QUANTIFYING GREENHOUSE GAS EMISSIONS AND CARBON STOCKS IN MAIZE-SOYBEAN CROPPING SYSTEMS IN SIAYA COUNTY, KENYA

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(MSc, ARM)

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DECLARATION

I, Anne Njeri Karanja, declare that this thesis is my original work and has not been presented for the award of a degree in any other university or for any other award

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DEDICATION

This thesis is dedicated to my two lovely children: Briedan Mwangi and Norbert Karanja

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LIST OF ACRONYMS AND ABBREVIATIONS

C	Carbon
CEC	Cation Exchange Capacity
CH_4	Methane
C: N	Carbon-to-Nitrogen ratio
CO_2	Carbon dioxide
CRU	Controlled Release Urea
EF	Emission Factor
FAO	Food and Agriculture Organization (UN)
GHG	Greenhouse Gas
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change (UN)
N	Nitrogen
NACOSTI	National Commision for Science, Technology and Innovation
NEMA	National Environmental management Authority
N_2O	Nitrous oxide
NH_3	Ammonia
NH_4+	Ammonium
NO_3-	Nitrate
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
UNFCCC	United Nations frameork Convention on Climate Change
WAP	Weeks after Planting
WFPS	Water Filled Pore Space

ABSTRACT

As climate change continues to threaten ecosystems' functions, agriculture remains one of the major source of greenhouse gas (GHG) emissions that are responsible for global warming. The major GHG in agriculture are; carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4). Unfortunately, agriculture is also one of the most affected sectors by climate change. There is therefore need to reduce emissions by adopting agricultural practices with mitigation potential. This is by enhancing soil carbon sequestration to offset emissions, or reducing emissions while safeguarding crop yields. However, little is still known about GHG quantities and intensities that major cropping systems in Kenya emmit. Site specific studies on GHG emissions to establish interventions for mitigation of climate change and enhanced crop production is therefore of essence. The objective of this study was to examine the effect of reduced tillage, crop residue retention and use of controlled release urea (CRU) in maize-soybean cropping systems on GHG emissions, soil N mineralization, organic carbon stocks and yields. Field measurements were carried out in a 13 year old researcher-managed trial in Siaya county, Kenya between March 2016 and January 2017. Four treatment combinations: ZT M-S NU (reduced tilage+maize soybean rotation+normal urea), ZT M-S CRU (reduced tillage+maize soybean rotation+controlled release urea), ZT M/S (reduced tillage+maize soybean intercrop without urea), CT M-S NU (Conventional tillage+maize soybean rotation+normal urea) were tested. The treatments were laid out in a randomized complete block design. DAYCENT model was used to simulate soil carbon, N_2O emissions and maize yields. Results showed that daily fluxes of N_2O ranged between -0.5-26 g ha^{-1} d^{-1} and -2-10 g ha^{-1} d^{-1} in the long and short rainy seasons respectively. Cumulatively, N_2O emissions were between 0.2 - 0.7 kg ha^{-1} and 0.2 - 0.4 kg ha^{-1} in the long and short rainy seasons respectively. In the long rainy season, ZT M-S CRU had significantly higher N_2O fluxes than the other treatments (P=0.05). In the short rainy season there were no significant effects of treatment on N_2O emissions. In the long rainy season, CO_2 daily fluxes were between 9 to 42 kg ha^{-1} while the cumulative emissions ranged between 2.5 to 2.8 t ha^{-1}. In the short rainy season daily CO_2 fluxes ranged between 6 to 30 kg ha^{-1} while cumulative emissions were 1.8- 2.5 t ha^{-1}. There was no significant effect of treatment on CO_2 emissions. Methane emissions were largely negative, and did not differ significantly among treatments. Yield was significantly low for ZT M/S but N_2O emission intensities were not significantly different among treatments. DAYCENT simulated soil carbon and maize yield within the same ranges observed by measurement. N_2O emissions by DAYCENT were higher during the peak of the seasons, but were comparable with observed measurements later in the seasons. Even though the long rainy season had higher N_2O and CO_2 emissions, the difference was not significant. These results indicate that emissions in the study area were low.These results further indicate that the current soil management practices in Siaya County influence GHG emissions, and the higher emissions observed with ZT M-S CRU in the long rainy season calls for further investigations of the effect of CRU on N_2O emissions. The lower emission intensity shown by ZT M/S despite having lower yield points to the need of evaluating cropping systems for climate change mitigation and adaptation. These results indicated that DAYCENT model can be used to simulate soil carbon and yield but not N_2O emissions in the study area.

CHAPTER ONE

INTRODUCTION

1.1 Background to the study

Climate variability as identified in many parts of the world has been on the rise in the last few decades (Rezaei et al., 2015). This poses a substantial challenge to food security for the millions of people in areas where food production is majorly dependent on rain-fed agriculture. This is particularly so in the tropical environments (Rojas-Downing, et al., 2017; Tesfaye et al., 2017). Climate variability is mainly characterised by rise in atmospheric temperature, prolonged droughts , erratic rainfalls, flush floods and prolonged dry spells, shift in soil biota, emergence of new species of weeds and pests as old ones get extinct (IPCC, 2014).

Climate change is projected to increase the spread of diseases to areas where they were not common before and rise in seal levels which may adversely affect agriculture. As reported by NEMA (2015), climate change is the most serious global challenge of our time and is primarily caused by greenhouse gas (GHG) emissions (Maccarthy et al., 2018; IPCC, 2013). GHG are defined as “gases in the atmosphere such as water vapour, carbon dioxide, methane and nitrous oxide that can absorb infrared radiation, trapping heat in the atmosphere” (IPCC 2014)

Global atmospheric concentrations of GHG namely carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) have increased over time (Oertel, et al., 2016; IPCC, 2014;). The increase of CO_2, CH_4 and N_2O is mainly due to anthropogenic activities. While CO_2 is mainly from the use of fossil fuel as a source of energy and

from land use and land use changes, N_2O is mainly from the use of inorganic fertilizers. CH_4 is mainly from paddy rice cultivation and enteric fermentation in ruminants (Smith et al., 2014; Ciais et al., 2013).

The three gases (CO_2, CH_4 and N_2O) are responsibe for approximately 80% of the current global radiative forcing (Myhre et al., 2013) and responsible for global warming which has created a shift in climatic conditions (IPCC, 2013). As further reported by IPCC (2014), "continued emission of greenhouse gases will cause further warming and long-lasting changes in all components of the climate system, increasing the likelihood of severe, pervasive and irreversible impacts for people and ecosystems." While GHG emissions are naturally due to biogeochemical processes, their intensities have increased in recent times as a result of industrialization (IPCC, 2014).

It should be noted that the net GHG fluxes are a result of myriad of complex soil biochemical processes (Eugster & Merbold, 2015). Net soil CO_2 is as a result of two main respiration processes namely; autotrophic respirations from plant roots, associated mycorrhizal fungi and heterotrophic respirations through oxidation of soil organic matter (Jovani-Sancho et al., 2017). Net N_2O fluxes are mainly as a result of a microbial production process in soils under oxygen (O_2) limiting environmental conditions (Butterbach-Bahl et al., 2013). Net soil CH_4 flux results from two antagonistic processes namely methanogenesis, which produces methane under anaerobic conditions, and methanotrophy which consumes methane (Eugster & Merbold, 2015; Pazinato et al., 2010).

Atmospheric concentrations of N_2O increased from 275 ppb in 1900 to about 317 ppb 2000 while CO_2 increased from ~300ppm to about 400ppm in the same period,

mainly as a result of anthropogenic factors (IPCC, 2014; Mosier and Kroeze, 2000). Agriculture is greatly recognized as one of the major contributors of GHGs (Metz, 2007; Robertson et al., 2000) contributing between 14 - 17% to the global anthropogenic GHG emissions (Ciais et al., 2013).

CO_2 and N_2O are the most important gases in upland cropping systems while CH_4 is mainly a concern in flooded soils and in livestock production systems. Although N_2O is emitted in less quantity than CO_2 and CH_4, it has a greater global warming potential of 298 times that of CO_2 in a span of 100 years (Myhre et al., 2013). Besides its contribution to climate change, N_2O destroys the ozone (O_3) layer, making it vulnerble to the penetration of harmful ultraviolet solar radiation to the earth surface.

The emission rate and quantities of these gases are influenced by a number of factors within a farming system and may considerably differ based on climatic conditions, soil properties and land management (Lal, 2010). Increasing N fertilizer application to boost crop yields may lead to elevated N_2O emissions (Hickman et al., 2011, Sommer et al., 2015). However since N is one of the major limiting nutrients in Kenyan soils (Kihara and Njoroge, 2013), judicious application or its management will go along way in reducing N_2O emission.

Greenhouse gas emissions from agricultural systems may considerably differ based on the climatic conditions, soil properties and land management (Pelster et al., 2012; Rosenstock et al., 2016). Therefore, accurate quantification of soil greenhouse gas fluxes from croplands is of great importance in determining whether a farming system is a net sink or source of GHGs (Ortiz-Gonzalo et al., 2017) which shall guide development of valuable mitigation and adaptation measures (Pelster et al., 2017).

According to the Kenya's Second National Communication report to the United Nations Framework Convention on Climate Change (UNFCCC, 2015), Kenya's GHG emission from the agricultural sector was about 20,000 Gg CO_2 equivalents (NEMA, 2015). It is estimated that total emissions from cereal based crops in Kenya rose from about 467 to 776 CO2eq Gg between the year 2000 and 2015 (FAOSTAT, 2016)

Generally in sub Saharan Africa (SSA) the main drivers of GHG emission in agriculture are poor farming practices such as conventional tillage which causes soil disturbance and inappropriate application of nitrogen (N) fertilizers (Butterbach-Bahl et al., 2013). Conventional tillage, for example, enhances organic matter decomposition by increasing the exposure of the residue to soil microbes. It also increases aeration and temperature, resulting in release of CO_2 and N_2O (Giacomini et al., 2007).

Removal of crop residues is another practice that has major effects on emissions. In SSA, crop residue is serves other household uses such as livestock feed (during dry season) or fuel. This usually leaves the soil with low organic matter and ultimately resulting to soil mining ranging between 14 – and 110 kg N per hectare per year (Zhou et al., 2014; Nandwa & Bekunda, 1998).

Agricultural intensification will therefore require practices that enhance crop yields and mitigate GHG emissions (Pretty et al., 2011). Reduced tillage, crop rotations, and crop residue retention are believed to enhance soil carbon sequestration and mitigate GHG emissions (Daan et al., 2008; Paustian et al., 2004; Robertson et al., 2000), but some studies have revealed that this is not always the case (Sommer et al., 2015, Millar et al., 2004).

The contribution of GHG emissions by major crops in Kenya needs to be identified and mitigation strategies developed or if there are existing ones they be adopted. In order to meet demand of the ever increasing population, address the issue of soil infertility and thus promote environmental resilience of the smallholder farmers, concerted efforts towards sustainability (Waha et al., 2018) is called for. This further complicates the GHG fluxes quantification, adaptation and mitigation. Case in point, the continued efforts to promote adoption of soil fertility technologies has resulted to both improved yields and soil heath (Mucheru-Muna et al., 2014). However, their individual contribution towards national greenhouse inventories largely remain unknown (Ciais et al., 2013).

Maize for example, is one of the major crops in Kenya grown on an estimated area of 1.4 million ha, and occupies about 30% of Kenya's arable land (Adamte et al., 2016). About 75% of this production is produced by small scale farmers (De Groote et al., 2005) which makes it more complex to estimate GHG emissions. This is because the process of accurately estimating GHG is expensive and tedious, and the use of default factors to calculate emissions could be erroneous (Richards et al., 2016) due to heterogeneity of tropical smallholder farming systems (Sommer et al., 2015; Hickman et al., 2014; Seebauer, 2014;Sugihara et al., 2012).

The extent to which conservation agriculture mitigate GHG in Kenyan maize cropping systems has not been comprehensively studied. A cropping system as used in this study refers to the crops (maize and soybean), their cropping sequence and the soil management (Ghanbari et al., 2010). According to FAO (2009), in the order of importance on the world cereals, maize ranks second after wheat. Maize is a critical

source of food and cash for both rural and urban households in Africa (Midega et al., 2018). In SSA, and particularly East Africa, maize is the most important source of food for rural households (Midega et al., 2018; Adamtey et al., 2016) and the staple food in Kenya (Schroeder et al., 2013).

This limitation has rendered uncertainty in the choice of adaptation and mitigation strategies (Pelster et al., 2017). An evaluation of farming practices in developing countries that improve carbon sequestration and mitigation of GHG emission is emphasized by Antle and Diagana (2003). GHG emission intensities is a vital parameter to quantifying emissions. Studies of Macharia et al. (2020) and Sommer et. al (2015) have established emission intensities for maize with use of manures in semi arid and sub humid environments respectively. There still remain the need to establish the emission intensities for maize cropping systems under different soil tillage practices. In addition most of the availble studies have investigated GHG emissions within a short period (less than a year) or with few number of sampling times during the cropping season. This study endeavoured to estimate GHG emissions in maize-soybean cropping systems using both field measurements and mechanistic modelling.

1.2 Statement of the problem

Climate change is a global threat to agriculture especially in SSA countries, such as Kenya, which mainly rely on rainfall for productivity. There is need to reduce this vulnerability by reducing GHG emissions from agricultural sector. This is because agriculture as much as is one of the most affected sectors of the economy, it remains a major contributor of GHG that leads to climate change globally (IPCC, 2001).

Carbon sequestration is one of the efficient ways of mitigating emissions, but this potential may be reduced if the sequestered carbon is counterchecked by increased N_2O emissions. A slight change in N_2O emissions may cause a big shift in global temperatures since N_2O has a global warming potential that is about 300 times that of CO_2. As crop productivity is enhanced through N fertilizers, direct or indirect increases in N_2O emissions are inevitable due to the high dynamic changes of N compounds for example the nitrification and denitrification processes in the soil ecosystem.

Climate change mitigation strategies can not be realized without adequate data poiting to the extent of emissions and prectices with mitigation potential. Unfortunately there is still limited data on GHG emissions from major cropping systems in Kenya. Only few studies have been done in Kenya to qauntify GHG emissions (Macharia et al., 2020; Sommer et al., 2015;Pelster et al., 2012; Hickman et al., 2011). This challenge has emanated from the high expenses associated with field measurements of GHG which are also highly time-consuming. As such, most of the field- based studies have reduced the number of gas measurements or have been done over short periods of less than one year. Modelling GHG emissions could alleviate this problem since it is cheaper and less time consuming, but it requires sufficient data and expertise to yield satisfactory emission estimates.

These challenges have led to the use of default emission values given by the IPCC to crete emssion inventories for Kenya. The problem with using default values is that they may underestimate or overestimate emissions for smallholder agricultural systems since they were obtained from a few generalized studies with a limited spatial coverage. The other problem with estimating GHG in small holder farms in Kenya is

associated with the diversity of agro ecosystems and crop choice. It is however critical to estimate emissions from major crops such as Maize, which is a staple crop for majority of Kenyans.

There are several studies which have have tried to adress this challenge in the last decade. For instance, the study by Macharia et al. (2020) investigated GHG emissions in continous maize cropping system in the semi arid zone in Eastern Kenya; Sommer et al (2015) studied N_2O emissions in a maize – green manure rotation system in a sub humid tropical zone in western Kenya. However, in Kenya maize is usually grown together with other food crops (especially legume) either in rotaion or intercrop.

Data on GHG emission in maize-legume cropping systems and associated soil carbon stocks to give a clearer picture of the state of emissions from agriculture in Kenya is still scanty.

1.3 Justification of the study

Agriculutre is a major contributor of greenhouse gases globally. GHG are responsible for climate change which is a major threat to life due to the impacts ranging from excessive rains, droughts and increased temperatures. Reducing the impact of agriculture on climate change and adapting to the current situation requires urgent intervention. Although studies have so far shown Kenya as low emitter, the situation is predicted to change with the increasing populations. This is because the higher demand for food may result in more use of nitrogenous fertilizers since most Kenyan soils are N deficient.

The interventions to mitigate emissions can only be achieved if Kenya as a country knows the sources and quantities of GHG associated with major agricultural crops such as maize. This study sort to quantify the contribution of maize cropping systems to GHG emissions and the levels of soil C. Results from this research work are expected to inform on targeted adaptation and mitigation strategies in soil management such as reduced tillage, fertilizer (type/form application rates, and timing) and crop residue management.

Resultant reduction in emission rates will reduce the impact on climate change ultimately improving the productivity of agriculture and the livelihoods of many farmers. Modelling of GHG emissions which this study adopted is expected to supplement field measuremnts in estimatin emissions. This could reduce the time and expences in conducting tedious and expensive field experiments as well as project scenarios for different management strategies. This will make it easy and quick to estimate emissions from systems of other crops. This in return will make it possible to predict the impact of long term climate change mitigation strategies on yield and GHG emissions before their actual implementation. This research also studied the potential of controlled release urea (CRU) in reducing N_2O emissions and increase maize and soybean yields.

CRU is designed to reduce N losses, thereby reducing N_2O emissions and pollution of underground water resources. Kenya being a member of Conference of Parties is mandated to submit its annual greenhouse gas emissions/removals inventories from major sectors such as agriculture to the United Nations framework convention on Climate Change (UNFCCC). This research work will contribute data needed for the

process of estimating GHG emissions in maize soybean cropping systems. Availabiltiy of data necessary to form a basis for designing GHG emission mitigation strategies will go along way in reducing climate change

1.4 Objectives

1.4.1 Overall study objective

To determine the quantities of greenhouse gas emissions, soil carbon stocks and yield in maize - soybean cropping systems

1.4.2 Specific study objectives:

i. To detarmine nitrogen mineralization and nitrous oxide (N_2O) emissions in maize-soybean cropping systems.
ii. To determine soil carbon stocks, carbon dioxide (CO_2) and methane (CH_4) emissions under different maize-soybean cropping systems.
iii. To determine maize and soybean yields and emission intensities in maize-soybean cropping systems
iv. To estimate yields, soil carbon and N_2O emissions in maize-soybean croppping system using DAYCENT model.

1.5 Research hypotheses

i. Soil management practice can significantly influence nitrogen mineralization and N_2O emissions.
ii. Intensified cropping systems can significantly increase soil carbon stocks and CO_2 emissions in small holder maize-soybean cropping systems.

iii. Cropping systems have an effect on maize/ soybean yields and N_2O emission intensity.

iv. DAYCENT Model can estimate maize yield, carbon stocks and N_2O emissions.

1.6 Conceptual frame work

Agriculture emits considerable amounts of GHGs globally (IPCC, 2001). Sub-Saharan Africa (SSA) agriculture is characterized by low input and low productivity. This means for satisfying food needs, more land is required for food production. This would translate to increased GHG emissions from land use change (IPCC, 2014). Farming practices such as tillage and crop residues removal from the fields are the main causes of these emissions (Giomini et al., 2007).

Tillage operations expose organic matter to microbial decomposition thereby emitting CO_2 and N_2O. The subsequent destruction of the soil structure leaves the soils susceptible to erosion, and reduces soil aggregates (Kihara, 2009) necessary for protecting organic matter from decomposition (Six et al., 2004). Smallholder systems in Kenya rarely return crop residue to the farm. This is mainly as a result of competition for crop residue for other uses such as fuel and animal feed (Giller et al., 2009)

Sustainable production systems such as conservation agriculture which entails permanent soil cover, minimum soil disturbance and inclusion of legumes in the cropping systems are some of the strategies that can enhance soil productivity and mitigate GHG emissions. Application of nitrogen fertilizers, either organic or inorganic plays a major role in determining the rate of emissions. Studies carried out in Kenyan smallholder systems show contrasting emission rates and amounts of the various GHG. This implies that emissions cannot be generalized for the entire country.

Detailed studies of GHG emissions in major cropping systems need to be carried out in order to determine the quantities and rates of emissions. GHG emissions should also be related to crop yields to give direction on the most appropriate mitigation and adaptation practices to adopt. Measurement of GHG in situ is time consuming and laborious and also expensive. Mechanistic models which have been used in developing countries can be employed to offset this obstacle. Models can estimate the emissions for a broader area, including the effects that cannot easily be studies in the field. Simulated emission values can easily be used to improve systems and mitigate future GHG emissions. As such, decision on the best bet systems could lead to lower overall GHG emissions in agricultural systems as compared to decisions made based on inaccurate estimates with dafault emission factors. Figure 1.1 shows a schematic representation of the conceptual framework.

