maximum plant heights were observed in T1, T6, T5 and T4 ($p < 0.05$), followed by T3 and T2. Similar tendencies were observed in number of tillers, with higher numbers in T4 and T6 (18 tillers) and lower numbers in T2 and T3 (14 and 13 tillers, resp.). These results concur with Moe et al. (Moe et al. 2019a) who reported that combined fertilizers had a significant positive effect on height, spikelets per sq m, tillering and grain yield. Karki et al. (Karki et al. 2018) emphasized that a combined application of cattle manure with chemical fertilizer and even poultry manure, is an effective approach to enhance rice growth.

Thousand-grain weight was significantly higher ($p < 0.05$) relative to the control in treatments fertilized with the three N sources as well as in the treatment with only cattle manure. The values achieved here were higher than those obtained by Moe et al. and Sing et al. (Singh et al. 2013; Moe et al. 2019b). Similar findings were observed by Ghoneim et al. (Ghoneim and Osman 2018) which reports that N fertilizer application significantly increased the 1000-grain weight, due to the production of a higher number of spikelets per panicle in the plants.

The grain yield collected from the field; experiments showed a variable response to different fertilizer treatments (Figure 5), T5 and T6 produced indeed significantly ($p < 0.05$) greater amounts of grain compared with the control treatment. There was no significant statistical difference between T1, T4, T5 and T6. The higher grain yield was observed in treatments with combined sources of N in agreement with Amanullah et al. (Amanullah and Hidayatullah 2016) who reported the combined application of manure and urea N was better than a single organic source to increase grain yield and yield components. This fact can also be explained by the use of mineral fertilizers combined with manure where organic N mineralization kept nutrient stress arrested through the entire plant growing period resulting in higher grain production (Moe et al. 2019a).

Likewise, our results are further supported by Banik et al. (2009) who stated that combined use of organic and synthetic fertilizers offers better synchrony of nutrient availability to the rice plant crop leading to higher biomass production and also to better nutrient use efficiency. A previous study conducted by Liu et al. (Liu et al. 2009) also highlighted that the combined application of manure and conventional N fertilizers could lead to a better yield than the use of solely conventional fertilizers.

One of the most limiting factors for improving production in tropical regions is related to the fast decomposition of organic matter with the negative consequence of poor nutrient retention (Adekiya et al. 2019). Adding different sources of organic manure could therefore contribute to achieve higher yields by keeping nutrients in the soil for a longer period. Manure only or combined application of manure with urea could improve physicochemical soil proprieties, namely, soil fertility, soil porosity and water holding capacity (Duan et al. 2016). In the present study, a positive impact on soil chemical proprieties was observed in terms of soil available P, available K, N-NH_4^+ and Ca content.

Our results are in accordance with Liu et al. (Liu et al. 2009) who report that the decomposition of manure slowly releases nutrients to the soil and improved soil chemical properties.

The increase in soil Ca from initially 2.43 to 4.68 cmol(+)/kg following treatment with cattle and poultry manure + urea may be due to the addition of organic manure that influences cation exchange capacity (Dikinya and Mufwanzala 2010).

Our results showed an increase of available P and N-NH_4^+ in the treatments with integrated fertilization. These findings are in concordance with Manitoba (Manitoba 2013), who reports that application of solid manure moves soil pH towards neutrality in acidic and alkaline soils, thus improving availability of macronutrients like K and micronutrients.

Smallholder farmers may become resistant to new technologies, mainly due to economic reasons, hence the reason for our approach to adopt the treatments tested in this study. Our findings show less cost in T6 which used three different sources of N fertilizers if compared with T1 that used only one N fertilizer (urea). Thus, using local sources of organic fertilizer has the potential to increase rice production and give smallholders opportunities to enhance conventional fertilizer efficiency with improved plant performance and soil management (Maccarthy et al. 2020).

3.4.2. The Effect of Combined Manure and Urea Treatments on Nutrient Uptake

Nutrient uptake is an important parameter in determining the effects of applied nutrients on crops. Therefore, knowledge of this index is fundamental to improving nutrient management strategies. Research related to nutrient uptake is useful to develop best management practices and to produce high yields while minimizing nutrient losses and costs associated with nutrient fertilization (Sahu et al. 2020). Inefficient nutrient use is one of the most limiting factors, considering the need to increase rice productivity.

Nitrogen uptake ratio was significantly different among the treatments considering that T6, T5, and T4 had a greater effect on N uptake than did T1, T2 and T3. These findings were consistent with previous studies where combined fertilizers increased N uptake and N use efficiency (John Hunter et al. 2016). Combined fertilizers, where organic manure is present, seem to be able to improve soil physico-chemical properties, promoting more favourable growth of rice plant roots.

Higher N uptake in roots, straw and grain in the presence of combined fertilizers in contrast to that in single fertilizers (manure or urea) is corroborated by Ming-gang et al.(Xu et al. 2008). Sahu et al. (Sahu et al. 2020) emphasised that higher N uptake in association with manure is likely to due to solubilisation of native nutrients, chelating complex forms of intermediate organic molecules produced during decomposition of the added manures, and the resulting mobilisation and accumulation of different nutrients in plant parts.

The combination of manure and urea fertilizer has a significant effect on P uptake with the highest registered in T5. According to Ming-gang et al.(Xu et al. 2008), P uptake is highly dependent on the type of fertilizer application, rice varieties and nutrient management. There was a great increase in total P uptake in the rice crop in the treatments with integrated application of manure and urea fertilizers compared to the use of a single fertilizer or the control. Similar results were observed in a study performed by Mitran et al. (Mitran and Mani 2017) who observed the highest P uptake in treatments amended with combined fertilizers. According to Kumar et al. (Kumar et al. 2020), the increased P uptake might be due to organic materials forming chelates with Al^{3+}(aluminium) and Fe^{3+} leading to more P available for plant uptake, particularly in soils with low P-fixing capacity.

Application of urea along with cattle and poultry manure (T4, T5 and T6) led to the best results for total K uptake in straw, grain and roots. This may be due to a higher availability of K in fertilizers and manure materials or a good spread of roots, resulting in greater K absorption (Mitran and Mani 2017). Thus, the combined manure and urea fertilizer might be the best solution for availability of N, P and K.

Most smallholder farmers face significant cash constraints, that hamper making the decision of taking risks in adopting innovative technology related to crop production. In this context, economic assessment is important to determine the feasibility of proposed solutions. We evaluated the cost of fertilizers, the cost per ton of rice produced, the monetary income and finally the profit. The economic returns were improved when manure and urea were combined (T4, T5 and T6). The economic returns for T2 and T3, appear not to be sustainable.