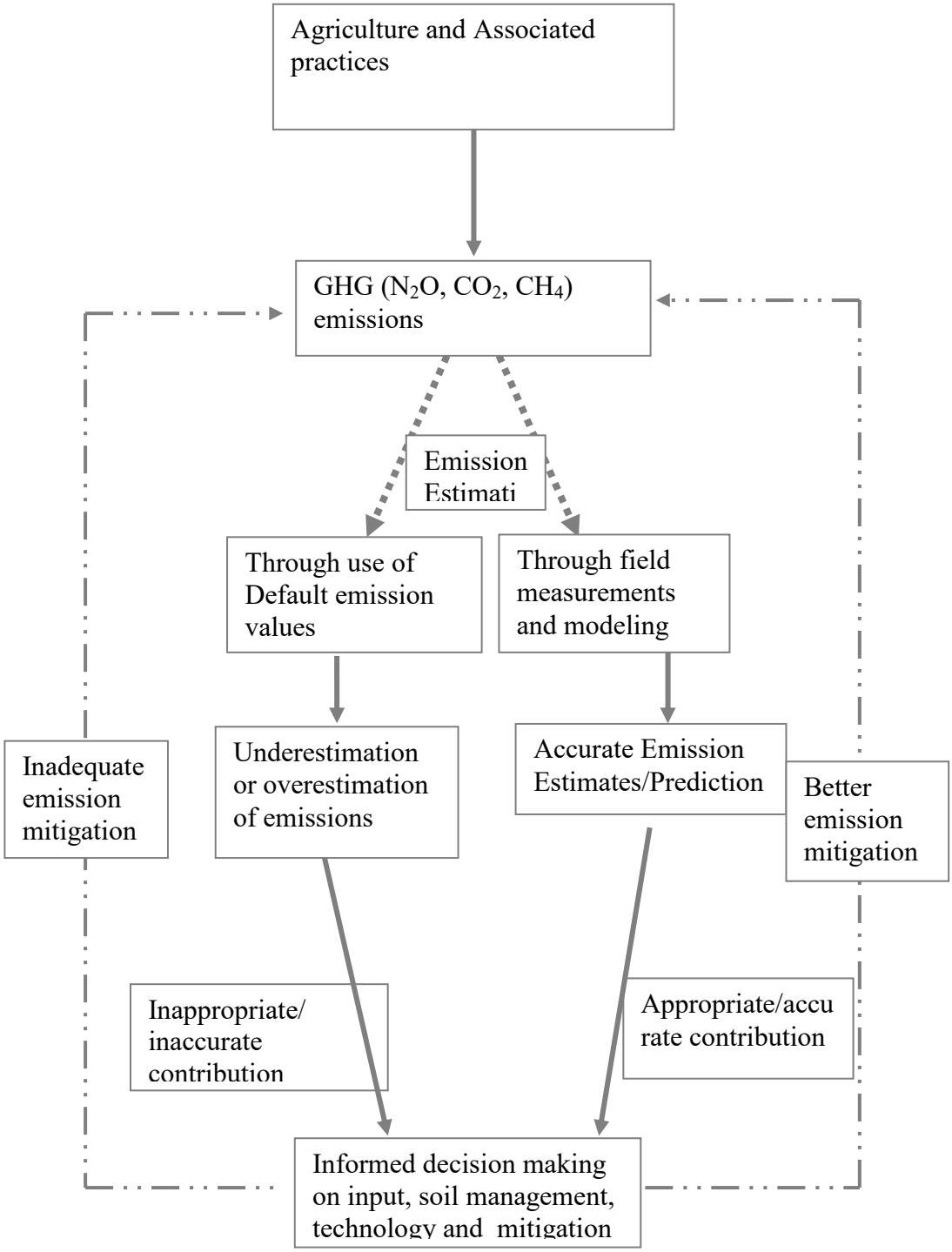

Figure 1.1: Diagrammatic representation of the conceptual framework (source; author, 2020)

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This chapter highlights key aspects related to greenhouse gas emissions and climate change, soil carbon and CO_2 emissions, effects of tillage on GHG emissions, Nitrous oxide emissions in agricultural systems, Effect of crop residue retention on GHG emission, methane emissions, modelling greenhouse gases using DAYCENT model, crop yield and GHG emissions and summary of the literarure highlighting literarure gaps.

2.2 Greenhouse gas emissions and climate change

Increases in global atmospheric temperature have been linked to increasing levels of greenhouse gases (GHG). The major GHGs include carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) which create a greenhouse effect making the earth temperatures to rise. This phenomenon is important in heating up the earth; otherwise the average temperatures would be around -18°C. Though this happens naturally, the levels of the GHGs have risen drastically from pre-industrial period causing a sharp increase in atmospheric temperatures and a shift in other climatic conditions (IPCC, 2014). For instance, between the years 1850 and 2000 concentrations rose from 280 to 400 ppm, 800 to 1800 ppb nd 270 to 330 ppb for CO_2, CH_4 and N_2O respectively (IPCC 2014) Global GHG emissions have risen from about 40 Gt CO_2eq in the year 2000 to about 52 Gt CO_2eq in 2015 (UN Climate Change, 2019).

Effects of climate change, particularly a rise in temperature and erratic rainfall are detrimental to agriculture in sub-Saharan countries that is highly dependent on rainfall. This is expected as renewable subsurface water sources decline as global temperatures increase (IPCC, 2014). The complexity of the situation for subsaharan africa is that Agriculture contributes the highest emissions, yet it is the sector most affected by climate change impacts. Livestock is the major source of GHG due to CH_4 emissions by enteric fermentation and anaerobic decomposition of dung. N_2O in livestock sector occur from manure and urine. In crop land, CH_4 is the major gas in flooded soils such as in irrigated rice paddies while N_2O is emitted following application of synthetic nitrogenous fertilizers. Rewetting of soil following a dry spell has been shown to result to increased GHG emissions (Gelfand et al., 2015) therefore agriculture must be practiced through methods that adapt to the current conditions while mitigating further emissions.

Greenhouse gas emissions from various sectors contribute to global climate change. Agricultural related activities are the major sources of GHG emissions comprising 40% of al emissions in Kenya (NEMA, 2015). In upland agriculture, CO_2 and N_2O are the most important gases while CH_4 is a major concern in flooded soils (eg paddy rice) and livestock based systems (NEMA, 2015).

2.3 Soil carbon and CO_2 emissions

The main source of atmospheric CO_2 is fossil fuel burning, though considerable amounts are also derived from agricultural activities in tropical conditions (Smith et al., 2014). The high temperatures in the tropics coupled with adequate soil moisture encourage microbial decomposition of organic matter leading to evolution of CO_2 gas.

This is particularly so during land preparation. Agricultural systems with mitigation potentials are those that can sequester enough soil carbon (C) to offset emissions elsewhere.

Generally soils account for about three times more C than the atmosphere, and about two times more than vegetation (IPCC, 2000; Eswaran et al., 1993). This implies that a slight change in soil carbon can impact a great change in atmospheric CO_2 accumulation. Agricultural soils can be sinks or sources of GHG depending on how they are managed (Lal, 2010). Increasing soil organic carbon (SOC) stocks in the soil is important to mitigate GHG concentrations in the atmosphere and in maintaining ecological functions such as soil fertility for enhanced food production, hydrology and soil biodiversity (Lal et al., 2007).

Efforts to mitigate GHG emissions have relied on farming systems believed to emit less and sequester C. Particular interest has been given to conservation agriculture (CA) which is based on three principles: reduced mechanical disturbance of soil, permanent soil cover and crop rotation with legumes (FAO, 2008). It is believed to increase soil organic matter (Dercon et al., 2010) and probably sequester C. GHG emissions are influenced by many factors such as climate, soil type, topography, crop species as well as management practices (Baggs et al., 2006).

2.4 Effects of tillage on GHG emissions

Tillage systems that leave residues on the farm increase the organic matter and water holding capacity of the soil (Alvarez & Steinbach, 2009). Conservation tillage is an agricultural strategy to mitigate atmospheric GHG emissions. Tillage operations that mix crop residues with soil and decrease soil aggregations facilitates microbial

degradation of soil organic matter (Six et al., 2004; Balesdent et al., 2001). Thus, a shift from high physical disturbance conventional tillage (CT) to reduced tillage (RT) to no tillage (NT) can increase soil organic carbon (SOC) storage (Allmaras et al., 2000; Huggins et al., 2007). Effects of switching from conventional to conservation tillage on GHG emissions are still unclear. For instance, Six et al. (2004) observed a higher N_2O emission under NT compared to CT in a dry environment, but the rates were lower in a humid environment. On the Contrary, Dalal et al. (2003) observed higher N_2O emissions in a humid environment.

The beneficial effects of reduced or zero tillage in sequestering C are achieved when micro aggregates form within macro aggregates, creating unfavorable conditions for microbial activities during organic carbon decomposition (Six et al., 2004). On the other hand these conditions favor denitrification processes that may increase N_2O emissions, consequently offsetting the benefits of the sequestered C (Chatskikh et al., 2007). An increased or reduced N_2O and CO_2 emission under reduced tillage has been observed in different studies (Jin et al., 2014).

Stratification of SOC following reduced tillage should also be accounted for in estimating C stocks (Giller et al., 2011). The importance of soil organic matter addition in tropical climates is emphasized by Giller et al., (2009), for its high turnover rates of organic matter by soil micro and macro organisms (Kihara, 2009). Reduced tillage has been shown to increase SOC in the top 7cm layer of the soil (Bayer et al., 2007; Deen & Kataki, 2003) but this increase was reported to reduce down the soil profile in the 7-15 cm depth. This indicates that the potential of reduced tillage to mitigate emissions can therefore not be based on the outcome of the top layer only.

Some other researches have shown that conservation tillage, especially no-tillage (NT), results in greater amounts of N_2O emissions than do intensive tillage systems (Halvorson et al., 2006; Koga et al., 2006; Grant et al., 2004; Flessa et al., 2002). This is attributed to the residue left by conservation tillage keeping the soil wetter and providing energy to the denitrifying microorganisms. However, the research by Omonode et al.(2011) indicates that NT produces less N_2O than does conventional tillage. This is attributed to conventional tillage causing more soil organic C to decompose due to higher levels of soil microbes-residue interactions and higher soil temperatures. Conservation agriculture has been highly promoted as a climate change mitigation strategy although various studies have shown it does not always lead to greenhouse mitigation (Dendooven et al., 2012).

2.5 Nitrous oxide emissions in agricultural systems

Though N_2O concentration release may be less compared to CO_2 in field crops such as maize, it remains one of the most important GHGs. N_2O has a global warming potential of almost 300 times that of CO_2 due to its long acting period, usually 100-150 years (Myhre et al., 2013; Forster et al., 2007). N_2O also has a higher absorbance capacity compared to CO_2 (Rohde, 1990).

The major source of N_2O in agricultural systems is nitrogen fertilizer use (Smith et al.2012). Although it is well established that soils are the dominating source for atmospheric N_2O, the complexity of the underlying microbial production and consumption processes and the links to biotic (e.g. inter- and intraspecies competition, food webs, plant–microbe interaction) and abiotic (e.g. soil climate, physics and chemistry) factors still remains relatively unknown (Butterbach-Bahl et al., 2013).

However, the current fertilizer use rate in SSA and particularly in small holder farms in Kenya is low. Many factors contribute to this trend but economic resource endowment has been sighted as a major factor in small holder systems. Low input in inorganic fertilizers has resulted in low GHG emissions so far (Pelster et al., 2017), but this situation is only short lived.

As human population is projected to increase, the demand for food will also increase. Increasing food production through use of nitrogenous fertilizers is one of the major strategies envisioned by the green revolution. This is because most Kenyan soils, as is the case in most tropical and subtropical regions, are N deficient (Kihara & Njoroge 2013; Gitari et al., 2019). An increase in N fertilizer use may however enhance N_2O emission (Hickman et al., 2011). The rates and amount of N_2O emissions are dependent on the type of N fertilizer applied as well as the mode of application (Ryan et al., 2012). These projected increases in N_2O emission could be reversed if N management is controlled.

The current emission levels are related to the low input use in small holder farms in SSA. Small holder farms occupy the largest area of cropland in SSA, and an increased use of inorganic fertilizers would result in huge N_2O emissions. Hickman et al. (2011) predicted the doubling of N_2O emissions by the year 2050 from the levels of the year 2000. However, if the increased demand for food production owing to rapid population growth is realized through low- emission production systems, then SSA will significantly reduce global emissions from the agriculture sector.

Efficient use of soil N by crops without being lost to the environment reduces N_2O emission rates (Nyawade et al., 2019). The form of N fertilizer applied also

determines the extent of N_2O emissions. Controlled release urea (CRU) can be used to mitigate emissions. These fertilizers are designed to release nutrients at a slower rate thus reducing the negative environmental effects of through leaching. They also prolong the time nutrients are accessible for plant uptake (Shoji & Gandeza, 1992). Controlled release fertilizer or slow release fertilizers are classified depending on the mechanism of nutrient release andd the manner in which they are formulated such that nutrients are released in synchrony with crop demand. The release pattern is controlled by inhibiting microbial activities by urease inhibitors or by coating with a semi permeable barrier that releases nutrients as temperature and soil moisture changes.

Research has shown that CRU does mitigate GHG emissions, but such studies have not been carried out in the Kenyan upland crop fields. However, studies elsewhere have reported positive effects especially in rice production systems while others have shown a negative effect (Trinh et al., 2017; Ji et al., 2014). This however does not ignore other factors such as soil type, crop species and climatic conditions which also have influence.

Soil properties such as texture are known to affect biological processes that lead to N_2O production. For instance, Jarecki et al. (2008) found that cumulative N_2O emissions were greater from sandy loam soils than from clay soils. These authors speculated that it was the higher cation exchange capacity (CEC) in the clay soil that reduced nitrogen (N) availability through increased adsorption of NH_4^+. Similarly, a loam soil was found to emit more of the applied fertilizer as N_2O than did a clay soil (Weitz et al., 2001). It is therefore important to consider all the dynamics when evaluating mitigation processes for different regions.

2.6 Effect of crop residue retention on GHG emission

Apart from inorganic sources of N, crop residues also contribute to soil N. Use of legumes in cereal based systems increase the nitrogen base of the soil through biological fixation (Ojiem, 2006) though the biomass may require additional mineral fertilizer for improved decomposition. This process of microbial decomposition of organic matter leads to GHG emissions, particularly N_2O and CO_2 in upland crop fields.

The extent of emissions is dependent on many factors but primarily soil moisture, temperature and availability of organic substrates. High N content in residues results in higher rate of decomposition and higher N_2O emissions than when the N content is low. Agricultural intensification in SSA has been tested and widely adopted to improve soil fertility and crop yield. (Giller et al., 2011; Ngome et al., 2011; Ojiem, 2006)

Application of high quality crop residues (mainly green manures) have however been shown to increase N_2O emissions thus raising questions on whether these systems are eco-friendly. Sommer et al. (2015) and Millar et al. (2004) showed increased emissions with more improved fallows/ green manures. Maize yield observed by Sommer et al. (2015) was not high enough to justify that high emission, neither were the yield high enough to justify the farmers abandoning one season for green manure (*Tephrosia candida*) production However, observation by Millar et al. (2004) had indicated an increased maize yield with increased fallow and therefore more likely to be adopted by farmers.

Benefits of conservation agriculture are usually arrived after several years of incorporation (Kihara 2009). These benefits however have mainly been based on soil

health improvement and crop yield increment. The potential of conservation tillage to mitigate GHG emissions still remains unevaluated for the sub-humid tropics in Kenya.

2.7 Methane emissions

Methane is one of fthe critical greenhouse gases, which absorb radiation, affects the chemistry of atmosphere and contributes to global climate change (Malyan et al., 2016). CH_4 emissions are usually common in flooded soil conditions and where animal manure is used. In upland cropping systems, the emissions are negligible but the impact of these small fluxes may not be overlooked. CH_4 has a global warning potential (GWP) of 72 and 25 times more than that of CO_2 over 20 and 100 years respectively (IPCC, 1997). However, CH_4 may be emitted in upland soils if pockets of excess water are available, especially in conservation agricultural practices.

CH_4 in soils is produced by methanogenesis under anaerobic conditions and is consumed by methanotrophic microorganisms that use O_2 and CH_4 for their metabolism under aerobic conditions (Smith et al., 2014; Ciais et al., 2013). CH_4 fluxes are strongly affected by the rate, mode and methods of application of fertilizers whereby application of Nitrogen fertilizers in the form of urea enhances CH_4 emissions due to drop in redox potential and increasing soil pH (Malyan et al., 2016).

2.8 Modelling greenhouse gases

One of the major drawbacks in making informed decision on crop management systems and resultant effects on soil is lack of adequate data from field experiment only (Grabisch, 2003). Crop modelling platforms offer decision support information to help optimize crop yields and improve management. In addition, crop modelling platforms

offer an opportunity to asses and quantify risks associated with their operational management decisions under climate variations (Staggenborg et al., 2005)

Effects of seasonal variability may alter the outcome of field experiments and leave questions on how the system would have responded to other conditions (Keating et al. (1991). Crop models are therefore able to optimally predict the outcome of what may not be obtained in an experimental setup. Process-based models account for impacts of soil type and weather conditions on emissions that are not possible to be estimated with emission factors (Giltrap et al., 2015). Due to limitation of measured emissions, seasonal or annual emissions are often estimated using linear interpolation between two observations points. In case of a low or high peak between two measurements after a long period, this method may underestimate or overestimate total emissions. Models can therefore reduce these oversights (Giltrap et al., 2015).

Models enhance understanding of system's behaviour, thereby providing a means for extrapolation of experimental data base to other scenarios that are difficult to obtain in field experiments (Grabisch, 2003). This allows for evaluation of impacts of long term application of management practices in different sites. Models require a great deal of experience and training, perhaps one of the reasons why models have not been used widely in Kenya .

The most credible models are those that simulate processes involved throughout the course of crop growing season on a daily basis such as soil and climate conditions, crop growth processes and farmers' management strategies (Li et al., 2005). Such models have been developed including the Cropping Systems (CropSyst model) (Stockle et al., 1994), denitrification–decomposition (DNDC) (Li et al. 2000),

DAYCENT (Parton et al. 1998; Del Grosso et al. 2005), and Agricultural Production System Simulator (APSIM) (McCown et al., 1996) among others. All these models have been developed to serve as analytical tools to study the effect of climate, soils and management on cropping systems productivity and environment. These models take into account plant growth and soil biogeochemical processes which are difficult to study in the field. These processes are driven by availability of soil water and nutrients as well as biophysical conditions of the soil.

2.8.1 DAYCENT model

DAYCENT model is a daily time step process based model which has been used to simulate GHG emissions, soil carbon and nutrients in different parts of the world. Like any other mechanistic model, DAYCENT's reliability in estimating GHG depends on the accuracy of data at both parametization and calibration stages. DAYCENT has been used to model GHG in Maize and soybean among other crops (Del Grosso et al., 2009). This makes it possible to use it in simulating GHG emissions in this study. It has also been used to create the USA greenhouse gas emission inventories since 2005 (Del Grosso et al., 2010).

Initial soil conditions play an important role in modelling gas emissions, but data for these conditions are lacking for most of sub-Saharan soils. DAYCENT Model can reliably give estimates of initial soil conditions for systems where such data does not exist. This however is possible if accurate measured data are available for calibrating the model. Data on GHG emissions in sub-Saharan Africa is still limited, perhaps being the reason why modelling which is cheaper has not been widely used.

2.8.2 Data requirement for DAYCENT model

Weather data are required such as rainfall, minimum and maximum temperature, solar radiation, wind speed and relative humidity. Data from a local weather station should be used when modelling at plot level (Del Grosso et al., 2001). Crop information such as growth parameters are required to simulate crop growth, nutrient uptake and accumulation. Soil management aspects including cultivation, fertilizer application, irrigation, manure/ organic matter addition should also be included during model set up. Model Initialization requires initial C levels, but this is usually not available. Long term simulations of native vegetation (at least 1000 years) until C levels are at equilibrium are therefore carried out to set the initial soil carbon levels. The advantage of this is that the model is more sensitive to recent management with verifiable data sets.

2.8.3 Model Calibration

Biogeochemical model calibration process comprises of fixing constants to a model after comparison of the results it gives to those from the standard model (Simba et al., 2013). Although the model has about 1000 parameters, only a few need to be adjusted during calibration. These should be done starting with soil water content; a major controlling factor. The cumulative sum of daily transpiration, evaporation, runoff, rainfall intercept should be as close to precipitation. Crop yields and plant growth rates followed by soil organic C and N should then follow.

2.8.4 Model evaluation

Evaluation of model performance is important to do by comparing simulated and observed results. It is important to compare results of different models before ruling

out model results with low coefficient (Del Grosso et al., 2005). This is mainly because field data is usually limited, and models can simulate outputs such as N_2O from biogeological processes.

2.9 Crop yield and GHG emissions

Yield is an important factor when evaluating the success of any cropping system. For instance, Pelster et al. (2017) observed low emissions in western Kenya, although the study pointed out that due to the low yields, the yield scaled emission was high. With such kind of scenarios, African agriculture may contribute significantly to GHG emissions, especially where the area under agriculture is increased to cater for increased demand for food as driven by increasing population.

Most emission studies have been carried out in developed nations with almost homogenous cropping systems. In Africa and particularly in Kenya, smallholder farms dominate agriculture, and the complexity of the farming systems requires a different approach in estimation of GHG emissions. On the other hand productivity of farms in Kenya is generally low. As suggested by Pelster et al. (2017), it would be better to consider emissions alongside the crop yields. This was clearly shown by their study in western Kenya where emissions were low, probably due to low fertilizer applications and low biomass to contribute significant crop residues. Even though these low emissions look promising on the face, if estimated over a large area the overall emissions per unit of grain yield is high.

Maize is commonly intercropped with legumes throughout Eastern and Southern African region (Giller, 2001). This practice maximizes utilization of land, labour and attains higher land productivity. Intercropping cereals and legumes may increase C in

lower soil depths (Boddey et al., 2010), reduce runoff and erosion. Crop growth and final yield of an intercropping system are also closely related to the spread of roots which determines the uptake and utilization of water and other nutrients (Gao et al., 2010; Gitari et al., 2018).

Intercropping has also positive effect in reducing N_2O emissions. As observed by Senbayram et al. (2015) in a study in Göttingen, Germany, cumulative mean N_2O fluxes were 31% lower in the intercrop of wheat and faba bean than in soils planted with N-fertilized wheat. Similar observations were observed *i.e.* a lower N_2O emission rate when maize was intercropped with soybean in a semi-arid region in North China Plain (Shen et al., 2018). This reduction in emission was associated with a reduction in the rate of nitrification as soil water content decreased due to increased evapotranspiration rates. According to Pelster et al. (2017) and Clayton et al. (1997), the rate of N_2O emissions is enhanced at water content of between 60-80% water filled pore spaces. Sole maize cropping system, although practiced by small holder farmers, is majorly a large scale farmers practice. Where it is practiced in small scale, it is often in rotation with other crops such as legumes (beans, cowpeas), sorghum, sweet potato etc.

Crop rotation with legumes is considered a soil health improvement strategy in sub Saharan Africa where N is a limiting nutrient, and fertilizer use is still low. Legumes can fix appreciable amounts of N which can be used by subsequent crop. Ngome et al. (2011) observed an accumulation of 51–74 kg N ha^{-1} of which 52-63% was derived from the atmosphere after incorporating *Arachis pintoi* biomass and maize yields increased from 0.5 to 3 Mg ha^{-1}. While most studies attribute increased N_2O emissions to use of inorganic N fertilizers, Sommer et al. (2015) reported increased N_2O

emissions when maize was in rotation with *Tephrosia candida* in western Kenya. Interestingly, the maize yields obtained was not high enough to justify the high emissions of N_2O by the system. There is therefore a dire need to strike a balance between GHG mitigation and increasing yields.

2.10 Greenhouse gas intensity

Greenhouse gas emission intensity refers to the emission rate of a given gas relative to the intensity of a specific activity or product. In a cropping system this would mean the g of N_2O emission per kg of grain produced. Some farming systems have high GHG emission rates but when this is related to crop yield, the emission intensity is low. Such systems are much more environmentaly friendly than systems that produce low yield even though their emission levels are low. In such systems, to achieve the desired crop demand, larger farm sizes may be required and ultimately lead to more emissions per unit of crop yield. Further more demand for more land would translate to conversion of virgin land for agricultural use. Land use change is one of the detrimental process leading to climate change (Smith et al., 2014) through emissions of chemically and radiatively active gases (Houghton et al., 2012).

2.11 Literature summary and research gaps

Climate change is a reality and has greatly affected the productivity of agriculture due to erratic rainfall with prolonged dry periods within seasons (Nyawade et al., 2020). The first step in mitigating climate change lies in understanding the GHG emissions emanating from different sectors. In Kenya, agriculture is a major source of GHG emissions. of the major GHGs, N_2O is the most important due to its high global

warming potential. This is further complicated by the high dynamics of N, which is the major determinant of N_2O emission.

Mitigation of GHG gas emissions can be achieved through various strategies. Farming systems that enhance carbon sequestration while reducing emissions at the same are considered effective. Reduced tillage systems for example have a big mitigation potential, but the extent to which the different principles mitigate emissions under prevailing agro ecological conditions in Kenya are still not clear. The complex nature of smallholder farms in Kenya calls for detailed study on the effects of cropping systems on GHG emissions.

Soil carbon stocks in most Kenyan soils in different agro ecological zones have been conducted. Some studies have shown increasing SOC levels with addition of soil organic matter. Sommer et al. (2018) shows decreasing levels of SOC despite additional organic matter in western Kenya. Soil carbon stocks and carbon balance has not been conducted under different smallholder maize cropping systems. Such a relationship can explain the losses or increases of SOC recorded in various studies. Further this can shed more light on emission mitigation intervention.

Farming systems that technically achieve low GHG emissions at the expense of crop yield may not be adopted by farmers since the core business of any farmer is to increase production (Linquist et al., 2012, Sommer et al., 2015). A consideration of emission intensity of the systems may prove a better way of deciding on the production systems to promote and adopt. In estimating GHG emissions for different crops, it would be preferable to consider the land under specific cropping system as pointed out in IPCC (2006).

There are many studies showing the effect of different management practices on yield of maize. Recently several studies have measured GHG in maize production systems. Most of these studies however have not related the emissions and yield. Sommer et al. (2015) shows there was no advantage of intensifying soil health with high quality green manure (*Tephrosia candida*) in mitigating emissions since the yield was not increased proportionaly to N_2O increase, resulting in a higher N_2O intensity of the system in Siaya, Kenya.

Reduction of emissions not a major concern of the farmer but productivity and economic growth and therefore any strategy should aim at mitigating GHG emissions while at the same time increasing yields. Relationship between emissions and major crops not determined to inform policy on appropriate mitigation strategies acceptable by the farmers. In Siaya county the effect of conservation agriculture on maize yield and N_2O emissions has not been done concurrently.

Controlled release urea (CRU) fertilizer has a great potential in mitigating nitrous oxide emissions as well as enhancing N use efficiency by crops. CRU fertilizers have been used in different soils to reduce GHG emissions. However there exists a knowledge gap in the potential of CRU to reduce N_2O emissions in Kenya. Whether they are suitable to mitigate emissions in Kenyan soils compared to conventional urea fertilizers is yet to be decided.

The contrasting results of the effect of CRU in reducing N_2O emissions is a clear indication that it is not always guaranteed thet they will reduce emissions, and hence there is need to investigate their effect on N_2O emissions and yield in Kenya. This study

sort to investigate the potential of using CRU in reducing N_2O emissions in maize based cropping system in western Kenya.

Models are reliable tools in understanding effects of management practices on soil, yield which would otherise take many years of research to get results. Models therefore shorten the period of obtaining results, allowing room for implementation of new technologies. They are easy to use and when calibrated with right data set, they are reliable.

DAYCENT model has been used to model GHG in maize and soybean in USA and develop the emission inventories (Del Grosso et al., 2001). The model has also been used in many other areas successfully and can therefore be used in Kenya. DAYCENT model has the potential to simulate carbon stocks in pre-agricultural period. In Kenya and especially in maize production systems, GHG data is limited. This is mainly due to the high costs and complexity of field GHG measurements.

According to the protocal, GHG data collected intensively during the onset of rains and during major management operations such as fertilizer application of irrigation episodes is encouraged. Additionally, GHG emissions should also be captured during the time between seasons. This kind of data is currently lacking for the system, and simulations based on such data may not be reliable. Sommer et al. (2015) showed good simulation of N_2O using Cropsyst model, but incidentally where the model had predicted higher levels of emissions, the study lacked observed data for those periods.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Introduction

This chapter gives information on the materials and methods used to achieve the study objectives. It gives a brief description of the study area, materials used and their sources as well as a detailed explanation of the field, laboratory and statistical procedures followed. The field work of this study was authorized by the National Commision for Science, Technology and Innovation (NACOSTI) (Appendix XIII).

3.2 Study site

The study was carried out in Siaya County (Figure 3.1) The area lies at 0° 7' N and 34° 24' E, and at an altitude of 1420 metres above sea level. The area has as a sub-humid climate with a mean annual temperature of 22.5 °C and rainfall of 1,200 to 2,206 mm (avg. 1727 mm) distributed over two rainy seasons.

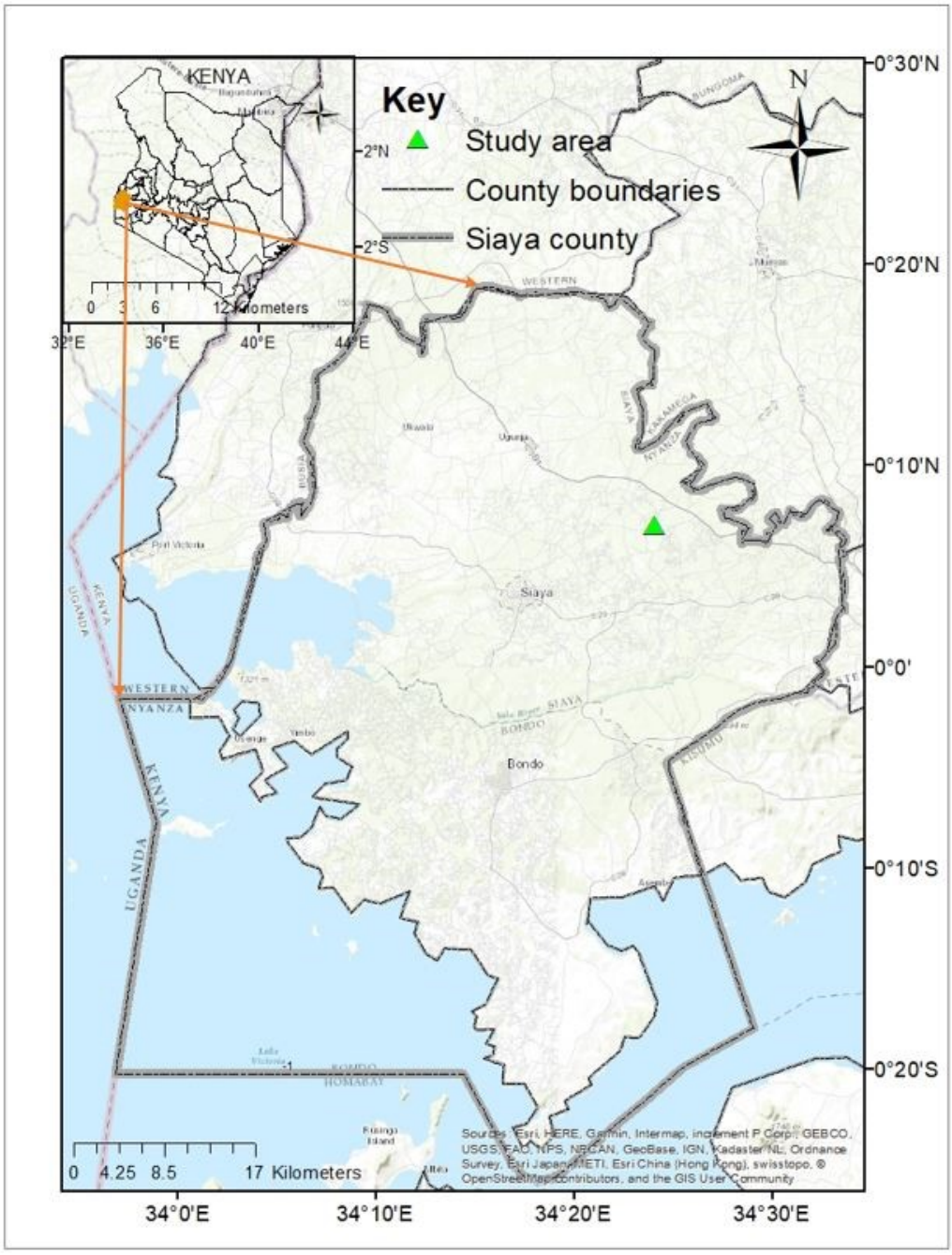

Figure 3.1: Map showing the physical location of the study area in Siaya County (source: Author, 2020)

The long rains starts in March through June while the short rains occur between September and December (Figure 3.2).

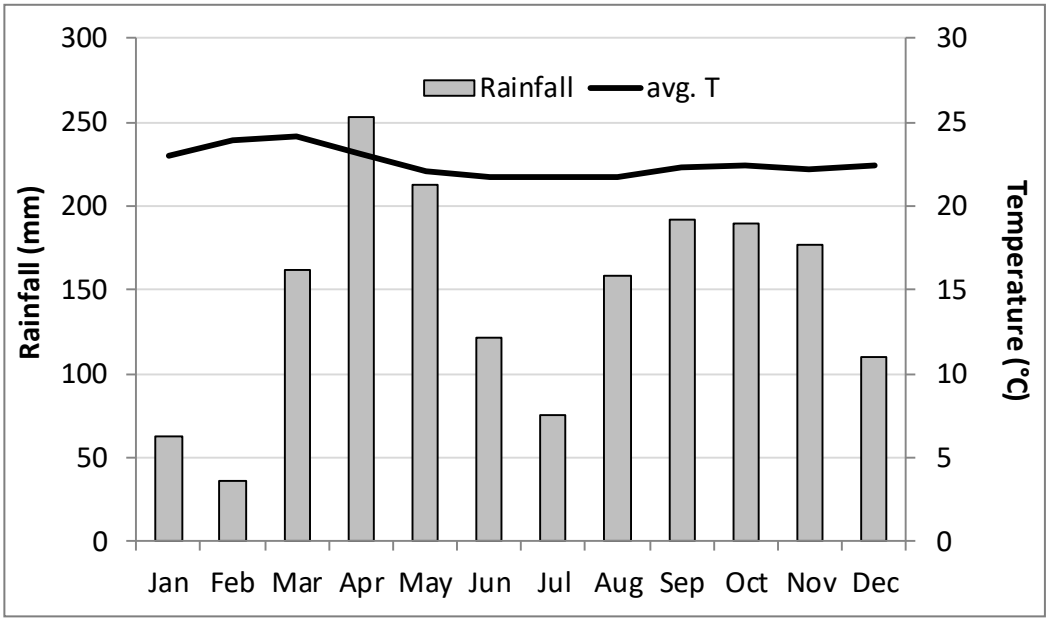

Figure 3.2: Average monthly rainfall and temperature for the study area (averaged for 1997-2016)

The study was carried out at International Centre for Tropical Agriculture (CIAT)'s long term maize trial which was established in 2003. The trialwas established to study the long term effects of reduced tillage, crop residue retention and incoporation of a legume (Soybean) in maize cropping systems. The soils in the area are generally acidic (pH between 4.9 and 5.5) ferralsols with low CEC, high aluminium saturation and with low organic matter content. Initial soil pH, C and N are shown in Appendix I.

Table 3. 1: General soil characteristis of the study area

Parameter	**Values**
Soil type	Oxidic Ferralsol
Sand: silt: clay ratio	15:21:64
pH (water)	5.08 (±0.27)
Extractable potassium (mg 100 g^{-1})	0.1 (±0.04)
Phosphorous (mg Pkg^{-1})	2.99 (±2.09)
Calcium (cmolc kg^{-1})	4.69 (±0.33)
Magnesium (cmolc kg^{-1})	1.68 (±0.13)
Iron (g kg^{-1}) oxalate extractable	2.6 (±0.04)
Aluminium (g kg^{-1}) 0xalate extractable	1.3 (±0.01)
Total SOC (%)	1.35 (±0.06)
Total Nitrogen (%)	0.15 (±0.02)

Source: Kihara, (2009)

According to the Kenya Population and Housing Census (KPHC) done in 2019, the population of Siaya County was estimated at 993,183 with an estimated growth increase of about 1.7% per annum. The study area is dominated by small holder farmers with land sizes less than 3ha. Farming is the main economic activity with maize (*Zea mays.* L) as the dominant crop grown alongside other crops such as beans (*Phaseolus vulgaris*), cassava (*esculenta*) and sorghum (*Sorghum bicolar*). Recently, soya bean (*Glycine max*) is gaining popularity in the region as a legume for its higher market value. This has come as demand for soybean as a raw materaila for animal feed and its higher nutritional properties. In addition, it has a higher rate of fixing nitrogen compared to common bean.

3.3 Experimental design and field layout

The experiment was laid out as a randomised complete block design with tillage as the main plot replicated four times. Details of the full trial are described in (Kihara, 2009). In brief, the on-farm trial compares conservation agricutulture with conventional agriculture. Treatments include crop residue management (retention or removal), fertilizer (N, P, K) management (application rates and timing) and different cropping systems of either continous maize, maize-soybean intercrop or rotation. For purposes of quantifying GHG emissions, this study selected three treatments namely: reduced tillage (ZT) maize-soybean rotation (M-S) with normal urea (NU) = (ZT M-S NU), reduced tillage (ZT) maize-soybean rotation (M-S) with controlled release urea (CRU) = (ZT M-S CRU), reduced tillage (ZT) maize /soybean intercrop (M/S) without urea = (ZT M/S) and a fourth treatment conventional tillage (CT) maize –soybean rotation (M-S) with normal urea (NU) = (CT M-S NU). CT M-S NU acted as the control.

3.4 Agronomic management of the experimental plots

Land preparation was done using hand held tools. Conventional tillage involved digging the soil up to 10-15 cm depth while reduced tilage was restricted to surface scratching to remove weeds up to about 3 cm depth. Under ZT system, maize stover (chopped to about 10cm) was applied one week before planting on the soil surface at the rate of 2t ha $^{-1}$ every season. The stover was sourced from the previous season in the treatments with soybean-maize rotation. (to be noted here that some of the treatments in the full trial had soybean in the long rains followed by short rains, and in this study the treatments selected had maize in the long rains and soybean in the short rains). Soybean residues were left in the field after harvest.

Two maize seeds, variety DH4 were planted at a spacing of 75 cm x 25 cm, and thinned to one per hill after germination. This variety was selected for its quick growth. Soybean (*Glycine max L.*) Merr; variety TGX 1448-2E) seeds were drilled at a spacing of 75 cm or drilled between maize rows (for the intercrop) at higher seeding rate and then thinned to a spacing of 5 cm two weeks after germination. This soybean variety was selected for its promiscous growth which produces a lot of biomass and encourages more biological nitrogen fixation. Planting was done on 5th April 2016 and 9th September for the long and short rainy season respectively.

Phosphorous (P) which was suplied as triple super phosphate (46% P_2O_5) and potassium (K) as muriate of potash (were applied to all treatments at the rate of 60 kg ha $^{-1}$ each at planting. The fertilizer was incorporated into soil by hand hoeing. N was supplied at the rate of 60 kg N ha $^{-1}$. The regular urea (46% N) was split at 1/3 during planting and 2/3 when maize reached knee height. The full dose of the controlled release urea (43% N) was applied once at planting.