Considering that there is significant livestock production in this region, the use of only manure (T2 and T3) or a 50–50 mixture of cattle and poultry manure (not tested in this study) could be more profitable for smallholders. We reached the conclusion that N was more readily available from poultry manure than from cow manure, with slower N release in the latter. This can explain the better effect of the combination of these two manures.

The use of manure is economically viable and therefore can be extended to farmers for adoption. The use of poultry manure, or even cattle manure, in irrigated systems also has the potential to increase returns on investments by smallholder farmers e.g., in the purchase of chemical fertilizer.

3.5. Conclusions

The results observed in this study suggest that integrated use of manure and synthetic urea N sources is more efficient than isolated application of urea or animal manure for rice growth and yields as well as soil quality. The premise in this study was that solutions proposed here should not lead to any increase in production costs and should contribute to a significant increase in rice yields even for farmers with low or no capacity to invest in chemical fertilizers.

The combination of urea, beef cattle manure and poultry litter at a rate of (40%:30%:30%) produced good results and is thus recommended to smallholder farmers for better optimum crop production on Chókwè Irrigation Scheme. Consequently, the smallholders should focus on manure combined with synthetic urea, which shows better results in response and economic evaluation. This study recommends more training be provided to smallholders to optimize alternatives and use of available resources such as animal manure fertilizer. This will help overcome difficulties in fertilization and contribute to enhance sustainable production and economic income in the region, also following a circular economy approach. Monitoring, however, is also advised to avoid any long-term environmental or health impacts that may occur.

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Chapter IV

Impact of soil fertilization and fallow practices on CH_4, CO_2 and N_2O emissions in rice paddy soils from Southeastern Mozambique: a laboratory study

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Impact of soil fertilization and fallow practices on CH_4, CO_2 and N_2O emissions in rice paddy soils from Southeastern Mozambique: a laboratory study

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Abstract

Rice is an essential crop and plays a fundamental role in the Mozambican diet. Many research studies on rice production in Africa had focused on issues related to productivity aspects. However, there is a gap related to environmental impacts, particularly the effect of the rice production in African soils on Greenhouse Gas Emissions (GHG). In the present study, we evaluated, in a laboratory experiment, the effect of soil management practices and organic and inorganic fertilization on the emission of methane (CH_4), carbon dioxide (CO_2) and nitrous oxide (N_2O). The soil management practices considered in this study were: fallow for 10 years, one year fallow and continuous rice production (soil collected in postharvest rice field). The fertilizers used were cattle manure and urea. A laboratory experiment was conducted for 57 days with nine treatments: Ten years fallow (control) – (10YF-Ct); Ten years fallow amended with cattle manure (10YF-CM); Ten years fallow amended with urea (10YF-Ur); One-year fallow (control) - (1YF-Ct); One-year fallow amended with cattle manure – (1YF-CM); One-year fallow amended with urea - (1YF-Ur); Continuous rice (control) - (CR-Ct); Continuous rice amended with cattle manure (CR-CM); Continuous rice amended with urea (CR-Ur);

Overall, the three gases present similar emission patterns of daily flows in all treatments, characterized by a continuous increase (up to 21 days for CH_4 and CO_2, and up to 28 days for N_2O) and followed by a decrease till day 57. During the first 21 days, 4 peaks in CH_4 emissions were registered, corresponding to 37-46% of the total emissions of this gas. Similarly, 3 peaks of CO_2 were reported in the first 21 days, corresponding to 23-37% of total emissions. For N_2O, the 5 peaks observed at 28 days correspond to 17-28% of total emissions. Significant differences in the cumulative emissions of CH_4 and N_2O gases were observed between treatments. Treatments CR-Ct, CR-CM and CR-Ur led to the lowest emissions of CH_4 and N_2O, while 10YF-Ct, 10 YF- CM and 10 YF-Ur led to the highest emissions of N_2O indicating that a long period of fallow might have negative impacts on GHG emissions. On the other hand, it was proved that fertilization affects the loss of N and C considering the gases studied, even if no significant increase of N_2O emissions was observed in fertilized treatments regarding the control. Application of fertiliser affected CO2 emission in the treatments.

Based on our results, it can then be recommended to use cattle manure as fertilizer and to promote the use of less years of fallow season as soil management to boost less emission on rice fields.

Keywords: Rice (Oryza sativa L.), Paddy field, fertilization, fallow, greenhouse emission

4.1. Introduction

Rice is the second most consumed crop with a total production estimated at over 759.9 million tonnes which covers more than 60% of the world population (Patel et al. 2010; FAO 2018b; Fahad et al. 2019), losing only to corn (FAO 2020). The Asian continent is responsible for about 90% of the world production of rice while Africa contributes only with 3.3% (Khush 2013; Chivenge et al. 2020). The low levels of production in the African continent are due to biotic factors (pests and diseases), abiotic factors (drought, salinity and toxicity of soils, vulnerability to climate change) and social factors (conflicts, extreme poverty and vulnerability) that prevent producers to invest in the acquisition of agricultural inputs such as fertilizers, improved seeds and pesticides, as well as in a more technical production system (Khush 2013; FAO 2017; UNDP 2018). Although many countries in sub-Saharan Africa are currently moving towards self-sufficiency in rice production (Africarice 2018), Mozambique, where rice is the second most consumed cereal after maize, produced around 400.000 tonnes/year what represents only 75% of populations needs (MASA 2019).

In many self-sufficient countries, the high levels of rice production and productivity achieved are largely associated with excessive fertilizer applications that lead to a drastic increase of soil pollution and strong emissions of greenhouse gases (methane – CH_4, nitrous oxide – N_2O and carbon dioxide-CO_2) which play a fundamental role in climate change (Liu et al. 2020). Indeed, it is widely known that the soil management practices associated to rice production favor the emission of CH_4 and N_2O (Ahmad et al. 2009; Ali et al. 2009), representing a clear threat to sustainable production. A recent study carried out by Carlson et al. (2016) reported that the world production of rice is responsible for about 48% of methane emission. Methane is produced under anaerobic soil conditions and it is favored by the amount of carbon in soil, temperature and soil density (Mitra et al. 2002; Jiang et al. 2019). Contrary to methane, that occurs only in anaerobic conditions, nitrous oxide is produced both in aerobic conditions favoring nitrification as well as in anaerobic conditions stimulating denitrification (Abao et al. 2000; Ahmad et al. 2009). To mitigate the emissions of CH_4 and N_2O in rice fields, several studies have been done focusing on actions to improve soil mobilization, water management, types of fertilizers and suitable rice varieties (Ahmad et al. 2009; Fangueiro et al. 2017; Begum et al. 2019). The system predominant in rice production in Mozambique is an anaerobic condition that favors the emission of greenhouse gases. Therefore, it is essential to promote sustainable production with an emphasis on the efficient use of agricultural inputs as fertilizers (Linquist et al. 2012). Fertilizers are one of the fundamental and indispensable inputs for rice production. Hence, several studies have been carried out to test the efficiency of the combination of organic (cattle and swine manure) and inorganic (urea) fertilization in reducing greenhouse gas emissions (Ji et al. 2014). The results obtained in these studies have proved to be promising. The use of cattle manure as organic fertilizer might be a good alternative since it contributes to soil enhancement but the impact of its use as fertilizer for rice growth needs to be assessed and compared with mineral fertilizer. On the other hand, soil management practices have been used in several countries as a strategy to reduce emission of greenhouse gases in rice fields (Fan et al. 2020). One of most used soil management practices is based in fallow land (Sander et al. 2018a) but recent studies refer that fallow in rice production increases methane emission while reducing nitrous oxide flux (Sander et al. 2018a; Reba et al. 2019).