3.5 Soil sampling and analysis

At the start of the experiment, soil available N was determined in the 0-10cm and 0-25cm depth. (Soil depth upto 25cm is assumed to be the one actively disturbed by cultivation and with high microbial activity hence the major source of GHG emissions (IPCC, 2006). During the experiment, soil was sampled at depths of 0 to 10 cm, 10 to 25 cm and 25 to 50 cm 4 and 6 times in the long and short rainy seasons respectively for analysis of N mineralization (NH_4^+ and NO_3^-). The sampling depth upto to 50 cm was to determine the downward movement of N.

During sampling, five samples of soil cores were randomly sampled from each depth per plot and mixed thoroughly. Subsamples weighing 100 g were placed in sampling bags and stored at 4 ^{o}C and transported to the laboratory at IlRI using standard commercial ice box fitted with ive cubes. Fresh soil (10 g) was mixed with 50 m of 0.5 K_2SO_4 and shaken for 60 minutes at 150 rpm on the Edmund Buhler GmbH SM-30 Lateral Shaker at room temperature. The samples were then centrifuged (Hettich Centrifuge, Tullingen, Germany) for 10 min at 3,000 rpm, after which the supernatant was passed through a 110 mm Whatman ™ filter (No. 42). The extract was frozen for analysis at a later date. Soil concentrations of nitrate (NO_3^-) and ammonium (NH_4^+) were determined using an elemental macro-analyser (Elementar Vario Max Cube).

For soil carbon analysis, soil was collected once in the 0-15 cm depth in August 2016 (after harvesting maize). Soil was collected from each treartment plot in randomly and thouroughly mixed. Soil subsamples of 100 g per plot were taken to Nairobi ILRI laboratory for analysis. Soil samples were oven dried at ≤ 40 $^{\circ}$C for 48 hours and ground to a fine powder using the soil mill (Retsch ball mill, Haan,Germany). The ground samples were sieved through a 2 mm mesh and analysed for soil carbon using an elemental C:N analyser (Elementar Vario Max Cube) at CIAT laboratories in Nairobi.

Computation of soil carbon balances was done based on the percentage of carbon returned to the soil as crop residues. For the ZT systems this included maize stover that was added every season, soybean stover and the estimated maize stumps afer harvesting. For the CT system it included the soybean stover and maize stumps left after harvesting.

Soil bulk density was determined from 0-50 cm depth through the core ring method (Blake & Hartge, 1986) and calculated according to the method by Okalebo et al. (2002).

$$\text{Bulk density } (g\ cm^{-3}) = \frac{(wt1 - wt2)}{V}$$

Where by *wt*1 is the initial moist weight (g) of soil after sampling, *wt*2 is the final weight (g) of soil after drying in an oven at 105 °C for 2 days and V is the volume (cm3) of a core ring metal cylinder

Soil temperature and moisture content were measured every time during gas sampling using a hand held real-time sensor (ProCheck**). The sensor was placed near each chamber. Soil moisture was expressed as the percentage of water filled pore spaces (WFPS %) calculated according to Liu et al (2007) as shown in equation 1.

$$WFPS = \frac{\text{Soil water content}(\%) \times \text{Soil bulk density}}{1 - \frac{\text{Soil bulk density}}{2.65}} \times 1(\quad (1)$$

Where WFPS= water field pore space

Soil pH was determined at the start of the experiment. Soil samples were collected from 5cores upto 25cm and thourougly mixed. A sub-sample was then obtained and oven dried at 40°C for 72 hours. The dry soil was then ground using a ballmill (Retschball mill, Haan, Germany). It was then mixed wih water in the ration of 1:2 (soil:water). Soil pH was determined from the suspension using a glass probe pH meter (Crison Instruments, Barcelona, Spain).

3.6 Plant data sampling and analysis

Aboveground biomass of maize was obtained by destructive sampling at 4 and 8 weeks after planting and also at harvest (physiological maturity). Six maize plants for this purpose was sampled randomly from the middle of treatment plots (to avoid edge effects). Soybean plants were cut at 4 weeks after planting and later every two weeks from a quadrat measuring 60 cm x 60 cm. Fresh and dry biomass weight of the plant samples were determined. Plant samples of both soybean and maize were dried, ground into a fine powder using a hammer mill (IKA mills, MF 10.2, Willington, N.C., USA). Carbon and Nitrogen concentrations in the dry plant samples were determined using the same C:N analyzer used for soil carbon analysis.

Leaf area index was measured using a ceptometer (Accupar®) at different times during crop growth. For maize in the long rainy season this was done at 3, 6 and 9 weeks after planting. For soybean it was done at 3, 6,9,11 and 13 weeks after planting.

Maize grain and stover yield was determined from a 2 m×1.2 m harvest area at physiological maturity stage and adjusted to 13% moisture content. Soybean grain and stover yield was determined at physiological maturity from a 60 cm× 60 cm quadrat.

3. 7 Greenhouse gases measurement

3.7.1 Gas sampling and analysis

Measurement of greenhouse gas emissions (GHG) was done by manual sampling using plastic static chambers following the CCAFS SAMPLES research protocol (Rosentock et al., 2013). The chambers that measured 0.37 m x 0.55 m x 0.25 m were mounted to frames which were inserted at 5cm in the soil one week before the

first sampling date. In each treatment plot three chambers were arranged in a diagonal manner. The chambers were placed such that at least one maize plant fell within the chamber. GHG measurements were done in 2-3 days intervals early in the season and at least once per week later-on in the season.

For the long rainy season gas sampling was done at 3, 5, 7, 10, 14, 18, 22, 29, 35, 44, 53, 66, 77, 92 and 103 days after planting date while in the short rainy season of 2016 sampling was done at 7days before planting and thereafter at 4, 6, 12, 16, 19, 25, 31, 38, 47, 55, 62, 69, 76, 90, 99, 133, 146 days after planting. During sampling, three gas samples were pooled together from each of the chambers per treatment at 0, 15, 30 and 45 minutes after chamber closure. This helped to check linearity of the gas accumulation in the chamber headspace (Arias-Navarro et al., 2013).

From each plot, 20 ml gas was withdrawn from each of the three chambers and mixed thoroughly in a 60 ml syringe fitted with a cock. 30 ml of the mixture was then emptied in a 30 ml glass vial closed with a rubber septum and flushed out by inserting a needle through the septum. The remaining 30 ml was emptied in the vial and transported to the laboratory for analysis within one week. Gas sampling was usually carried out between 9.00 am and 2.00 pm for consistency. This time represented the time of maximum microbial and respiratory activity of soil in the soil and plant roots. GHG CO_2 CH_4 and N_2O concentrations were determined through gas chromatography at International Livestock Research Institute (ILRI) laboratory in Nairobi.

3.7.2 GHG flux calculations

Changes in gas concentration rates in the chamber headspace within the 45 minutes after chamber closed were used to calculate the daily fluxes. Calculating gas fluxes followed the formula shown in equation 2.

$$F = \frac{\Delta C * M * p * h}{R * T} \quad (2)$$

"where F is the gas flux (μg $N/m^2/min$),Δ c (ppb/min) is the slope of the linear regression fitted to the increase in gas volumetric concentration measured over 45 minutes, M is the molar weight of the gas (kg/kmol), p is the atmospheric air pressure (Pa) measured with a barometer at day of sampling, h is the total chamber height (m), R is the ideal gas constant equal 0.08314 (m^3 Pa/kmol/K) and T is the air temperature (K) inside the chamber" (Sommer et al., 2015). Cumulative fluxes were calculated by trapezoidal integration between two consecutive sampling dates (Pelster et al., 2017). N_2O intensities were calculated as grams (g) of N_2O emitted per kilogram (kg) of maize and soybean grain yield per year.

3.8 Modelling GHG emissions

DAYCENT Model is a mechanistic model for simulating terrestrial ecosystems giving daily outputs of plant productivity; trace gases, soil organic matter among other land based parameters (Del Grosso et al., 2001). It has been widely used in modeling both natural and managed land. The model relies on data sets that are stored and calculated in the different submodels (Appendix X) N_2O simulations by DAYCENT are derived from nitrification and denitrification processes in the N gas submodel.

3.8.1 Meteorological data

Weather data was obtained from CIAT's weather station at Nyabeda which had been recorded at hourly intervals since 2013 for rainfall, minimum and maximum temperatures. Missing values of rainfall and temperature data, as well as solar radiation, humidity and wind speed data which was required by DAYCENT was supplemented from global NASA-POWER Agroclimatology database (http://power.larc.nasa.gov). Atmospheric pressure was taken every time during gas sampling using a barometer. Temperature within the chamber was taken at 0 and 45minutes after the chambers were closed during each gas sampling episode.

3. 8. 2 Other data sets

A complete list of data required by the model are summarised in table 3.2. The data was mainly obtained during the long term trial including the observation period for GHG emissions in 2016.

3.8.3 Model parametazation and calibration

Calibration of DAYCENT model was done using data from the long term trial and folowing the steps outlined in appendix XI. The model was then used to simulate 14 years for the two major cropping systems tested in this study namely ZT M-S NU and CT M-S NU.

Table 3. 2: Summary of the input data required to run DAYCENT Model

File	Parameter
Location	Latitude, Longitude, Altitude
Soil	pH, Permanent wilting point, Field capacity, Bulk density, Soil texture, C, N,
Management	Fertilizer (application date, amount, source - organic and inorganic, and application mode Tillage (reduced, conventional- land preparation dates, weeding) Residue (dates of application, amount, N content)
Crop	Species, variety, planting date, physiological maturity, harvesting date, percentage of stover harvested
Weather	Rainfall, solar radiation, air temperature, humidity and wind speed

3.8.4 Spin-up runs to estimate initial soil carbon levels

Initial soil status was obtained by simulating land use for the past 3500 years. It was assumed that the site was under evergreen tropical forest until 1950 when it was converted to agricultural land primarily under maize and sorghum.

Between 1950 and 1990 a maize-sorghum rotation system without fertilizer inputs was simulated. This was assumed to be the period when agricultural practices started in the study area. Between 1991 up to 2002 maize with 100 kg/ha DAP, was simulated to represent the common farmers practice in the region, in terms of fertilizer use.

3.8.5 Simulation of emissions at CT1

Simulation of GHG emissions between 2003-2016 was done using data from CT1 long term maize trial. Cropping systems were maize-soybean rotation with 60 kg/ha N application under conservation or conventional tillage. More details on the long term experiment can be found in Sommer et al. (2015).

3.8.6 Model vailidation

Validation of the simulated data was done by calculating the root square mean error (RMSE) and relative RMSE (RRMSE). A coefficient of efficiencey, modified from Wilmott index of agreement (Wilmott et al., 1982) was used to determine similarity of simulated and measured emission values. The closer the E value is to 1, the better the model fit reliability of simulated gas emissions.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(observed_i - simulated_i)^2}{n}}$$

$$RRMSE = \frac{RMSE}{Average(observed)} * 100$$

$$E = 1 - \frac{\sum_{i=1}^{n}|observed_i - simulated_i|}{\sum_{i=1}^{n}|observed_i - Average_{obs}|}$$

3.9 Statistical analysis

To reduce uncertainties commonly associated with static chamber measurements, all fluxes where the corresponding R^2 of the linear regression of CO_2 increased over time above 0.9 were considered reliable based on the methodology (Appendix III). A flux detection limit through this method was calculated after Parkin et al. (2012). Data was checked for normality using Shapiro-Wilktest (Shapiro

&Wilk,1965). Data was subjected to Analysis of variance (ANOVA) using GenStat version 15. Posthoc analysis was done using Fishers protected LSD test for mean separation. Probability was tested at 5 % or 1 % . Pearson correlation was used to determine the relationship between N_2O emission and NO_3^+ and SOC; grain and stover yield; C output and input.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Introduction

This chapter highlights the results of the measured parameters aligned to the study objectives. Section 4.2 and 4.3 presents auxiliary data. Section 4.4 on nitrogen mineralization and 4.5 on Nitrous oxide emission presents data for objective 1. Section 4.6 to 4.8 presents results for objective 2 on soil carbon, carbon dioxide and methane emissions. Section 4.9 presents results on crop growth and emission intensities aligned with objective 3. Section 4.10 presents data on DAYCENT modeling, which is the fourth objective.

4.2 Rainfall and temperature

Rainfall was mainly distributed in two major seasons (Figure 4.1) with the long rains running from April through July while the short rains occurred from September through December). There was a prolonged period of days with no rainfall in the month of June and July during the long rainy season. Temperature ranged between 15 $^{\circ}$C (minimum) and 33 $^{\circ}$C (maximum) with minimal fluctuations throughout the year.

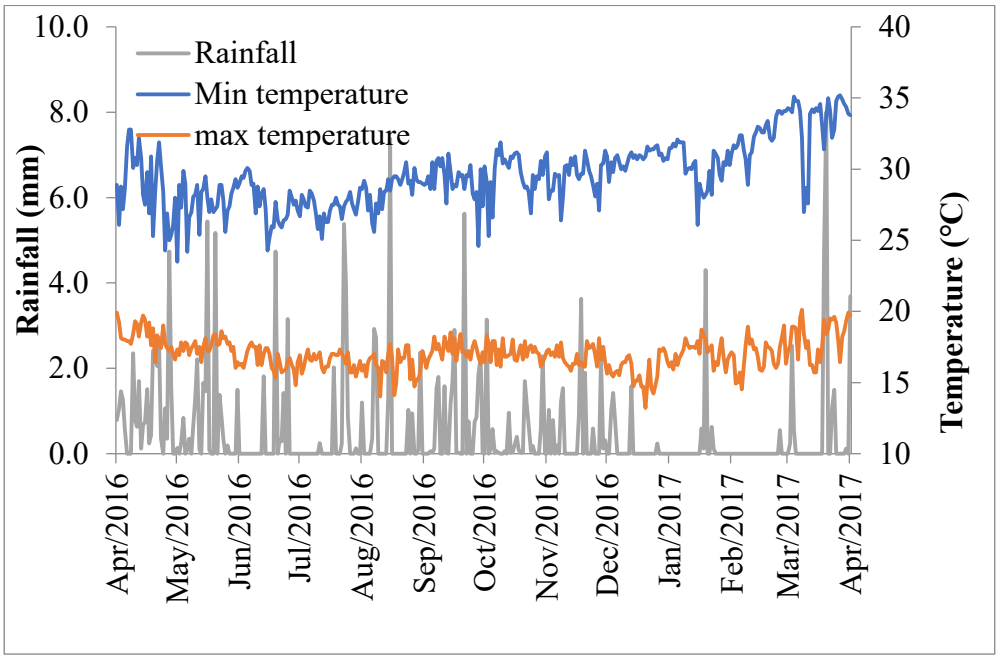

Figure 4.1: Daily rainfall, maximum and minimum temperatures for Nyabeda in 2016/2017

4.3 Soil moisture content

Soil moisture levels were not significantly different among treatments in either season at 5 % probability level at all sampling times. Soil moisture content in the long rainy season was above 60 % WFPS between the month of April and May (Figure 4.2). From June the soil moisture started to decline to about 20 % WFPS in July. In the short rainy season, soil moisture content was about 40 % WPFS at the begining of September, but increased towards October to more than 60 % (Figure 4.2). In mid-November however there was a small peak but it declined shortly there after to about 30 % WFPS).

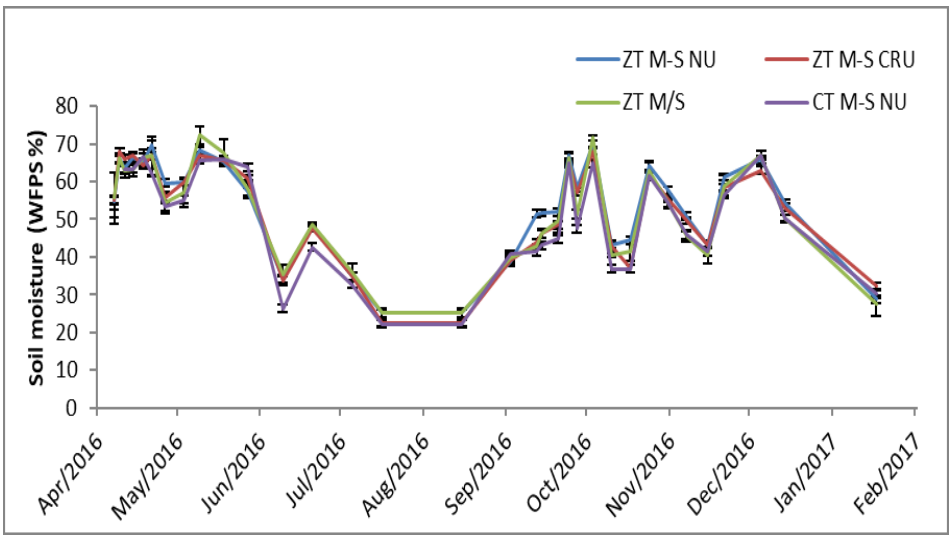

Figure 4.2: Soil moisture content (WFPS %) in Nyabeda, 2016/2017. Bars indicate standard error of means

Legend: ZT M-S NU (reduced tilage with residues+maize-soybean rotation + normal urea), ZT M-S CRU (reduced tillage with residues+maize soybean-rotation+controlled release urea), ZT M/S (reduced tillage with residues+maize soybean intercrop without urea), CT M-S NU (conventional tillage without resisdues+maize-soybean rotation +normal urea

The non-significant differences observed in soil moisture among treatments were inconsistent with observations of Huang et al. (2017) who observed lower soil moisture in intercropped system than single crops. In their study the reduction in soil moisture was attributed to competition between crops of different species. The observations of this study were contrally to that of Dou & Hons, (2006) who observed higher moisture in conservation agriculture , and attributed it to less soil disturbance and soil cover by crop residues that reduce evapotranspiration rate

Not surprisingl, soil moisture content was higher in the begining of either season. This coincided with higher rainfall recorded at the beginning of the seasons in April asnd September for the long and short rains respectively.

4.4 Soil mineral nitrogen dynamics

4.4.1 Nitrate concentration

In the short rainy season, NO_3^- concentration in the 0-10 cm depth was not significantly different across treatments at 3 and 13 WAP. However, NO_3^- concentration was significantly lower for ZT M/S between 6 and 9 WAP at 1%.probability level (Table 4.1). All the other three treatments did not record significant differences among them. For the same depth (0-10 cm), ZT M/S showed significantly lower NO_3^- than other treatments ($p < 0.001$) at 11 WAP, CT M-S NU showed significantly lower NO_3^- than both ZT M-S NU and ZT M-S CRU, but these two had no significant differences.

In the 10-25 cm depth, CT M-S NU had significantly higher NO_3 concentrations than ZT M/S and ZT M-S NU but not ZT M-S CRU at 3 WAP ($p = 0.005$). At 6 WAP, ZT M/S showed significantly lower ($p = 0.01$) NO_3^- concentration compared to the other treatments. At 9 WAP, ZT M/S showed significantly lower NO_3^- than other treatments ($p < 0.001$). CT M-S NU had significantly higer concentration than ZT M-S CRU but not ZT M-S NU. At 11 WAP, ZT M/S showed significantly lower ($p = 0.001$) NO_3^- than other treatments. All other treatments at 11WAP did not show significantly different NO_3^- concentrations.

Table 4. 1: Concentration of nitrate at different weeks after planting (WAP) during 2016 short rains at CIAT's long term trial in Siaya County

Treatment	Concentration of nitrate-N (mg kg^{-1})				
	3 WAP	6 WAP	9 WAP	11 WAP	13 WAP
			Depth (0-10 cm)		
ZT M-S NU	14.4	13.0[a]	15.0[a]	23.3[a]	6.0
ZT M-S CRU	17.8	12.6[a]	13.0[a]	22.0[a]	8.2
ZT M/S	11.0	4.4[b]	3.8[b]	4.1[c]	1.9
CT M-S NU	20.5	16.7[a]	16.8[a]	9.8[b]	5.4
P value	0.5	**0.001**	**<0.001**	**<0.001**	0.1
			Depth (10-25 cm)		
ZT M-S NU	7.7[c]	13.2[a]	9.3[ab]	11.7[a]	10.0[a]
ZT M-S CRU	13.5[ab]	10.5[a]	8.6[b]	10.5[a]	11.5[a]
ZT M/S	10.5[bc]	4.7[b]	3.0[c]	4.8[b]	2.2[b]
CT M-S NU	14.6[a]	15.7[a]	11.3[a]	11.4[a]	4.9[b]
P value	**0.005**	**0.01**	**<0.001**	**0.001**	**<0.001**
			Depth (25-50 cm)		
ZT M-S NU	6.2	7.2[b]	4.1[c]	8.3[b]	4.5[a]
ZT M-S CRU	7.0	6.4[b]	15.1[ab]	7.2[b]	5.4[a]
ZT M/S	5.7	4.3[c]	6.8[bc]	3.7[c]	1.2[b]
CT M-S NU	8.6	9.3[a]	16.8[a]	10.9[a]	5.4[a]
P value	0.15	**<0.001**	**0.02**	**<0.001**	**0.003**

Means within a column followed by the same letter are not significantly diffferent ($P<0.05$)

Legend: WAP (weeks after planting), ZT M-S NU (reduced tilage, maize soybean rotationw with normal urea), ZT M-S CRU (reduced tillage, maize soybean rotation with controlled release urea), ZT M/S (reduced tillage, maize soybean intercrop without urea), CT M-S NU (conventional tillage, maize soybean rotation with normal urea.