To our knowledge, there is no information available on GHG emissions from rice paddies in Mozambique, so it is essential to gather information that assists in decision-making on the best practices in soil management and fertilization that allow reducing emissions of greenhouse gases in a context in which there is a growing pressure to intensify the use of fertilizers in order to increase rice yields.

The aim of this study was to evaluate, in control conditions, the effect of soil management (fallow) and organic and inorganic fertilization on methane, nitrous oxide and carbon dioxide gas emissions in Mozambican paddy field soils.

4.2. Material and Methods

4.2.1. Cattle manure analysis

The fresh cattle manure was obtained from an extensive livestock production system in Lisbon (Portugal). It was stored for two days in small plastic barrels at 4ºC in a freezer prior to use in our assay. The samples were submitted to analysis for determination of total N, mineral N (NH4—N and NO3—N), total K, total P, pH, electrical conductivity, dry matter, total organic carbon, C/N ratio, organic matter, moisture content, and total content of Cu, Zn, Mn, Fe, (Table 4.1). Total nitrogen was assessed using the Kjeldahl method (Bremner and Mulvaney 1982). The mineral N was determined by extraction of 2 M KCl (cattle manure/liquid: 1:10 w/v) (Mulvaney 1996) followed by determination of the NH4+–N and NO3-–N concentrations by automated segmented-flow spectrophotometer through Berthelot and hydrazinium reduction methods succeeded by sulphanilamide diazotizing according to (Junior 2001). The pH was measured in a manure/water suspension (1:2,5 w/v ratio) using a pH meter (Aqua Lytic). The electrical conductivity (EC) was measured in the same suspension with a conductivity electrode (Tiquia and Tam 2000). The organic matter was quantified by the loss-on-ignition after incineration at 500-550ºC of dry sample (for 5 h) reported by (Tiquia and Tam 2000). K and P contents were quantified after hydrochloric acid (HCl) treatment of the ash through graphite furnace atomic absorption spectrophotometry (Unicam M Series), except for phosphorous, which was determined using the ammonium vanadomolybdate method by molecular absorption spectrophotometry (Hitachi 2000). The micronutrients Cu, Zn, Fe and Mn were extracted after hydrochloric acid (HCl) treatment of the ash through graphite furnace atomic absorption spectrophotometry (Unicam M Series). All the main characteristics of the cattle manure used in the experiments are presented in the table (4.1).

Table 4.1: Main characteristics of the cattle manure used in the experiments (N = 3)

Parameters	**Cattle Manure**
pH	7.10
Electrical conductivity (mS.cm^{-1})	13.40
Dry matter (%)	84.05
Organic Matter (g kg $^{-1}$)	12.54
Total N (g kg $^{-1}$)	2.26
NH_4-N (g kg $^{-1}$)	0.25
NO_3-N (g kg $^{-1}$)	0.01
K (g kg $^{-1}$)	0.74
P (g kg $^{-1}$)	0.39
Cu (mg kg $^{-1}$)	0.00
Zn (mg kg $^{-1}$)	0.01
Mn (mg kg $^{-1}$)	0.02
Fe (mg kg $^{-1}$)	0.17

4.2.2. Soil analysis

The soil samples were obtained from the Umbeluzí Agrarian Station (26° 3'5.49"S and 32°22'18.65"E), located in Boane district about 35 km from Maputo City, capital of Mozambique. The soil used in this study was classified as Mollic Ustifluvent with the texture sandy loam (Burridge et al. 2016). Soil samples were collected in the summer season in 2019 from the 0-20 cm topsoil layer. The soil samples were subject to manual sieve (< 2 mm) to remove undesired materials (e.g., roots, larger soil fragments, and organic residues) and then kept at room temperature prior use. Soil samples were then analysed for total organic carbon, C/N ratio, Cu, Zn, Fe and Mn, available P, Total N, CE, and pH as described in Ismael et al. 2021. More information regarding the soil used here can be found in (Ezeokoli et al. 2021).

4.2.3. Incubation

Two different fertilizers (cattle manure and urea) were used in combination with three different soil managements as follow: (i) ten-years fallow (10YF), (ii) one-year fallow (1YF) and (iii) postharvest (PH) (Table 4.2). Three replicates of each soil (200 g) from different soil management were separately amended with cattle manure (3,3 g) or urea (0,14 g) equivalent to an application of 100 mg of N kg^{-1} dry soil. A control from each soil management with no fertilization was also considered. The mixtures were filled to a Kilner jar (1010 ml) and flooded with de-ionized water (2,8 cm above soil surface) to simulate flooded conditions of rice production, totalizing 9 treatments as follow:

1. Ten years fallow (control) – (10YF-Ct)
2. Ten years amended with cattle manure (10YF-CM);
3. Ten years amended with urea (10YF-Ur);
4. One-year fallow (control) - (1YF-Ct);

5. One-year fallow amended with cattle manure – (1YF-CM);
6. One-year fallow amended with urea - (1YF-Ur).
7. Continuous (control) - (CR-Ct);
8. Continuous amended with cattle manure (CR -CM);
9. Continuous amended with urea (CR-Ur);