At 13 WAP, both ZT M/S and CT M-S NU had significantly low NO_3^- concentrations, and these were significantly lower than that of ZT M-S NU and ZT M-S CRU ($p < 0.001$) in the 0-10 cm depth.

In the 25-50 cm depth, all tretments did not show significant differences in NO_3^- at 5 % probability level at 3 WAP. At 6 and 11 WAP, CT M-S NU showed significantly

higher NO_3^- than other treatments. ZT M-S NU and ZT M-S CRU had no significant difference between them but they were significantly higher than ZT M/S ($p < 0.001$). At 9 WAP, ZT M-S NU had significantly lower NO_3^- concentration than ZT M-S CRU and CT M-S NU but similar with ZT M/S ($p = 0.02$). At 13 WAP ZT M/S had significantly lower NO_3^- compared to the other treatment which did not show significant difference among them ($p = 0.003$)

The decrease in nitrate concentrations as the season progressed could be attributed to plant uptake of N (Fierer & Schimel, 2002) and downward movement in the soil profile as reported by Giller et al. (2011) who attributed high accumulation of nitrate in lower soil layers in western Kenya to downward movement of nitrate. This leaching process of N in clay soils has also been reported by Kimetu et al. (2007) and it is particularly common under conventional tillage systems (Randall & Iragavarapu, 1995).

4.4.2 Ammonium concentration

In the 0-10 cm depth, NH_4^+ concentrations were not significantly different across treatments at all sampling times at 5 % probability level (Table 4.2). In the 10-25 cm depth, NH_4^+ concentration was significantly higher for ZT M/S than ZT M-S NU and CT M-S NU but not ZT M-S CRU ($p = 0.016$). CT M-S NU, ZT M-S CRU and ZT M-S NU did not show significantly different NH_4^+ concentrations from each other. At 6 WAP, ZT M/S showed signifcantly higher NH_4^+ concentration than other treatments which were not significantly different among them ($p = 0.02$). Treatments did not show significant differences between 9 and 13 WAP at 5 % probability level in this depth. In

the 25-50 cm depth, treatments did not show significant differences among them in the season at 5% probability level.

Table 4. 2: Concentration of ammonium at different weeks after planting (WAP) during 2016 short rainy season in Nyabeda, Siaya County

Treatment	Concentration of ammonium-N (mg kg^{-1})				
	3 WAP	6 WAP	9 WAP	11 WAP	13 WAP
			Depth (0-10 cm)		
ZT M-S NU	1.3	1.4	1.2	3.5	2.6
ZT M-S CRU	1.5	1.1	1.1	3.3	1.6
ZT M/S	1.2	1.7	1.6	3.1	1.7
CT M-S NU	1.3	0.6	0.8	4.4	2.5
P value	0.8	0.12	0.6	0.5	0.2
			Depth (10-25 cm)		
ZT M-S NU	0.8^{b}	1.0^{b}	1.2	4.0	1.5
ZT M-S CRU	1.3^{ab}	1.3^{b}	0.9	3.9	1.4
ZT M/S	2.0^{a}	2.2^{a}	1.5	3.4	1.9
CT M-S NU	0.8^{b}	1.5^{b}	0.8	4.3	1.9
P value	**0.016**	**0.02**	0.07	0.7	0.3
			Depth (25-50 cm)		
ZT M-S NU	1.4	1.6	1.7	3.2	2.0
ZT M-S CRU	1.2	1.4	0.8	4.0	2.3
ZT M/S	1.6	1.8	1.3	5.3	2.0
CT M-S NU	1.2	1.3	0.6	4.9	2.4
P value	0.9	0.50	0.3	0.4	0.8

Means within a column followed by the same letter are not significantly difffernt at 5 % probability level.

Legend: WAP (weeks after planting), ZT M-S NU (reduced tilage, maize soybean rotationw with normal urea), ZT M-S CRU (reduced tillage, maize soybean rotation with controlled release urea), ZT M/S (reduced tillage, maize soybean intercrop without urea), CT M-S NU (conventional tillage, maize soybean rotation with normal urea.

The observed higher nitrate than ammonia could have resulted from the constant conversion of ammonium to nitrate. The process could have been favoured by the mostly moist soil conditions during the experiment, similar to the observations of Vanlauwe et al. (2001).

The observed decline in ammonium concentrations as the seasons progressed could be attributed to its conversion to nitrate by micro-organisms (Magana, 2016; Mikkelsen, 2009; Berber et al., 1992). This observation was evident in the 6^{th} and 9^{th} WAP. The decline could also be attributed to volatilization of ammonia (NH_3) due to hydrolysation of urea (Mikkelsen, 2009). Volatilization of NH_3 is usually associated with soils with high alkalinity, but in this situation it could have resulted from the temporally rise in pH when urea hydrolysed to form bicarbonate (Mikkelsen. 2009). A similar trend where ammonium declined following application of controlled release urea fertilizers in a black cotton soil in China was observed by Tong et al. (2017). The significantly higher NH_4^+ observed in ZT M/S could have resulted from a higher buffering effect due to extra crop residue in this treatment.

4.5 Nitrous oxide (N_2O) emissions

4.5.1 Daily N_2O emissions

In the long rainy season, N_2O emissions had a similar pattern for all the treatments (Figure 4.3a). Emissions were low (1.5-3 g N_2O-N ha^{-1} d^{-1}) in the first three days after planting but increased in the third week after planting to 26 g N_2O -N ha^{-1} d^{-1} in ZT M-S CRU

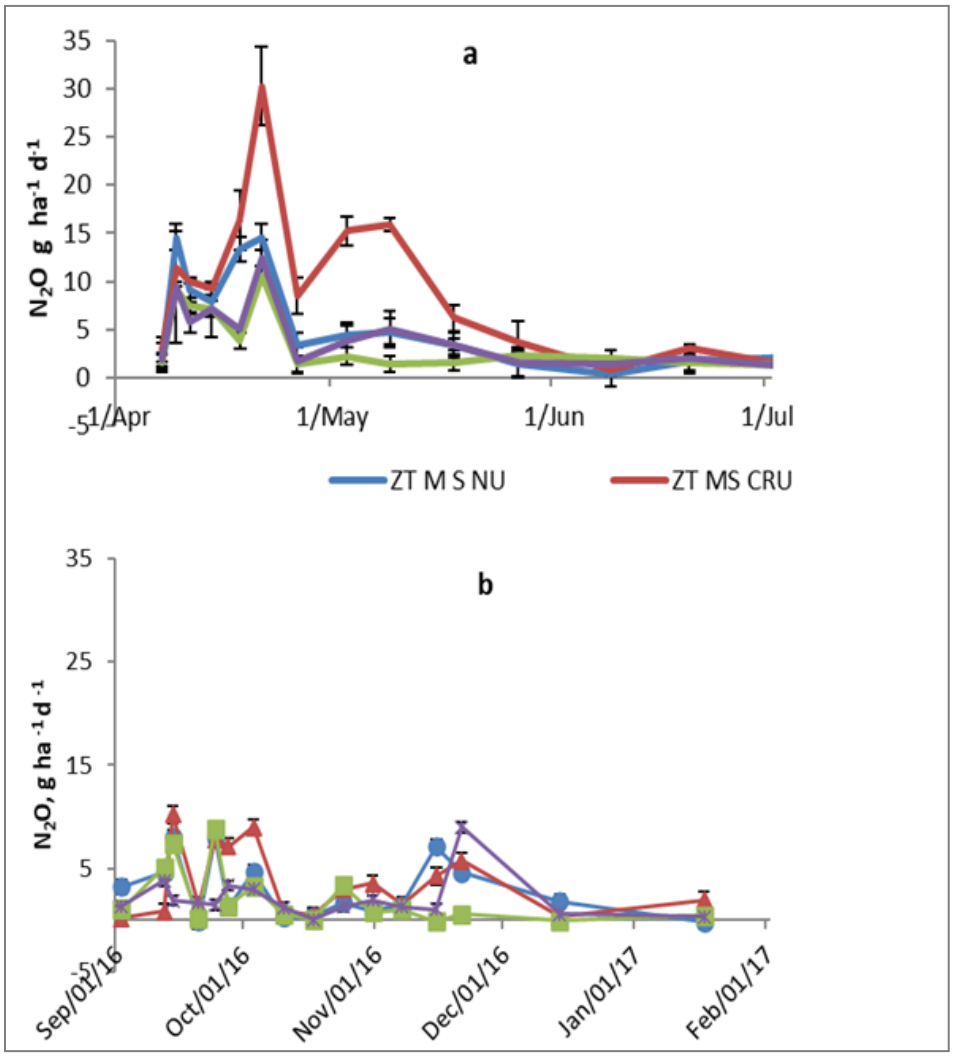

Figure 4.3*:* Nitrous oxide (N_2O) in Nyabeda during the 2016 long rains (a) and short rains (b). Bars indicate standard deviation of means.

Legend: ZT M-S NU (reduced tilage, maize soybean rotationw with normal urea), ZT M-S CRU (reduced tillage, maize soybean rotation with controlled release urea), ZT M/S (reduced tillage, maize soybean intercrop without urea), CT M-S NU (conventional tillage, maize soybean rotation with normal urea.

Maximum emissions during this season occurred between mid-April and mid-May while the lowest emissions were observed in June where some rates were slightly negative for ZT M-S NU and ZT M-S CRU treatments.

In the third week after planting ZT M/S had significantly lower emissions ($p=0.01$) than the other treatments. From the fourth to the seventh week after planting ZT M-S CRU had significantly higher fluxes than the other treatments ($p=0.003$). From the 8th week after planting the fluxes were not significantly different across all the treatments and they continued to decline to as low as 0.5 g N_2O -N ha^{-1} d^{-1} which was observed for CT M-S NU treatment.

In the short rainy season, fluxes ranged between -0.2 and 10 g N_2O -N ha^{-1} d^{-1} (Figure 4.3 b). Irrespective of the treatment, fluxes had two small peaks between mid-September and early October and later in mid-November. There were no significant differences in emissions between the treatments.

The observed N_2O emission levels were comparable to others observed in other similar studies in East Africa (Macharia et al., 2020; Sommer et al., 2015; Pelster et al., 2017). The levels of N_2O emissions are generally low and could be attributed to the inherent low nitrogen in soils of this region (Kihara & Njoroge 2013) and the comparably low N fertilizer application rate (60 kg N ha^{-1}). The levels of nitrogen have been reported to be insufficient to satisfy plant-uptake and N-exports in maize mono-cropping systems (Sommer et al. 2015) in the study area.

Low N_2O emissions were also observed in other smallholder farming systems in the region as reported by Pelster et al., (2017) under grazed grassland or annual croplands with low N application. The authors attributed the low N_2O emissions to low N fertilizer use common in the region. However, the increase in N_2O emissions from the 3rd day to the 5th day after planting could also have been enhanced by availability of nitrate from the ammonification and nitrification process of urea fertilizer.

Urea in the soil is usually broken down by hydrolysis into ammonium within 4 days after application and converted to nitrate under moist soil conditions. A similar observation was made by Huang et al. (2017) who studied emissions in a silt loam soil in China and observed emission peaks within one week after N fertilizer application in a maize soybean intercrop.

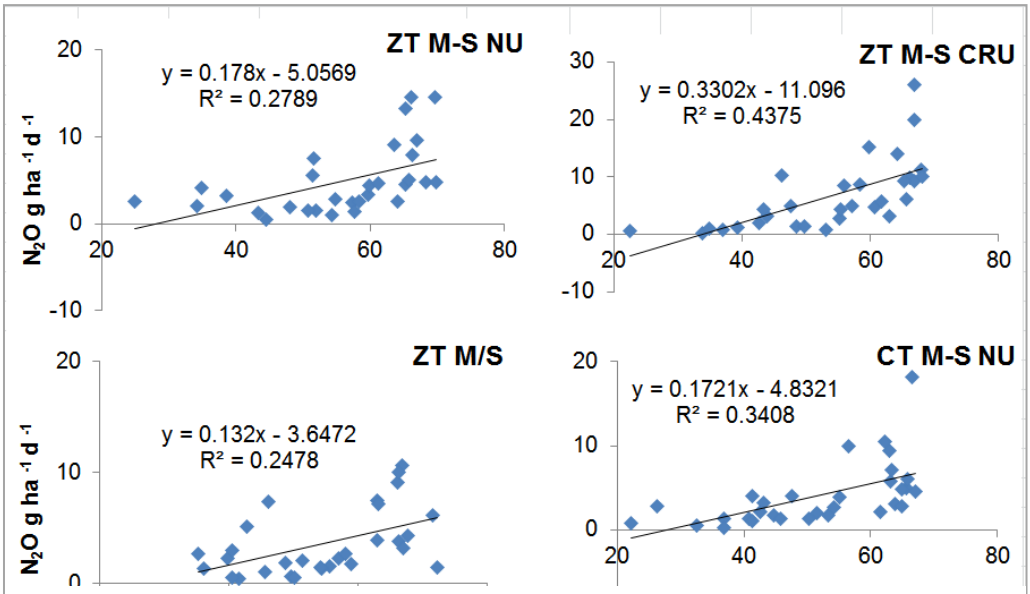

Figure 4.4: Linear corelation between N_2O emissions and soil moiture content (WFPS %)

Legend: ZT M-S NU (reduced tilage, maize soybean rotationw with normal urea), ZT M-S CRU (reduced tillage, maize soybean rotation with controlled release urea), ZT M/S (reduced tillage, maize soybean intercrop without urea), CT M-S NU (conventional tillage, maize soybean rotation with normal urea.

Tillage practice in this study did not effect N_2O emissions significantly, even though in the short rainy season lower N_2O emissions were observed in the CT M-S NU treatment. This observation was contrary to the study of Six et al. (2004) who reported lesser N_2O emissions in zero or reduced tillage than conventional tillage. However, Beyer et al. (2015) reported less N_2O emissions under conventional tillage. N_2O emissions have been shown to occur when there is sufficient nitrogen (N) substrate in

the soil and both moisture and temperature are favourable (Merbold et al., 2011, Dobbie et al. 1999) but not enough oxygen. Most of the emissions occurred when moisture levels were high (>60% WFPS).There was a high corelation ($p < 0.001$) between soil moisture content and N_2O emissons as shown in Figure 4.4

The N_2O emissions most likely could have been due to denitrification processes of the available NO_3^+ in the soil (Liu & Greaver, 2009). As most of the emissions occurred during the first three weeks after planting, denitrification could have been the main process of N_2O emissions due to the high moisture levels in the soil during this period. Soil moisture levels at >60% WFPS by the 5^{th} day after planting (Figure 4.2) may have resulted in anaerobic conditions that enhanced the activity of denitrifying bacteria converting nitrate in the soil to nitrous oxide. This observation was consistent with observation of Pelster et al., (2017) in Western Kenya. In their study denitrification was reported to have occurred when moisture content reached or surpassed 60 % WFPS.

This threshold in soil moisture content was also emphasized in a study by Clayton et al. (1997) which observed a critical WFPS of 65% below which emissions were insignificant in a temperate soil in Scotland. Higher emission rates of N_2O observed in this study with increased soil moisture was also consistent with observations of Wang et al. (2016) who likewise observed an increase in N_2O emission rates with increasing soil moisture in a semiarid loess plateau in China.

Low moisture content and apparent low N in the soil could partly explain the negative fluxes observed in the month of June, although the circumstances that lead to

soils absorbing N_2O are not clear. The lower N_2O fluxes in the short compared to the long rainy season, though not significant, could be explained majorly by the low rainfall amount and subsequent low soil moisture content in the short rainy season.

These findings are consistent with those observed by Dick et al. (2008) in semi-arid conditions in Mali. Davidson et al. (2000) also attributed N_2O emissions to soil moisture. The observed seasonal difference in emissions could also be attributed to the different crops in the two seasons (maize in long and soybean in the short rainy season). Type of crop has been shown to contribute to differences in emissions even within a similar agro ecosystem (Dobbie et al., 1999).

Contrary to the expectation that controlled release urea CRU could result to less N_2O emissions, the highest N_2O emissions in the long rainy season were observed under the reduced tillage system with (CRU). This observation was similar to that reported by Soars et al. (2015) who observed higher emissions with CRU compared to regular urea. CRU is designed to release urea as temperature and moisture levels increases, aiming at matching N release with crop demand (Trenkel, 2010).

High moisture and temperature right from the planting time might have enhanced the release of N when maize plants were still too young and with few or no roots to take up all the N released . This could have left large amounts of NO_3^- available for denitrifying microbes thereby increasing their activity in microbial decomposition of soil organic matter (Dobbie et al., 1999). This lack of synchrony between nutrient release and demand by plants could have led to higher N_2O emissions following application of CRU as had been pointed out by Hu et al. (2013) and Venterea et al. (2011). Contrary to the observation made by this study, Mctaggart et al. (2003)

observed a reduction in N_2O emissions by CRU from an Andosol when moisture levels were above 85 % WFPS. In the same study, CRU did not show lower emissions when soil moisture content was moderate at 55 % to 70 % WFPS.

In the long rainy season, reduced tillage system with maize/soybean intercrop which had no urea N fertilizer (ZT M/S) had the least emissions. This observation could be attributed to limited N supply since the only source of N for this treatment was organic matter available in the soil during that period through mineralization of crop residues.In addition, the amount of nitrogen mineralised from the residues might have been too little, and competition for it from both maize and soybean could have led to little N for microbes responsible for N_2O production processes.

According to a recent study by Huang et al. (2017) intercropping maize and soybean reduced N_2O emissions. The authors attributed the reduction in N_2O to the observed lower soil moisture caused by increased evapotranspiration rates and low nitrates in the soil. However, this study did not show significant effect of intercropping on soil moisture levels . The lower (though not significant) emissions from the intercrop could be largely attributed to lower soil N. This was more so because this treatment did not receive any additional inorganic N fertilizer for the 13 years the trial had existed. The rest of the treatments could have derived their comparably elevated N_2O emissions from the additional N fertilizer applied (Syakila & Kroeze, 2011; Fowler et al., 2009; Bouwman et al., 2002,). The mineral fertilizer seemed to have an impact on emissions in this study, though in the overall it was very little and largely insignificant.

4.5.2 Effect of fertilizer type on N_2O emission

Comparing CRU and NU effect on N_2O emission in the reduced tillage system in the long rainy season, CRU showed significantly higher N_2O emissions than the NU at p=0.05 (Figure 4.5 a) early in the season. A positive correlation was observed between nitrate concentrations and N_2O emissions by NU (p=0.05) throughout the season. Ammonium concentration was not significantly different between the urea types and there was no observed effect on the N_2O fluxes. There was a positive correlation (R=0.7) between nitrate and N_2O emission by CRU early in the season.The significantly higher N_2O emissions by the CRU treated soil cound be attributed to higher NO_3^- concentration (Passianato et al., 2003).

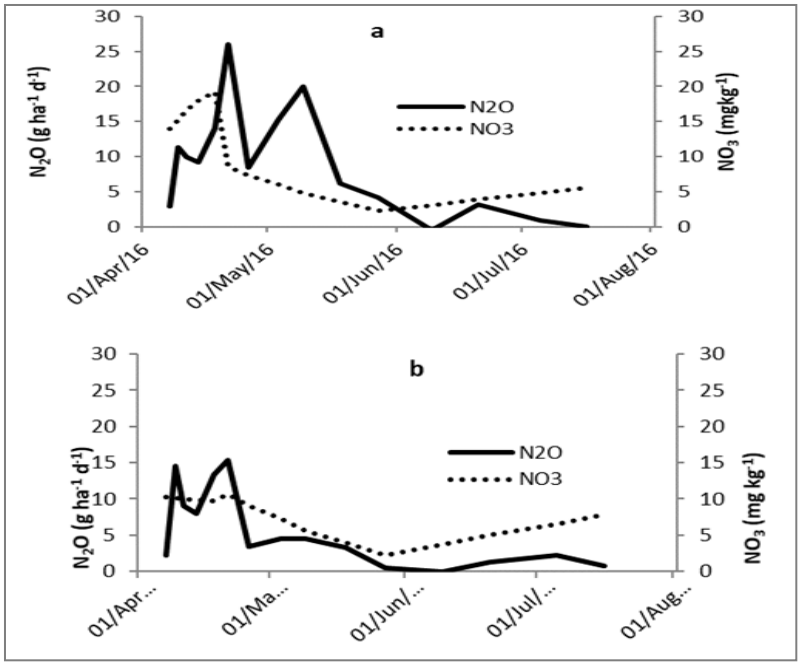

Figure 4.5: Effect of urea type on N_2O emission, NO_3^- and NH_4^+ concentration during the long rainy season of 2016 for: CRU (controlled release urea (a) and NU (normal urea) (b

4.5. 3 Cumulative N_2O emissions

Cumulative seasonal emissions for the two seasons ranged between 0.2 and 0.4 kg N_2O -N ha^{-1} per season, with the exception of ZT M-S CRU treatment which reached 0.7 kg N_2O –N ha^{-1} in the long rainy season.

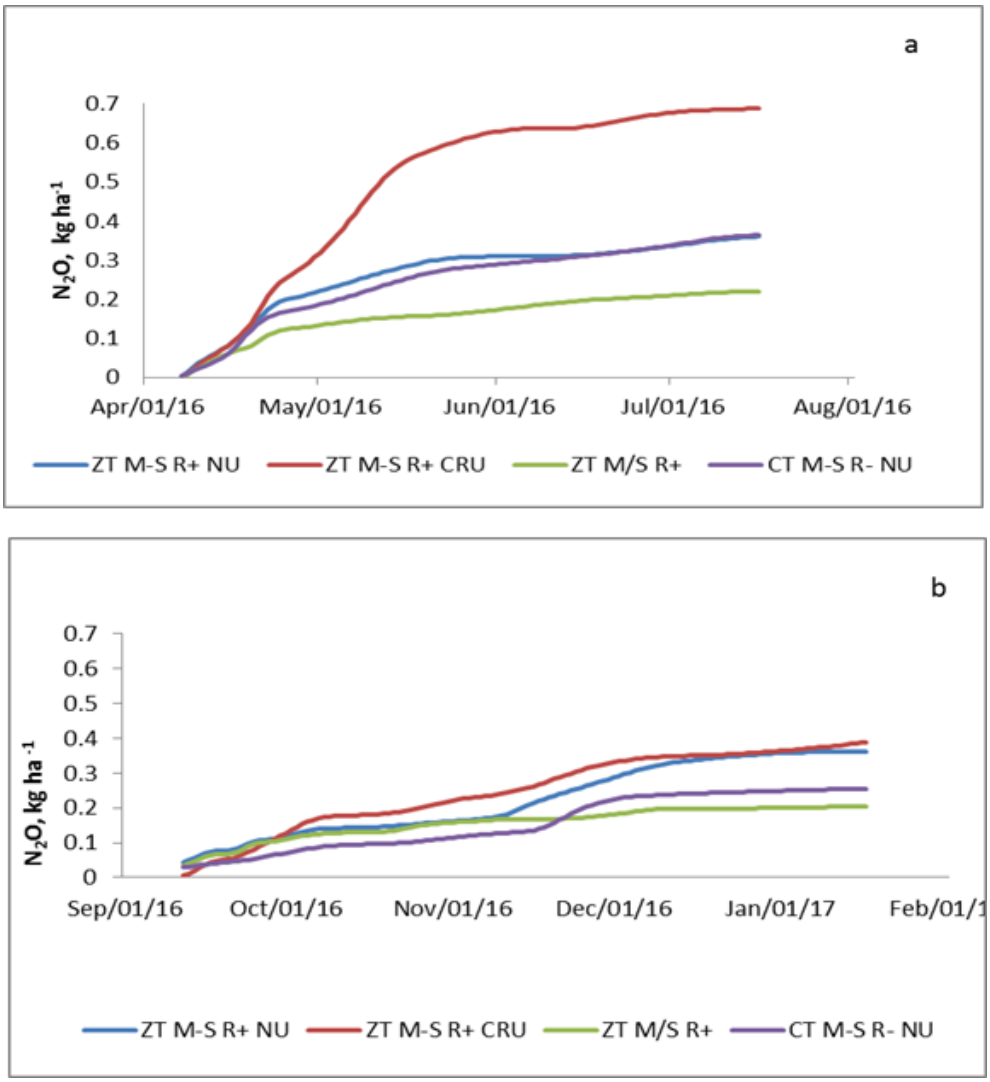

Figure 4.6: Linear interpolated N_2O cumulative fluxes for the long (a) and short (b) rains 2016

Legend: ZT M-S NU (reduced tilage, maize soybean rotationw with normal urea), ZT M-S CRU (reduced tillage, maize soybean rotation with controlled release urea), ZT M/S (reduced tillage, maize soybean intercrop without urea), CT M-S NU (conventional tillage, maize soybean rotation with normal urea.

The significantly higher cumulative fluxes observed for ZT M-S CRU during the long rainy season (p=0.02) (Figure 4.6 a) could have resulted from excess release of urea due to sufficient temperatures and soil water (Trenkel, 2010). This could therefore result in emissions since crop demand for N at early stages of crop growth is usually low (Subedi & Ma, 2005).

During the short rainy season there were no significant N_2O emissions differences across all treatments (Figure 4.6 b). The low N_2O emissions observed were consistent with other studies done in sub-Saharan Africa (Pelster et al., 2017). T CT treatment observed less (but not significant) N_2O emissions than ZT treatments. This could mainly be attributed to the fact that in the reduced tillage treatments had received crop residues unlike the conventional tillage system. Addition of organic matter could have increased the N_2O emission (Laegried and Aastveit 2002). A similar observation observation was reported by Beyer et al. (2015).

4.6 Carbon dioxide (CO_2) emissions

4.6.1 Daily CO_2 emissions

Irrespective of the treatment, emissions increased as from the beginning of the long rainy season and declined towards the end of the season. The highest emissions during this season were observed in May and June (Figure 4.7) Emissions remained above 15 kg CO_2 ha^{-1} d^{-1} throughout the season apart from the CT M-S NU treatment which reached 10 kg CO_2 ha^{-1} d^{-1} at harvesting (Figure 4.7). CO_2 emissions were not significantly different across treatments throughout the season except from the 6^{th} week after planting when the concentrations recorded in ZT M-S CRU and CT M-S NU

treatments were significantly higher than those recorded in ZT M-S NU and ZT M/S treatments (p=0.003)

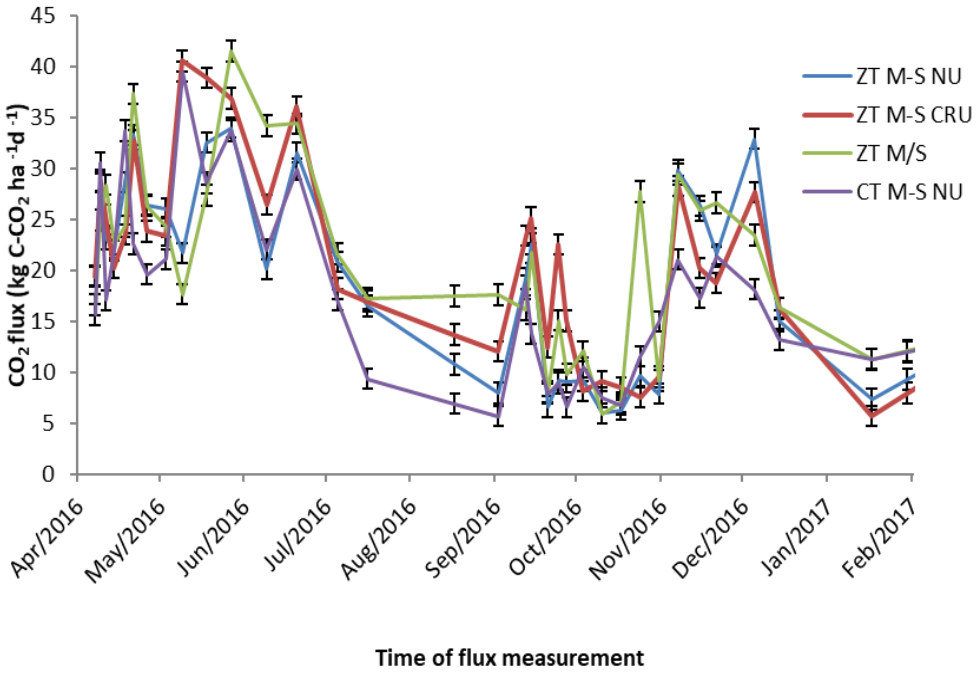

Figure 4.7: Daily CO_2 emissions at CT1 in 2016.

Legend: ZT M-S NU (reduced tilage, maize soybean rotationw with normal urea), ZT M-S CRU (reduced tillage, maize soybean rotation with controlled release urea), ZT M/S (reduced tillage, maize soybean intercrop without urea), CT M-S NU (conventional tillage, maize soybean rotation with normal urea.s

In the short rainy season however, emissions of CO_2 increased in the first three weeks after planting then declined in the month of Novembe but increased again up to mid December from mid December emissions decreased up to the end of the season in January 2017. During this season, emissions from ZT M/S treatment were notably higher than the other treatments but the difference was not significant at 5 % probability level. It was observed that emissions throughout the year never went below 5kg ha^{-1} d^{-1}

CO_2 emissions in tropical agricultural systems are regulated largely by soil moisture as well as availability of organic substrate necessary for microbial activity. Apart from soil moisture, organic substrates have been shown to play a major role in determining the extent of emissions (Luo et al., 2013).

The observed increased emissions early in the season could have been triggered by abundance of crop residue applied before planting (Malhi & Lemke, 2007). The lowest CO_2 emissions observed at CT M-S NU treatment which had not received maize stover residues further supports the role of organic substrate in CO_2 emission. Addition of N fertilizer did not seem to have a big impact on CO_2 emissions as ZT M/S which did not receive N fertilizer had the highest CO_2 emissions. The amount and type of organic residue also determines the extent of emissions. Millar et al. (2004) observed increased emissions when leguminous residues were incorporated into the soil.

The intercrop treatment showed more CO_2 emissions, probably because soybean residues were usually left on the field every season. This system also did not receive any additional inorganic N fertilizer, suggesting that inorganic N was not a major factor in CO_2 emissions. This study did not observe increased CO_2 emission after top dressing with N fertilizer. These findings are consistent with those of Gelfand et al. (2015) who observed no influence of N availability on CO_2 indicating that CO_2 is more influenced by soil carbon rather than N. Cumulative CO_2 fluxes were within the range of previously observed emissions by other studies in Kenya (Pelster et al., 2017; Baggs et al., 2006; Millar et al., 2004), Tanzania (Sugihara et al., 2012) and in Zimbabwe (Mapanda et al., 2011). In general, the findings of this study indicate that CO_2 emissions responded to elevated soil moisture levels which are in agreement with other studies

(Arias-Navarro et al., 2017; Gelfand et al; 2015; Zhou et al; 2013) which observed increased emissions in wetter soils.

4.6.2 Cumulative carbon dioxide emissions

Cumulative CO_2 fluxes ranged between 2.5-2.8 and 1.8-2.5 t ha^{-1} for the long and short rainy seasons respectively.This was consistent with observations of other studies carried out in East Africa ranging between from 1.0 to 15.9 t ha^{-1} yr^{-1} CO_2 (Macharia et al., 2020; Pelster et al., 2017; Rosenstock et al., 2016). There were no significant differences in emissions across the treatment.

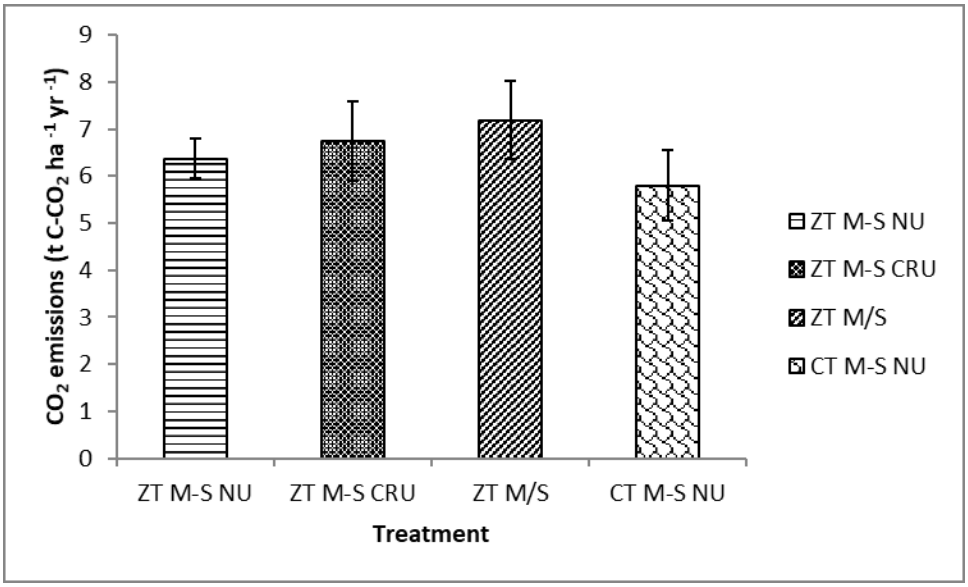

Figure 4.8: Cumulative CO_2 emissions 2016 at CIAT trial.

Legend: ZT M-S NU (reduced tilage +maize soybean rotation + normal urea), ZT M-S CRU (reduced tillage + maize soybean rotation + controlled release urea), ZT M/S (reduced tillage + maize soybean intercrop without urea), CT M-S NU (conventional tillage + maize soybean rotation +normal urea

It was however notable that CT M-S NU treatment emitted the least emissions in both seasons while the ZT M/S treatment had the highest emissions in both seasons

(Figure 4.8).This observation was consistent with that of Jin et al. (2014) who reported an increase in CO_2 emissions under reduced tillage system. An addition of organic matter as crop residues for all the ZT treatents could also be linked to this observation. Organic matter has been reported to increase CO_2 emissions under favourable conditions such as soil moisture (Gärdenäs et al., 2011).

4.7 Methane (CH_4) emissions

4.7. 1 Daily CH_4 emissions

The CH4 emissions were extremely low in the beginning of the season (<10 g ha^{-1} d^{-1}) and in mid-June (Figure 4.9.). Significant differences in emissions were only observed at 3 weeks after planting where CT M-S NU was significantly lower than the other treatments (P=0.015) and it had a negative flux (Figure 4.9). Throughout the season the fluxes were mainly negative. Between 9th June and 20th June CH4 emissions increased from -3 to 4.5 g ha^{-1} d^{-1} and 2 g ha^{-1} d^{-1} for the ZT M-S NU and ZT M-S CRU respectively, after which the fluxes reduced to negative.

Methane levels throughout the short rains remained negative. This observation was similar to that of Macharia et al. (2020) where CH_4 remained largely negative in a maize cropping system in Eastern Kenya. Between October and November the fluxes were slightly above zero but never exceeded 7 g ha^{-1} d^{-1} (Figure 4.9).There were no significant differences in methane fluxes across all treatments throughout the season. Large error bars indicated the inability of the chambers to detect very low emissions (Parkin et al., 2012).

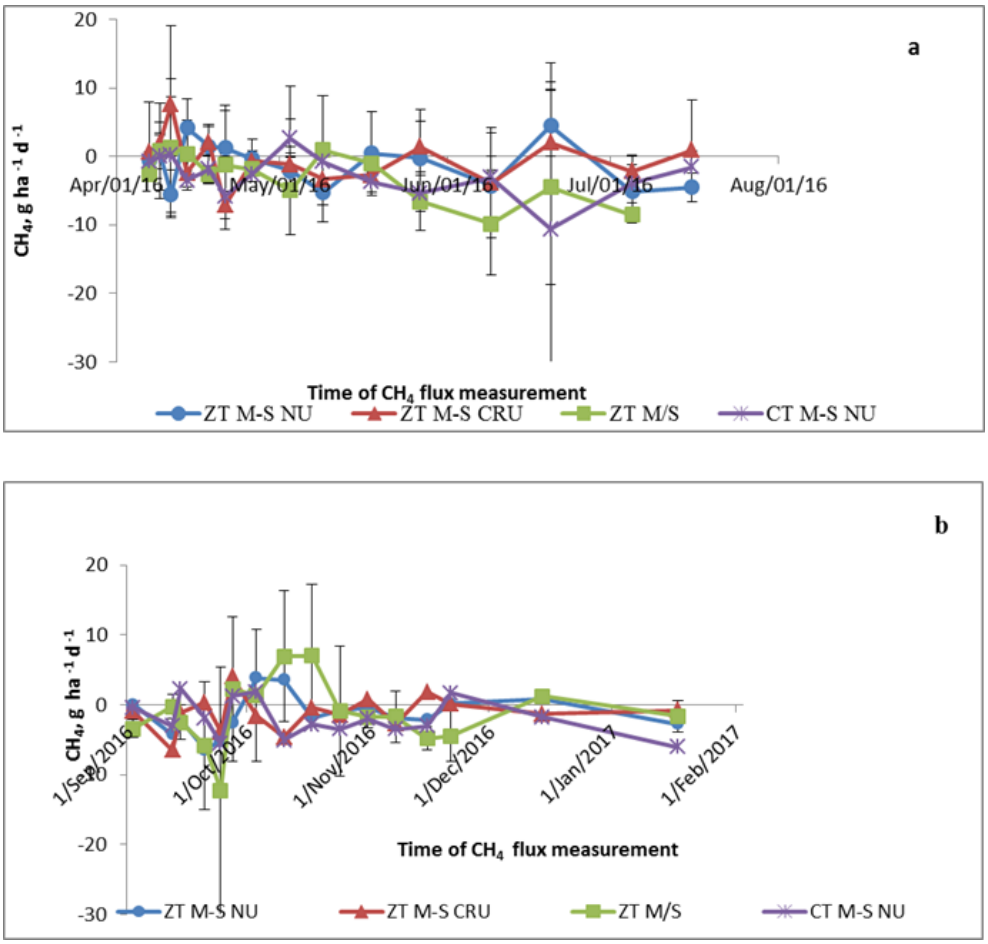

Figure 4.9: Methane emissions in the long rains (a) and short rains (b) in Nyabeda 2016. Bars indicate standard error of means

Legend: ZT M-S NU (reduced tilage, maize soybean rotationw with normal urea), ZT M-S CRU (reduced tillage, maize soybean rotation with controlled release urea), ZT M/S (reduced tillage, maize soybean intercrop without urea), CT M-S NU (conventional tillage, maize soybean rotation with normal urea.

The low emissions could be attributed to lack of anerobic conditions in the field to promote methanogenesis (Smith et al., 2014) The observations in this study were in agreement with those of Jiang et al. (2017), who observed very low methane emissions in upland maize cropping system.

4.7.2 Cumulative CH_4 emissions

Irrespective of the treatment, cumulative methane emission levels remained negative in both seasons (Figure 4.10). ZT M/S showed some increase from October to November although the fluxes were only slightly above 10 g CH_4 ha^{-1} d^{-1}.