Each treatment was incubated at 20ºC for 57 days. The lid of the jar was kept loosely open to ensure aerobic condition and to avoid strong water losses. To quantify gas emission of N_2O, CH_4 and CO_2, a procedure similar to these described in Fangueiro et al. (2015b) was used. Briefly, air samples were taken from the headspace of each jar immediately after Kilner jar closure, and after 30 and 60 minutes of closure. Headspace air was collected using a 60-mL syringe and 30 mL of headspace air were transferred to a 20 mL glass vial sealed with a Teflon septum. Headspace air samples were collected on day 1, 2, 5, 8, 9, 12, 14, 16, 20, 21, 23, 28, 35, 42, 44, 49, 57 and Nitrous oxide, methane and carbon dioxide quantified using a Gas Chromatography (GC-2014, Shimadzu, Japan). The fluxes of N_2O, CH_4 and CO_2 emissions in each Kilner jar were determined by the linear increase in gas concentration. The cumulative emission was calculated considering the average of two sampling occasions and multiplied by the time interval among the real measurements as described by Fangueiro et al. (2017) . The Global Warming Potential for each treatment (Mg CO_2 eq ha^{-1}) over a 100-year GWP was calculated using the following equation, as described by (Fangueiro et al. 2016):

$$\text{GWP} = \text{Cum } CO_2 + (\text{Cum } N_2O \times 265) + (\text{Cum } CH_4 \times 28)$$

Table 4.2: Soil characteristics of the sample used in the experimental incubation; values correspond to mean ± SD

Parameters	**10YF**	**1YF**	**CR**
pH	7.17 ± 0.93	6.62 ± 0.13	8.25 ± 0.21
Electrical conductivity (mS cm^{-1})	5.18 ± 6.35	1.07 ± 0.30	1.14 ± 0.24
Organic Matter (g kg^{-1})	27.68 ± 8.74	24.09 ± 3.88	26.23 ± 3.16
WHC (g.kg^{-1})	553 ± 72.3	560 ± 22.36	582.22 ± 27.28
Total N (g.kg^{-1})	0.68 ± 0.09	0.74 ± 0.02	0.91 ± 0.12
NH4-N (mg kg^{-1})	33.28 ± 58.40	2.13 ± 0.82	6.97 ± 2.35
NO3-N (mg.kg -1)	29.18 ± 51.46	0.10 ± 0.30	0.07 ± 0.20
Available K (mg.kg -1)	215.8 ± 54.84	255.43 ± 49.67	248.63 ± 42.42
Available P (mg.kg -1)	134.12 ± 66.11	104.33 ± 32.33	140.99 ± 43.23
SOC (g.kg -1)	16.09 ± 5.05	14 ± 2.04	15.24 ± 1.84
Cu (mg.kg -1)	6.40 ± 1.50	9.26 ± 1.59	14.12 ± 1.00
Zn (mg.kg -1)	6.99 ± 3.51	7 ± 2.66	7.53 ± 2.55
Mn (mg.kg -1)	363.49 ± 78.48	422.97 ± 67.58	294.37 ± 20.19
Fe (mg.kg -1)	227.13 ± 41.11	421.01 ± 147.60	6.97 ± 2.35

4.2.4. Statistical analysis

The results were analyzed by Kurskal-Wallis test equivalent of an ANOVA (Analysis of Variance) considering the assumption of homogeneity of variance between the treatments is violated in the ANOVA analysis. The analyses were carried out using “R” Software (version 3.3.2).

4.3. Results

4.3.1. Methane emission

Figure (4.1) shows the daily flows of CH_4 in the nine treatments under evaluation. In all treatments, the daily CH_4 emission rates obtained were lower than 0.05 mg C kg^{-1} dry soil d^{-1}. In most treatments, the CH_4 emission flow increased significantly in the first 21 days. Significant differences in the CH_4 emission were observed between treatments only on days 1, 44 and 57 days. The peaks of CH_4 emission were obtained in the CR-Ct, 1YF-Ct, 1YF-Ur and 10YF-Ur treatments at 12, 14, 20 and 21 days, respectively. Methane emissions observed in these four days (12, 14, 20 and 21 days) are responsible for 37-46% of the total CH_4 emission. In most treatments, the higher and lower CH_4 emissions were observed at day 21 and 8, respectively. In general, after 21 days of experiment, a decrease of the daily emission of CH_4 flows was observed for most treatments up to day 57, except for the CR-Ct, CR-CM and CR-Ur treatments which registered an increasing trend till day 49.