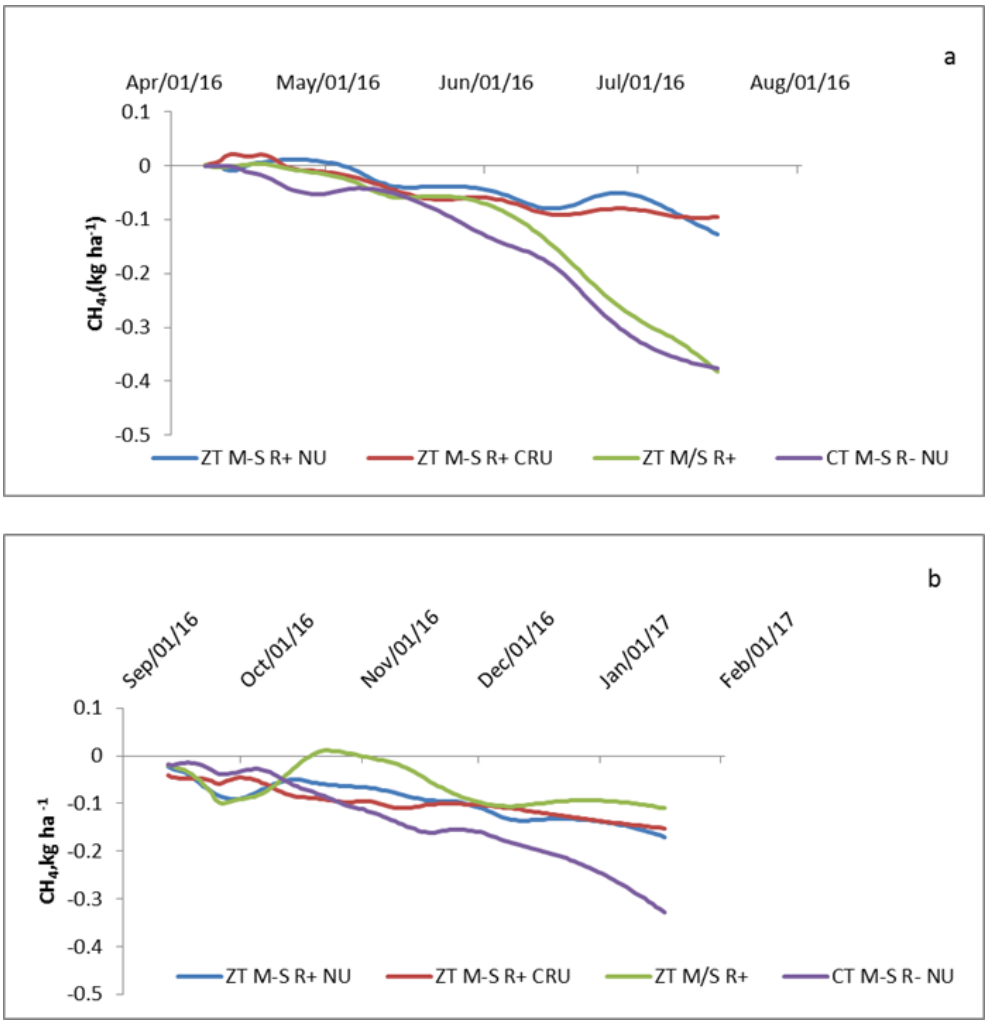

Figure 4.10: Cumulative CH_4 emissions for the long (a) and short (b) rains 2016 in Nyabeda.

Legend: ZT M-S NU (reduced tilage, maize soybean rotationw with normal urea), ZT M-S CRU (reduced tillage, maize soybean rotation with controlled release urea), ZT M/S (reduced tillage, maize soybean intercrop without urea), CT M-S NU (conventional tillage, maize soybean rotation with normal urea.

The observed negative methane fluxes were probably due to soil uptake through methanotrophic bacteria when the soil was aerated. However according to Serrano-Silva et al. (2014), This phenomenon takes place under conducive enviroment for methanotrophic bacteria that thrives where the water table is shallow (not the case for this study).

Methane emissions are usually associated with anaerobic conditions especially in flooded soils. Observation of negative fluxes was made even when the soil moisture was high (>70 % WFPS) implying that the presence of nitrate in the soil could have inhibited its production by increasing the redox potential (Liu & Greaver, 2009).

4.8 Soil carbon stocks

4.8.1 Soil organic carbon

Soil carbon measured in 2016 was not significantly different across treatments at p=0.05, although ZT M/S treatment showed the highest amount at 35.3 t ha $^{-1}$ while CT M-S NU treatment had the least stocks (32.6 t ha $^{-1}$) (Figure 4.11).

The slight differences between the highest and the lowest carbon stocks exhibited by ZT M/S treatment could be attributed to the higher amount of crop residues added as maize stover at the rate of 2 t ha $^{-1}$ every season as well as soybean residues every season which amounted to about I.5 t on average.

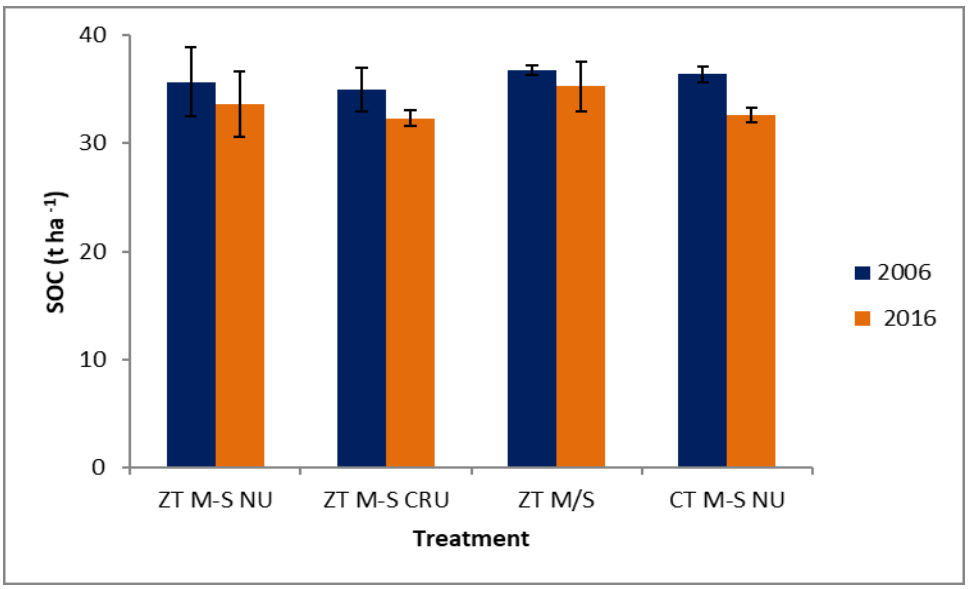

Figure 4.11: Soil carbon stocks (t C ha $^{-1}$) of the top 15 cm for 2006 and 2016 at Nyabeda.

Bars denote standard error of means

Legend: ZT M-S NU (reduced tilage+maize soybean rotation+normal urea), ZT M-S CRU (reduced tillage+maize soybean rotation+controlled release urea), ZT M/S (reduced tillage+maize soybean intercrop without urea), CT M-S NU (conventional tillage+maize soybean rotation+normal urea; data for 2006 are from Sommer et al., 2018;

On the contrary, low carbon stocks recorded for treatment CT M-S NU could be attributed to the less crop residues (only that of root stocks of both maize in the long rainy season and soybean in the short rainy season as well as soybean stover) compared to other treatments that received additional 2 t ha^{-1} maize stover. Crop residues have been shown to contribute to an increase of soil carbon (Masvaya et al., 2017; Kihara, 2009; Malhi & Lemke, 2007). Kuo-Hsien (2011) observed lower C with CT than ZT systems using DAYCENT model which was attributed to higher heterotrophic respitation in CT.

4.8.2 Soil carbon balance

CT M-S NU showed a negative carbon balance when considering C input as C added by crop residues and C output as C emitted as CO_2. ZT M/S had the highest C balance (Table 4.3). The negative balance observed in treatment CT M-S NU was most likely due to the fact that this treatment unlike the others did not receive additional maize residues and the only source of organic matter was the soybean residues and root stocks that remained after harvesting. Soybean residues which have a lower C: N ratio (<20), making decomposition by microbes easier and faster than for residues of maize (C: N ratio >30). This could be the reason CO_2 emission was relatively high (not significantly lower than the other treatments at 5 % probability level) since CO_2 emission is a function of available nutrients and favourable climatic conditions for microbial decomposition of organic matter.

When comparing carbon stocks for 2016 and 2006, all treatments had negative SOC balances where treatment CT M-S NU had the highest losses while treatments ZT M/S had the least SOC losses over the years. However, the obseved losses were not significantly different. This phenomenon could be attributed to the higher crop residues addition to the ZT M/S system. CO_2 emissions from organic matter have been associated with the most recent materials (Pausch et al., 2012). In agreement with these results, Dendooven et al. (2012) observed more SOC losses in tilled soil than none tilled soil. Despite the losses, the SOC balance (though negative) could be attributed to the resistance of some SOM to microbial decomposition as reported by Lehmann et al. (2015).

Table 4. 3: Soil carbon stocks and annual carbon balance (t h $^{-1}$) as influenced by cropping system

Treatment	Annual C input	Annual C output (CO_2 emission)	Annual C balance	SOC 2006	SOC 2016	SOC balance, 2006-2016
ZT M-S NU	3.24a	6.37	-2.79	35.69	33.64	-2.05
ZT M-S CRU	3.13a	6.73	-3.3	34.99	32.31	-2.68
ZT M/S	3.65a	7.18	-3.2	36.77	35.25	-1.53
CT M-S NU	1.30b	5.80	-4.2	36.4	32.57	-3.83
P	**<.001**	0.21	0.26	0.72	0.4	0.27
LSD	0.52	0.47	2.6	4.06	4.4	1.56
SED	0.15	0.66	1.1	1.17	1.7	0.64

Means followed by similar superscript letter in the same column are not significantly different at 5 % probability level.

Legend: ZT M-S NU (reduced tilage, maize soybean rotationw with normal urea), ZT M-S CRU (reduced tillage, maize soybean rotation with controlled release urea), ZT M/S (reduced tillage, maize soybean intercrop without urea), CT M-S NU (conventional tillage, maize soybean rotation with normal urea.

There could also have been losses due to root excudates (Keiluweit et al., 2015), but that was not considered in this study. There was a weak correlation between C losses (Annual C output), and amount of organic matter returned to the soil (Annual C input) which was not significant at 5 % probability level. The C output (loss) inceased as C input increased. This could be attribted to the microbial decomposition of crop residues in the systems to release CO_2. (Smith et al., 2014)

4.9 Crop growth parameters

4.9.1 Carbon, nitrogen uptake and C: N ratios

N uptake in maize was significantly higher ($p = 0.03$) for CT M-S NU and ZT M-S NU than ZT M/S at 3 WAP (Table 4.4). At the same time, N uptake was not significantly different between ZT M/S and ZT M-S CRU. At 6 WAP, ZT M-S CRU showed significantly higher ($p=0.03$) N uptake than the other treatments. At 9 WAP, none of the treatments showed significant differences in N uptake at 5% probability level. Carbon concentration in maize was not significantly different across treatments at any growth period. C: N ratio for maize was also not significantly different at any time of the growth period across all treatments.

Table 4. 4: Concentrations of N, C (%) and C: N ratios of maize at different time of growth during the 2016 long rains in Nyabeda

Treatment	N uptake (%)			Carbon content (%)			C:N ratios		
	3WAP	6 WAP	9 WAP	3WAP	6 WAP	9 WAP	3 WAP	6 WAP	9 WAP
ZT M-S NU	4.8[a]	2.9[b]	2.4	35.8	36.4	40.0	8.1	12.2	17.3
ZT M-S CRU	4.5[ab]	3.4[a]	2.4	33.8	35.2	40.3	7.7	11.8	17.7
ZT M/S	3.9[b]	2.7[b]	2.2	35.0	36.7	40.0	7.3	12.5	18.3
CT M-S NU	4.8[a]	2.9[b]	2.4	35.6	34.0	40.3	7.7	12.1	16
P value	**0.03**	**0.03**	0.7	0.6	0.4	0.9	0.6	0.9	0.4
LSD	0.6	0.40	0.4	3.4	3.9	1.4	1.3	2.4	2.9
SED	0.3	0.40	0.3	2	1.8	0.6	0.56	1.06	1.27

Means within a column followed by the same letter are not significantly diffferent ($P<0.05$)

Legend: WAP (weeks after planting), ZT M-S NU (reduced tilage, maize soybean rotationw with normal urea), ZT M-S CRU (reduced tillage, maize soybean rotation with controlled release urea), ZT M/S (reduced tillage, maize soybean intercrop without urea), CT M-S NU (conventional tillage, maize soybean rotation with normal urea.

For soybean, C concentration throughout the growing period was not significantly different across treatments (Table 4.4). Soybean N concentration was significantly lower for ZT M/S than other for other treatments at 3WAP ($p=0.02$) and 11 WAP ($p=0.001$). At 13 WAP, ZT M-S NU showed significantly higher N concentration than other treatments ($p=0.001$). At the same time, N concentration was not significantly different between ZT M-S CRU and CT M-S NU. However, these two treatments showed significantly higher N that ZT M/S.

The significantly low N concentrations for ZT M/S could be attributed to the significantly lower N in the soil for this treatment. C: N ratio was significantly higher for ZT M/S at 3WAP ($p=0.01$), 11WAP ($p=0.02$), and 13 WAP ($p=002$) than other treatments. This observation could be as a result of lower N concentration of soybean in this treatment yet the carbon concentration was not significantly different across treatments.

There was a significantly high positive corelation ($R^2=0.95$) between N concentration and C: N ratio which was observed at 3, 11 and 13 WAP at 1 % probability level ($p<0.001$). The higher the N concentration the lower the C: N ratio and vice versa.

Table 4. 5: Concentrations of N, C (%) and C: N ratio of soybean at different times during the 2016 short rainy season in Nyabeda.

	Carbon content (%)				
Treatment	3 WAP	6 WAP	9 WAP	11 WAP	13 WAP
ZT M-S NU	40.15	42.8	41.82	43.33	41.82
ZT M-S CRU	38.94	43.05	41.8	42.16	42.91
ZT M/S	40.58	43.13	42.02	42.38	42.78
CT M-S NU	39.94	42.36	41.43	41.69	40.13
P	0.2	0.09	0.7	0.3	0.09
lsd	1.628	0.655	1.182	1.714	2.435
sed	0.72	0.29	0.522	0.757	1.076
	Nitrogen concentrations (%)				
ZT M-S NU	4.35[ab]	3.54	3.28	3.62[a]	3.4[a]
ZT M-S CRU	5.14[a]	4.21	3.08	3.54[a]	2.868[b]
ZT M/S	3.44[b]	2.96	2.53	2.08[b]	2.202[c]
CT M-S NU	4.79[a]	3.58	3.75	3.36[a]	2.706[b]
P	**0.02**	0.09	0.3	**0.004**	**<0.001**
lsd	1.017	0.968	1.275	0.34	0.4009
sed	0.45	0.428	0.564	0.77	0.1772
	C: N ratio				
ZT M-S NU	9.4[b]	12.37	13.51	12.3[b]	12.36[b]
ZT M-S CRU	7.57[b]	10.27	13.84	11.9[b]	15.18[b]
ZT M/S	11.91[a]	15.32	16.91	22.6[a]	19.87[a]
CT M-S NU	8.54[b]	11.99	11.41	12.5[b]	14.86[b]
P	**0.01**	0.16	0.10	**0.02**	**0.002**
lsd	2.354	4.501	4.335	6.72	2.849
sed	1.041	1.99	1.916	2.97	1.26

Means within a column followed by the same letter are not significantly diffferent at 5 % probability level.

Legend: WAP (weeks after planting), ZT M-S NU (reduced tilage, maize soybean rotationw with normal urea), ZT M-S CRU (reduced tillage, maize soybean rotation with controlled release urea), ZT M/S (reduced tillage, maize soybean intercrop without urea), CT M-S NU (conventional tillage, maize soybean rotation with normal urea.

4.9.2 Maize and soybean leaf area index

Leaf area index (LAI) remained largely unsignificantly different across treatments throughout the growing period for maize and soybean (Table 4.6). However,

at 13 WAP for ZT M/S showed significantly lower LAI for soybean compared to other treatments (p= 0.02).

Table 4. 6: Leaf area index (m^2/m^2)of maize at different times during the 2016 long rainy season in Nyabeda

Treatment	3 WAP	6 WAP	9 WAP
ZT M-S NU	1.028	3.31	1.72
ZT M-S CRU	0.595	3.1	2.042
ZT M/S	1.077	3.753	2.145
CT M-S NU	1.283	3.39	2.34
P	0.10	0.06	0.2
LSD	0.50	0.5	0.6
SED	0.30	0.2	0.2

Legend: WAP (weeks after planting), ZT M-S NU (reduced tilage, maize soybean rotationw with normal urea), ZT M-S CRU (reduced tillage, maize soybean rotation with controlled release urea), ZT M/S (reduced tillage, maize soybean intercrop without urea), CT M-S NU (conventional tillage, maize soybean rotation with normal urea.

The significantly low LAI in soybean at 13 WAP could be attributed to the low N uptake (Table 4.7). N has been shown to be a major nutrient responsible for crop growth and reduced leaf senecsence (Subedi & Ma, 2005)

Table 4. 7: Leaf area index (m^2/m^2) for soybean during the 2016 short rainy season in Nyabeda

Treatment	3 WAP	6 WAP	9 WAP	11 WAP	13 WAP
ZT M-S NU	0.3	0.6	0.7	3.1	3.4[a]
ZT M-S CRU	0.2	0.5	0.8	3.2	3.7[a]
ZT M/S	0.2	0.5	0.9	2.8	2.3[b]
CT M-S NU	0.2	0.5	0.7	3.7	3.5[a]
P value	0.6	0.9	0.7	0.4	**0.02**
Lsd	0.18	0.3	0.4	1.1	0.8
Sed	0.08	0.1	0.2	0.5	0.4

Means followed by similar superscript letter in the same column are not significantly different (p=0.05).

Legend: WAP (weeks after planting), ZT M-S NU (reduced tilage, maize soybean rotationw with normal urea), ZT M-S CRU (reduced tillage, maize soybean rotation with controlled release urea), ZT M/S (reduced tillage, maize soybean intercrop without urea), CT M-S NU (conventional tillage, maize soybean rotation with normal urea.

4.9.3 Maize and soybean yields

4.9.3.1 Maize yields

Maize grain yield ranged from 0.8 to 1.7 t ha $^{-1}$ while stover yield was 3.7 and 8.6 t ha $^{-1}$ with ZT M/S recording the lowest (table 4.8). Grain and stover yield were significantly lower by almost 50 % for the ZT+M/S treatment (p=0.005) than for the other treatments in the long rainy season. This difference could have been due to N limitation since ZT+M/S treatment was not supplied with inorganic N fertilizer as discussed in section 4.5, which showed this treatment had significantly lower soil N). The main source of N for this treatment was from crop (maize and soybean) residues.

Nitrogen has been shown to increase grain and stover yield (Ahmad et al., 2016, Anyanzwa et al., 2010). Insufficient N supply especially in early growth stages has been linked to subsequent low yields (Fageria & Baligar, 2005). Generally, the yield observed in this study (0.8-1.7 t ha^{-1}) was lower than expected for the area The low yield across all treatments could be attributed to a prolonged period of no rainfall in the month of June, which could have resulted in moisture stress at the critical time of grain filling. Maize grain yield increased proportionally with with stover weights in all treatments (p=0.001) at 5 % probability level.

Maize grain yield was higher in the conventional tillage system than in the reduced tillage system. This observation is consistent with findings of Malhi & Lemke, (2007) and Masvaya et al. (2017) who reported higher grain yield in conventional compared to zero tillage.

Table 4. 8: Maize grain and stover yield (t ha^{-1}) in the 2016 long rainy season in Nyabeda.

Treatment	Maize grain yield (t ha^{-1})	Maize stover yield (t ha^{-1})
ZT M-S NU	1.6^{a}	8.6^{a}
ZT M/S	0.8^{b}	3.7^{b}
ZT M-S CRU	1.6^{a}	7.5^{a}
CT M-S NU	1.7^{a}	8.1^{a}
P value	**0.005**	**0.01**
SED	0.2	0.2

Means followed by similar superscript letter in the same column are not significantly different (p=0.05).