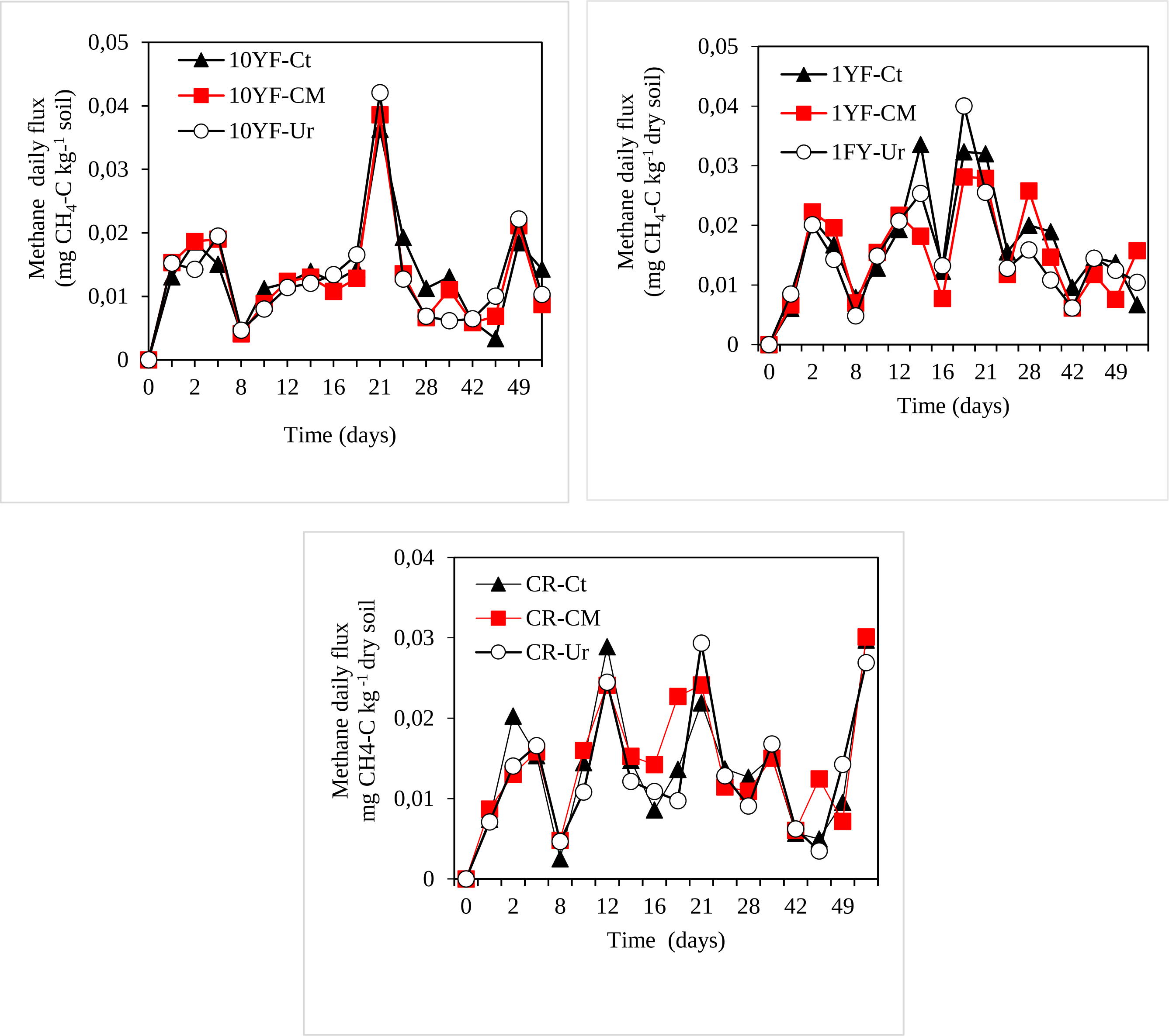

Figure 4.1: Methane flux emission rates (mg C kg^{-1} dry soil day^{-1}) observed over the experiment time incubation in the treatments considered.

Cumulative emissions of CH_4 differed significantly ($p < 0.05$) between treatments (Table 4.3). The treatments 1YF-Ct (0.938 mg C kg $^{-1}$ dry soil), 1YF-CM (0.860 mg C kg $^{-1}$ dry soil) and 1YF-Ur (0.829 mg C kg $^{-1}$ dry soil) presented the highest cumulative emissions of CH_4 while the lowest values were obtained in the treatments 10YF-Ct (0753 mg C kg $^{-1}$ dry soil), 10YF-CM (0.701 mg C kg $^{-1}$ dry soil) and 10YF-Ur (0.702 mg C kg $^{-1}$ dry soil) according to table (4.3). The cumulative CH_4 emissions represent between 1 and 29 % of the total C applied.

4.3.2. Carbon dioxide emission

The CO_2 emission pattern is similar to that reported in CH_4, in which there is a steady increase in CO_2 emissions in the first 21 days, reaching the first peaks at 14, 16 and 21 days (which are responsible for the emission of 23-37% of all CO_2 obtained during the experiment), decreasing up to 49 days and at 57 days a new peak was recorded, where high CO_2 emission rates were observed in the CR-Ct, CR-CM and CR-Ur treatments. Significant differences between treatments were observed on days 1, 2, 16, 28 and 57.

In most treatments, the highest CO_2 emissions were observed at 1YF-Ct, 1YF-CM and 1YF-Ur treatments.

The cumulative CO_2 emissions during the experiment represent 621-774 mg C kg-1 dry soil but no significant differences were observed among treatments ($p > 0.05$).

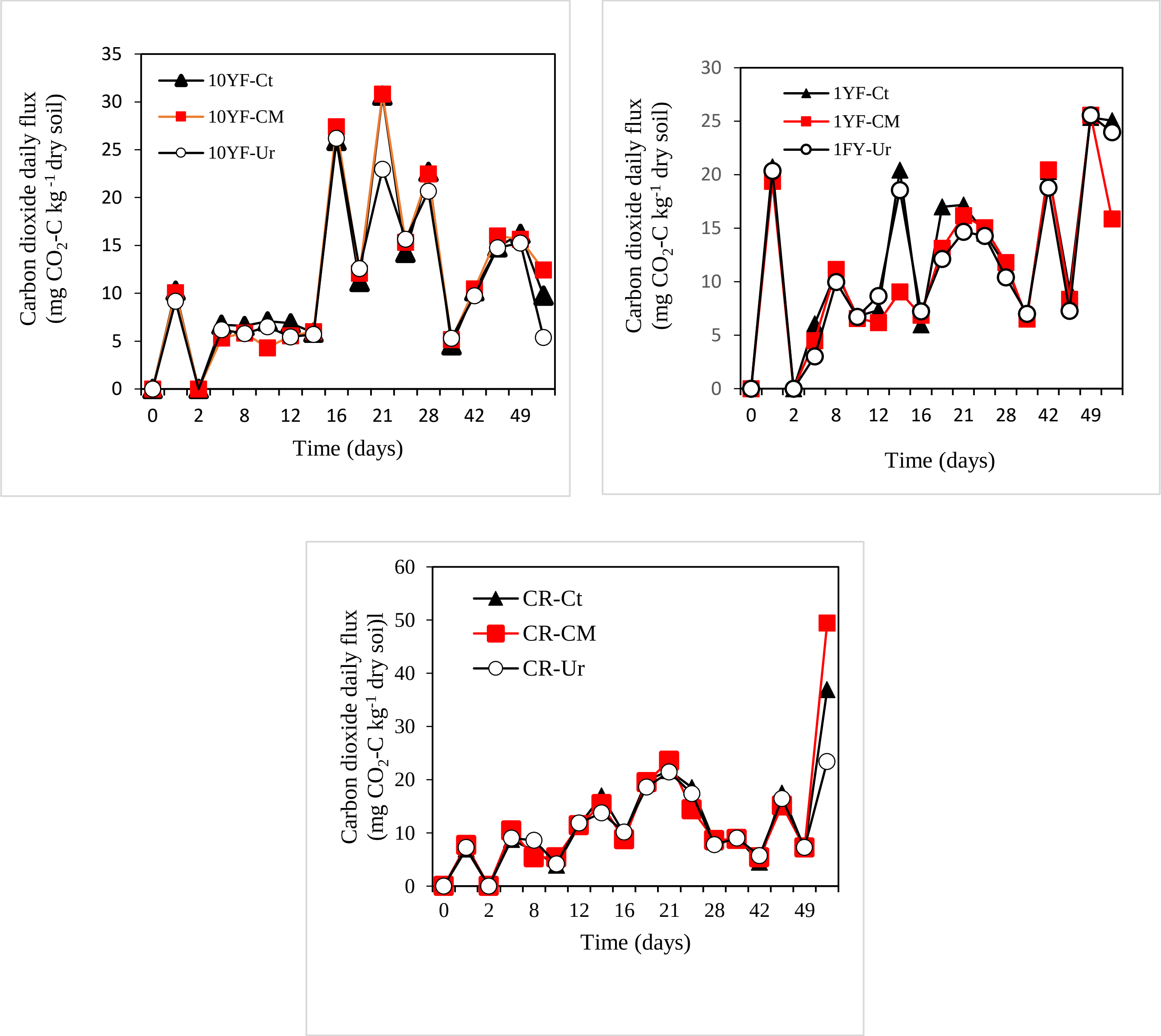

Figure 4.2: Carbon dioxide emission rates fluxes (mg C kg^{-1} dry soil day^{-1}) observed over the experiment time incubation in the treatments considered.

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4.3.3. Nitrous oxide emission

The treatments considered here led to different patterns in terms of N_2O emissions with significant differences between treatments observed in N_2O daily fluxes measured on days 1, 9, 12, 20, 21, 23, 28, 42 and 44. The highest value of N_2O emission was obtained at day 28 in treatments 10YF-Ct (0.06 mg N_2O-N kg^{-1} dry soil), 10YF-CM (0,08 mg N_2O-N kg^{-1} dry soil) and 10YF-Ur (0.05 mg N_2O-N kg^{-1} dry soil). The first 28 days of incubation are marked by the increasing trend in N_2O emission, and five peaks were recorded, the first at day 2 for PH-CM treatment, the second at day 14 (PH-Ur), the third at day 16 (CR-Ct), the fourth at day 20 (1YF-Ct and 1YF-Ur) and the fifth at 28 days (for 10YF-Ct, 10YF-CM and 10YF-Ur treatments). After the maximum emission observed at day 16 in CR-Ct treatment, there was a continuous decrease in the following days, once again registering a slight growth from 49 to 57 days. Our results indicated that 10YF-Ct, 10 YF-CM and 10 YF-Ur treatments lead to a higher increase of nitrous oxide emissions than the other treatments. On the other hand, the lowest emission of nitrous gas was observed in the CR-Ct, CR-CM and CR-Ur.

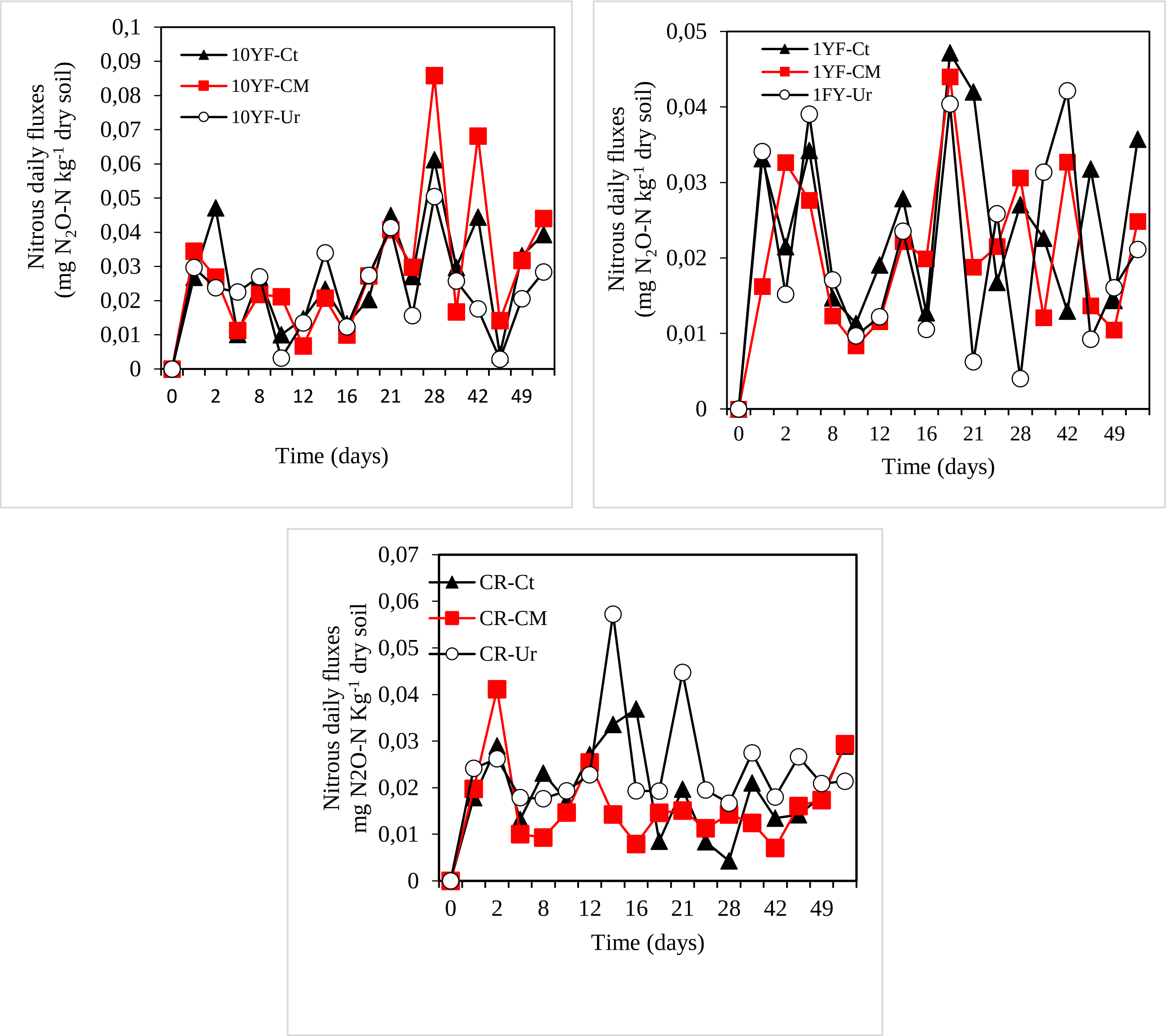

Figure 4.3: Nitrous oxide emission (mg N kg^{-1} dry soil day^{-1}) rates observed over the experiment time incubation in the treatments considered.

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Significant differences were observed between treatments in the cumulative N_2O emissions during the experiment time with the highest cumulative emission observed in the 10YF-CM treatment (1,899 mg N kg^{-1} dry soil) and the lowest in the PH-CM treatment (0.885 mg N kg^{-1} dry soil). The cumulative N_2O emission from treatment 10YF-Ct was significantly higher ($p<0.05$) than those from all, while no significant differences ($p<0.05$) existed among all the treatments (Table 4.3).

The total amount of N_2O emitted represent between 2 and 28 % of the total N applied.

4.3.4. Global Warming Potential

The GWP did not differ significantly ($p > 0.05$) between treatment as presented in (Table 4). The GWP from 10YF and 1YF was higher than soils from continuously rice productions (Table 4.3). The use of manure instead of urea did not affect the GWP independently of the soil management considered. The highest values of GWP were found in 10YF-CM and 10YF-Ct. While the lowest values of GWP were observed in CR-Ct, CR-CM and CR-Ur treatments.

Table 4.3: Cumulative amounts of nitrous oxide, methane, carbon dioxide and global warming potential during the experiment (N = 3)

Treatments	Parameters								
	N_2O (mg N kg $^{-1}$ dry soil)	% N applied	CH_4 (mg C kg $^{-1}$ dry soil)	% C applied as CH_4	CO_2 (mg C kg $^{-1}$ dry soil)	% C applied as CO_2	Applied C (C kg^{-1} soil)	Applied N (mg N kg^{-1} soil)	GWP (mg CO_2-eq kg^{-1} dry soil)
10YF-Ct	1,722a	NA	0,753b	NA	698,835a	NA	NA	NA	487
10YF-CM	1,899ab	28,78a	0,701b	0,91	710,327a	16,12a	77	76	535
10YF-Ur	1,347abc	2,09b	0,702b	25,00 a	654,045a	NA	3	64	382
1YF-Ct	1,338ab	N.A.	0,938a	NA	774,783a	NA	NA	NA	334
1YF-CM	1,182abc	17,91b	0,860ab	1,11b	699,598a	20,57a	77	76	306
1FY-Ur	1,199abc	1,86b	0,829ab	29,61a	729,220a	NA	3	64	390
CR-Ct	1,038bc	NA	0,774ab	NA	681,951a	N.A.	NA	NA	406
CR-CM	0,885c	13,41b	0,787ab	1,02 b	716,842a	64,01a	77	76	353
CR-Ur	1,304 abc	2,03b	0,759b	27,13 b	620,962 a	NA	3	64	365
P soil managements	*	ns	*	ns	*	ns			n.s
P fertilisation	ns	***	ns	**	ns	*			n.s
P soil managements*fertilisation	ns	ns	ns	ns	ns	ns			n.s

Note: α = ***; ** and * denote significance at 0.1%, 1%, and 5%, respectively according to the Tukey test
NA- Not applicable. Same letters in a row are not significantly different at level of $p <0.05$. % N applied; %C applied as CH4; %C applied as CO2; Applied C and Applied N; GWP: Global Warming Potential.

4.4. Discussion

Soil is responsible for a large part of the atmospheric greenhouse gases emissions such as nitrous oxide, methane and carbon dioxide, and the intensity and rate of emission is affected by several factors as humidity, temperature, exposure and pressure, vegetation fires, soil pH, nutrients, vegetation and land-use change (Oertel et al. 2016).

In the present study, a growing trend in the emission of CH_4 was observed in all treatments over the first 21 days which might be associated with the decomposition of organic matter (Bridgham and Ye 2015) (Bridgham et al. 2013). In rice culture, different studies at a global level have been carried out to understand the role of organic matter in CH_4 emission r in paddy conditions (Boateng et al. 2017). In the present work, the production of methane occurred in all treatments, even in unfertilized treatments. This result is not surprising if we take into account that the soils used are quite rich in organic matter (2-3%, Table 4.1), which is essential in the production of CH_4 (Table 4.1). Low CH_4 emission values were not expected in the present study since soils were incubated in anaerobic conditions but factors as porosity (Ahmad et al. 2009) or the pH value of the soils used, that can inhibit methanogenesis, (Jugsujinda et al. 1996; Fangueiro et al. 2015c) can explain some of the low values of CH_4 observed in some treatments. The peaks of CH_4 emission observed on days 12 (CR-Ct treatment), 14 (1YF-Ct), 20 (1YF-Ur) and 21 (10YF-Ur) might be related to the beginning of C consumption by soil microorganisms that favor greatly the production of CH_4 (Fangueiro et al. 2017). The high CH_4 emissions reported on these days may reflect high concentrations of methanogenic bacteria observed usually after approximately 15 days of incubation (Ko et al. 2000) .

In light of our results, it is not possible to obtain a clear association between soil management practices and CH_4 emission even if (Ali et al. 2009) suggest that undisturbed fields favor CH_4 emission due to the slow decomposition of organic matter but do not stimulate other GHG emission.

Our results point to a progressive increase in CO_2 emissions up to 21 days followed by a decrease in emission levels. There are numerous mechanisms that could have provided this increasing CO_2. According to (Lou et al. 2007), CO_2 in the soil can be produced in several forms, among which the biological oxidation of organic matter or decomposition of vegetable residues. (Curtin et al. 1998; Sander et al. 2018b) refer that fertilization with vegetable residues rapidly increases the carbon available in the soil, thereby affecting CO_2 emission levels. This behavior in the emission of CO_2 was expected in manure treatments since the fertilization made increased the levels of organic C in the soil, which is fundamental for the emission of CO_2. Furthermore, organic matter and vegetable debris accumulated over the years may have played a key role in CO_2 emissions since biological oxidation of organic material and decomposition of vegetable debris may have occurred, further stimulating the production of this gas, as suggested by (Bilandžija et al. 2016). In the light of these authors, we believe that the continuous increase in CO_2 emissions was due to the process of decomposition of organic matter that apparently have reached maximum decomposition at 21 days.

The decrease in CO_2 emission levels after 21 days suggests the possibility of deoxidation of organic matter by heterotrophic microorganisms (Robertson et al. 2000). However, it is to believe that the peaks observed on days 14, 16 and 21 are associated with fermentation and rapid decomposition of organic material, favoring the production of CO_2 (Pathak et al. 2005). The lowest CO_2 emissions were observed on day 2, and, in the 10YF-

Ur, 1YF-CM and CR-Ct treatments negative, CO_2 fluxes were observed as already reported in previous studies (Pandey et al. 2012) Tran et al. 2018). (Li et al. 2010) which related the occurrence of negative emissions to the anaerobicity caused by the flooding of the containing jars that drastically reduce aerobic respiration. CO_2 can act as an oxidizing agent, so its concentrations can be reduced in the soil causing pressure to lead to the diffusion of atmospheric CO_2 (Pandey et al. 2012). We mentioned in the present study that the first 28 days were marked by an increase of N_2O emission. This behaviour in the emission of this gas was expected since the fertilization increased the concentration of nitrogen in the soil, which is fundamental for the emission of N_2O. (Naser et al. 2020) suggested that the nitrogen initially present in the soil before the flooding serves as the basis for the emission of N_2O. After 28 days there was a decrease in the emission of nitrous oxide due to the depletion of nitrogen initially present in the soil.

Animal manure as well as inorganic fertilizers are well known for releasing considerable amounts of CH_4, CO_2 and N_2O after application to the soil (Sasada et al. 2011; Thangarajan et al. 2013; Brenzinger et al. 2018). However, in the present work, the cumulative emissions of the CH_4, CO_2 and N_2O gases obtained for the 9 treatments (Table 4.3) indicated that the effect of fertilization under different forms of soil management practices is not directly related with gaseous emissions. Indeed, no correlation was observed between fertilization or soil management practices and the emission of CH_4, CO_2 and N_2O. This is in agreement with results reported in previous studies: (Sasada et al. 2011) which revealed that there are no significant differences between organic and inorganic fertilizers in terms of CH_4 and N_2O emissions while (Win et al. 2014) considering the effect of the application of swine manure on the emission of greenhouse gases, found that there were no differences between organic and mineral fertilization. For

(Wang et al. 2016) the low emissions that occur in plots fertilized with organic fertilizers (straw or green manure) are related to the addition of carbon substrates that lead to an increase in the final reduction of N_2O in N_2 through denitrification. In the light of these authors, we can conclude that the absence of a clear effect of fertilizers on the emission of gases may reflect the occurrence of a denitrification process favored by bovine manure and straw accumulated over the years in the soil. The absence of significant differences in CO_2 emissions in the 9 treatments may reflect the common pattern of organic matter decomposition. It is to believe that the soil organic matter suffers microbial decomposition leading to the emission of CO_2 in response to altered amounts of C and N in the soil as suggested by (Perelo et al. 2005). (Cayuela et al. 2010) suggest that in soils rich in organic matter, baseline respiration increases and consequently CO_2 emission follow similar trends even after organic fertilizers application. In our study, soils were subject to the same climatic conditions and an application of equivalent amount of nitrogen in the fertilized treatments, indicating that the fertilizers were not determinants in the quantity of CO_2 emitted. These findings can help us to explain the lack of correlation between fertilization and different forms of soil management practices.

4.5. Conclusion

The present study provides relevant information that allowed us to understand the level of GHG emissions from Mozambican paddy soils, considering that there is a lack of information. Our study indicates that soil management affects the cumulative emissions of the three gases. Treatments CR-Ct, CR-CM and CR-Ur led to the lowest emissions of CH_4 and N_2O. The observed results demonstrate that the period of fallow can be an important source of GHG emissions with relative importance on CH_4 and N_2O.

On the other hand, it was showed that fertilization affect the loss of N and C considering the gases studied, even if no significant increase of N_2O emissions was observed in fertilized treatments regarding the control. Application of fertiliser affected CO_2 emission in the treatments. It can then be recommended to use cattle manure as fertilizer and promote the use of less years of fallow season as soil management to promote less emission on the fields.

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Chapter V

General conclusions and recommendations

5.1 Conclusion

This PhD thesis has as the main objective of providing technical and scientific information to improve fertilization strategies on rice production in Chókwè Irrigation Scheme (Mozambique) addressed to smallholder's rice producers. To support the general goal of the thesis, specific objectives were considered, namely:

a) To assess rice farming system typologies in the CIS to better understand the drivers and constraints for smallholder rice farmers and to propose alternative policies for decision-makers to improve production and productivity.

b) To characterize the rice production in Chókwè Irrigation Scheme (CIS) and analyse the several systems of rice production and their drivers.

c) To understand the management of cultivation practices in irrigated rice production systems.

d) To evaluate the agronomic effect and economic benefits of combined fertilization of rice production using mineral fertilizers and organic materials as N sources in Mozambican conditions.

e) To evaluate the effect of soil management and organic and inorganic fertilization on methane, nitrous oxide and carbon dioxide gas emissions in Mozambican paddy field soils.

The above-mentioned objectives were transformed into general objectives of each chapter and scientific paper. We found that rice production in Chókwè is practiced in a diversified way by smallholders. Four production typologies were identified, namely: a) the subsistence farming system (FS), b) specialized rice FS, c) mixed crops FS, and d) rice–livestock FS. Therefore, two typologies are more practiced by farmers, namely: Subsistence and Rice Livestock. These typologies are practiced according to the experience, age, financial availability, availability of labour, possession of lower lands, and distance from the agricultural fields to the farms.

Regarding the soil management practices, associated with rice productivity, we noted that the highest yield grain (425 gm^{-2}), plant height (115 cm), number of tillers (18) and thousand-grain weight (34g) were observed in treatments combining urea with manure, integrated use of organic and inorganic materials. Nevertheless, results can be more efficient and competitive if multiple organic fertilizers are combined, with supplemental addition of nitrogen (N).

The effect of soil management practices and organic and inorganic fertilization on the greenhouse gas emission (CH_4, CO_2 and N_2O) were assessed. Throughout the nine treatments, namely: a) Ten years fallow (control) – (10YF-Ct); b) Ten years amended with cattle manure (10YF-CM); c) Ten years amended with urea (10YF-Ur); d) One-year fallow (control) - (1YF-Ct); e) One-year fallow amended with cattle manure - (1YF-CM); f) One-year fallow amended with urea - (1YF-Ur); g) Continuous Rice (control) - (CR-Ct); h) Continuous Rice amended with cattle manure (CR-CM); i) Continuous Rice amended with urea (CR-Ur), we observed that although the treatments showed relatively significant differences in the cumulative emissions of CH_4 and N_2O gases, in contrast to CO_2, their effect or impact through agricultural practices in Chókwè is quite diffuse and limited.

In this context, in order to improve the production and productivity of rice in the Chókwè Irrigation Scheme (CIS), as well as to support small farmers to improve their income and soil conservation, a set of multilevel actions are necessary and urgent:

- Increase scientific research on the impact of organic and inorganic fertilizers application on greenhouse gas emissions, as well as the effectiveness of organic fertilizers.
- Expand production typologies such as: a) the subsistence farming system (FS) and b) specialized rice FS for most smallholders.
- Increase training and technical knowledge on good rice production and productivity practices for small farmers, especially female farmers.
- Increase the technical and financial assistance mechanisms for small farmers, to facilitate the acquisition of agricultural materials and inputs.
- Establish affordable and profitable agricultural value chains for small farmers.
- Encourage and support the use of improved organic fertilizers on a large scale by small and large rice farmers.
- Facilitate access (customs fees) for the acquisition of equipment and technologies to improve productivity by small farmers.
- Encourage and facilitate the establishment of small farmers associations, and direct or provide agricultural financing and credits.
- Ensure a market competitive scale for the rice that is competitive and advantageous to small farmers.

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