Legend: ZT M-S NU (reduced tilage, maize soybean rotationw with normal urea), ZT M-S CRU (reduced tillage, maize soybean rotation with controlled release urea), ZT M/S (reduced tillage, maize soybean intercrop without urea), CT M-S NU (conventional tillage, maize soybean rotation with normal urea.

4.9.3.2 Soybean yield

Soybean grain yield ranged from 0.4 to 1.2 t ha $^{-1}$ (Table 4.9) which was comparable to the average yield of 0.9 t ha $^{-1}$ estimated by FAO for Kenya in the year 2016 (FAOSTAT, 2016). Compared to other treatments, ZT M/S showed significantly lower grain (p=0.003) and stover (p=0.001) yields. The observed difference could be attributed to a limitation of N in the soil as discussed in section 4.4 of this study where N mineralization was significantly lower for ZT M/S. As explained in chapter three, this system did not receive inorganic N fertilizer and it therefore relied on the possible biological N fixation by soybean as well as N mineralization from crop residues as the main source of N.

Table 4. 9: Soybean grain and stover yields in the 2016 short rainy season in Nyabeda

Treatment	Grain yield (t ha $^{-1}$)	Stover yield (t ha^{-1})
ZT M-S N U	1.2^{a}	2.9^{a}
ZT M-S CRU	1.0^{a}	3.2^{a}
ZT M/S	0.4^{b}	1.6^{b}
CT M-S NU	1.2^{a}	3.2^{a}
P value	**0.003**	**0.001**
LSD	0.3	0.7
SED	0.2	0.3

Means followed by similar superscript letter in the same column are not significantly different (p=0.05).
Legend: ZT M-S NU (reduced tilage + maize soybean rotation + normal urea), ZT M-S CRU (reduced tillage + maize soybean rotation + controlled release urea), ZT M/S (reduced tillage + maize soybean intercrop without urea), CT M-S NU (Conventional tillage + maize soybean rotation + normal urea

While legumes, especially soybean can biologically fix appreciable amounts of N (Ngome et al., 2011). In this case,however, the amount of fixed N did not seem to

satisfy the N requirements for both soybeans and maize in the treatment combination hence the low yield. This indicates the importance of N as major nutrient that determines crop yield (Anyanzwa et al., 2010)

4.10 Nitrous oxide emission intensities

Emission intensity of N_2O in the four treatments ranged between 0.2 and 0.5 g N per kg of grain (Table 4.10). These intensities were comparable to those observed in a similar study in western Kenya (Sommer et al., 2015). There were no significant differences at 5 % probability of emission intensities between the treatments. However, treatment ZT M-S CRU had slightly higher EI compared to the rest of the treatments, which could be attributed to the significantly higher emissions observed in the 2016 long rainy season. Emission intensities followed the same trend as the emission rates, probably because none of the systems showed a significant yield increase as a result of agricultural intensification.

Table 4. 10: N_2O emission intensities of different cropping systems in Nyabeda

Treatment	**Emission Intensity** (g N per kg grain)
ZT M-S NU	0.3
ZT M-S CRU	0.5
ZT M/S	0.2
CT M-S NU	0.3
P value	0.09
LSD	0.02
SED	0.09

Legend: ZT M-S NU (reduced tilage, maize soybean rotationw with normal urea), ZT M-S CRU (reduced tillage, maize soybean rotation with controlled release urea), ZT M/S (reduced tillage, maize soybean intercrop without urea), CT M-S NU (conventional tillage, maize soybean rotation with normal urea.

4.11 Biophysical modeling of greenhouse gases and soil carbon

4.11.1 Initial soil organic carbon levels

The model simulated initial SOC levels reached equilibrium at about 9 t ha^{-1} from the assumed evergreen forest in the top 20 cm soil depth (Figure 4.12). These SOC levels were in agreement with those described for the same forest type in the region (Sommer et al., 2018, Vågen et al., 2016). Forests are considered a sink for carbon stocks through accumulation of C fixed by photosynthesis (FAO, 2017).

The simulated SOC levels declined exponentially from the time the forest was converted to agricultural land (1950) to about 5 t ha^{-1} in 2002 (Figure 4.12). This decline did not equilibrate, probably due to decomposition of soil organic matter

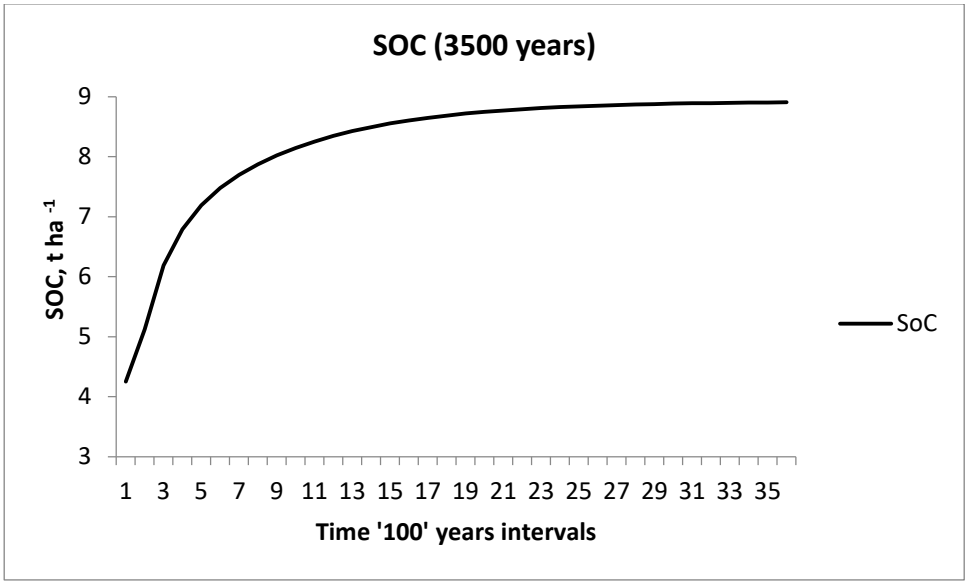

Figure 4.12: DAYCENT simulated soil organic carbon (SOC) at 20 cm depth for Nyabeda (3500 years before conversion of forest land to agriculture)

Loss of SOC due to land use changes has been recognized by IPCC, (2014) and is related to anthropogenic CO_2 emissions. Simulated SOC levels started to increase gradually from the year 2003 following the more intensive agriculture that left soybean residues.

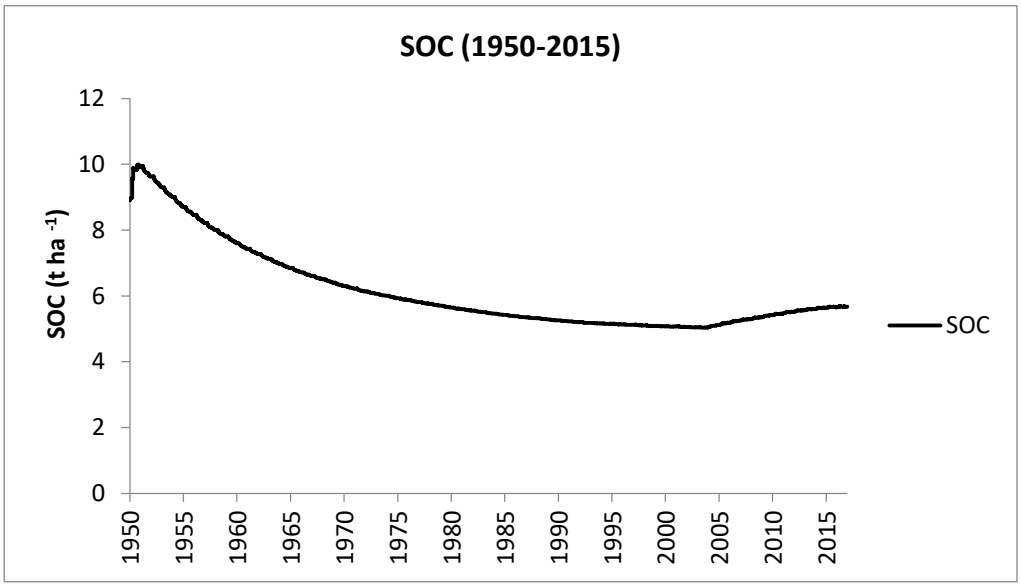

Figure 4.13: DAYCENT simulated soil organic carbon (SOC) at 20 cm depth since conversion of original vegetation to agriculture (1950-2016)

4.11.2. Model derived maize yields

The model simulated maize yield of below 2 t ha $^{-1}$ in the 1990s (Figure 4.13). These were comparable to the ones reported by the Ministry of agriculture (2009) for the same period. In their report the authors attributed the low maize yields largely to low soil fertility. Before and in the 1990s, farmers rarely applied fertilizer to crop land, leading to decline in yields. The simulation was based on crop production with little fertilizer inputs, and the yields declined with declining soil fertility. Many studies have

associated low yields in sub Saharan Africa to poor soil fertility, and lack of nutrient replenishment (Vanlauwe et al., 2001, Nandwa & Bekunda, 2008).

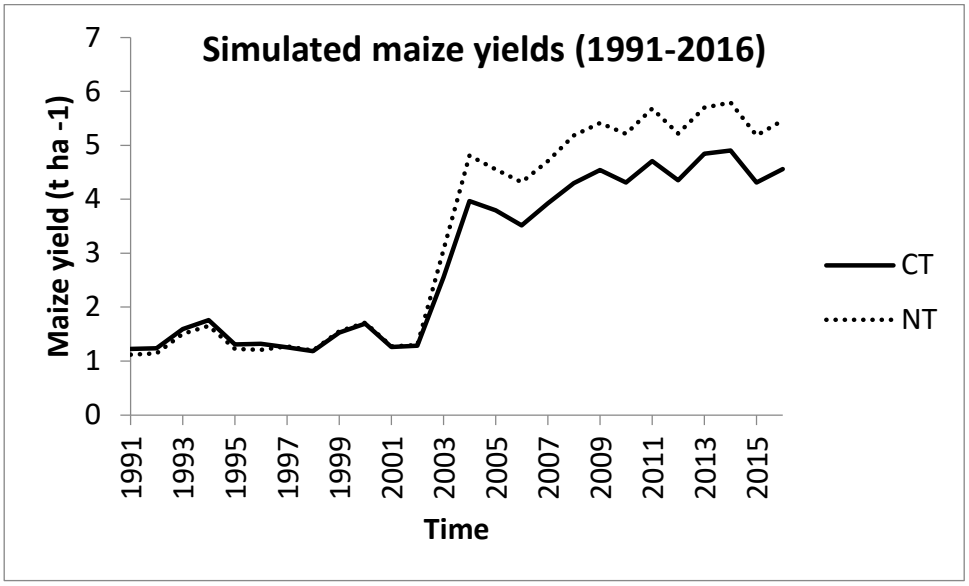

Figure 4. 14: DAYCENT simulated maize yields for Conventional tillage (CT) and reduced tillage (NT) between 1991 and 2016)

The significant sharp increase in maize yields observed between 2003 and 2005 must be attributed to the response of N fertilizer (Kihara & Njoroge 2013; Anyanzwa et al., 2010) following its application from 2003. N fertilizer has been shown to enhance crop yields especially in N deficient African soils. The model simulated higher maize yield for the reduced tillage system with residue added, which could be attributed to the enhancement of productivity by N in the crop residues. A combination of crop residues and nitrogen fertilizer has been shown to increase crop yield over that without residues (Ahmad et al., 2016; Ali et al., 2013).

With a few exceptions, the model simulated maize yields were closely related to observed yield with a RMSE of 1.3 t ha-1 and a RRMSE of 22% (Figure 4.15). The model overestimated maize yields in 2013 and 2016. Such observations had been

reported by Kuo-Hsien. (2011) who observed overestimation of above ground forest biomass in some seasons. However, in this study, these two seasons had significantly lower observed yield compared to other seasons and the overestimation could not be directly linked to the model. The close observations between simulated and measured yield was in agreement with that reported by Sommer et al. (2015) who observed very close model fit in the same region using CropSyst model. A comparison of different model results has been advocated for (Sommer et al., 2015)

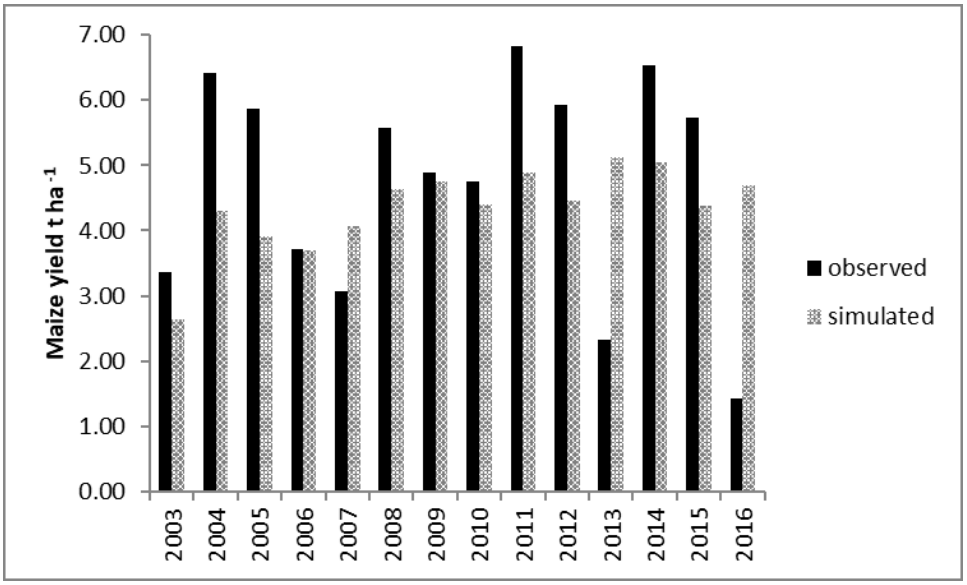

Figure 4.15: Simulated and observed maize yield for CT (2003-2016)

(Observed yield for 2003-2015 obtained from the CIAT long term data set)

4.11.3 Simulated nitrous oxide emissions

Irrespective of the tillage system, the model simulated N_2O emissions trends were similar to those observed in this study (Figure 4.16). Both the model and field observations showed higher N_2O emissions in the beginning of the seasons and emissions declined towards the end of the season. The long rainy season had much higher emission peaks than the short rainy season. Under the two tillage systems, the

model simulated higher N_2O emissions than the measured emissions. The root mean squared error RMSE was 20 g N ha $^{-1}$ while the relative root mean squared error was 30%.

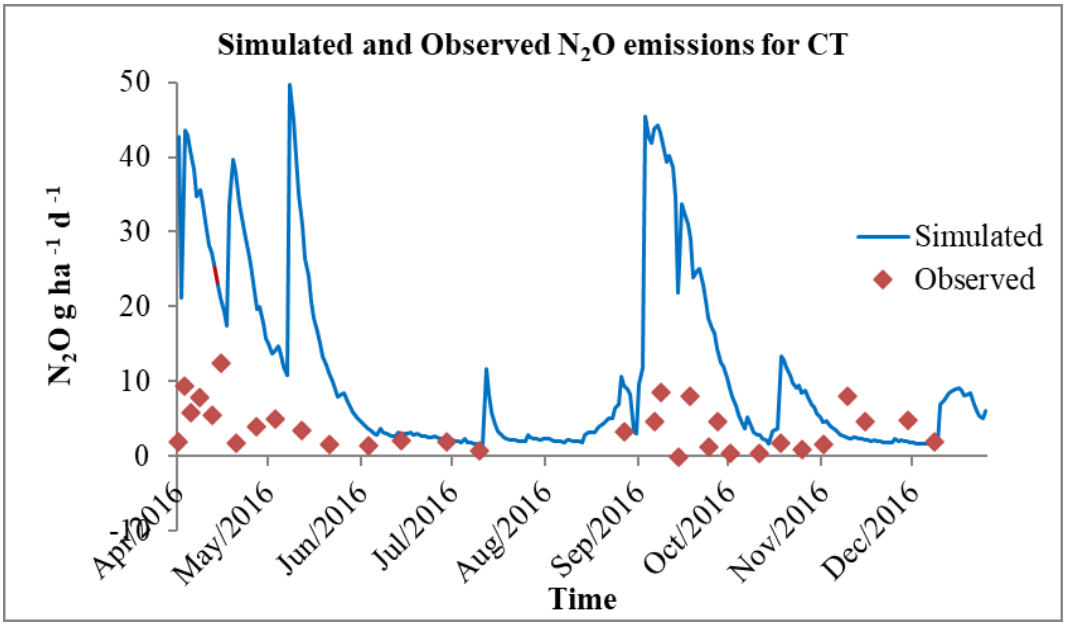

Figure 4.16: Simulated and observed N_2O emissions for CT (conventional tillage) in Nyabeda, 2016

The model fit was good during late season, and where the simulated N_2O emissions matched the observed ones in 2016. However the model fit was poor, and overestimated emissions at the beginning of the seasons. A similar trend was observed by Sommer et al. (2015) while simulating emissions in the same area. In their study the authors reported over estimation of emissions by CropSyst model, but the simulated and observed emissions matched whenever emissions were low (below 5 g $^{-1}$ ha d $^{-1}$). This trend could be attributed to unavailability of sensitive data to the model, which was largely developed for developed countries.

Contrary to this observation, Del Grosso et al. (2005) observed very positive fit of DAYCENT simulated N_2O emissions with observed emissions in different cropping systems in USA.

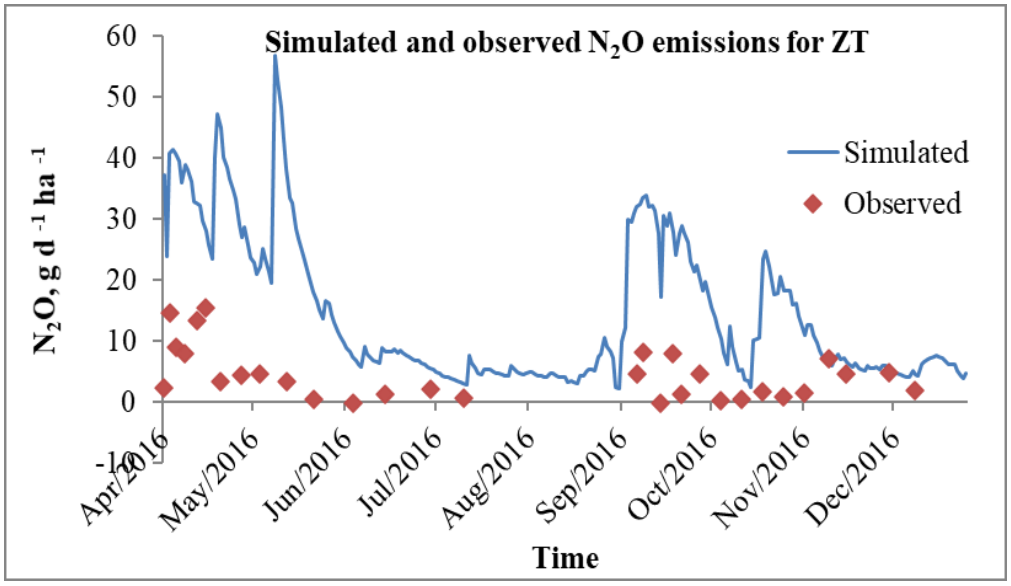

Figure 4.17: Simulated and observed N_2O emissions for reduced tillage (ZT) in Nyabeda, 2016

4.11.4 Relationship between SOC and N_2O emissions

N_2O emissions increased from maximum of about 30 g ha $^{-1}$ d $^{-1}$ in 1991 to 70 g ha $^{-1}$ d $^{-1}$ in 2016 (Figure 4.18). However the simulated N_2O emissions were as low as 2 g ha $^{-1}$ d $^{-1,}$ N_2O emissions were significantly ($p < 0.001$) correlated with SOC levels (Figure 4.19). N_2O has been shown to increase in soils treated with additional organic matter (Millar et al., 2004). Macharia et al. (2020) showed increased N_2O emissions after application of farmyard manure in a semi-arid soil in Kenya. Irrespective of the SOC levels and soil management, the model simulated N_2O emissions less than 2 g ha $^{-1}$ d $^{-1}$ during off seasons. This observation underpinned the observation that N_2O

emissions are a function of combined factors of SOC and N fertilizer, which in this case was assumed not to have been applied in the 1990's.

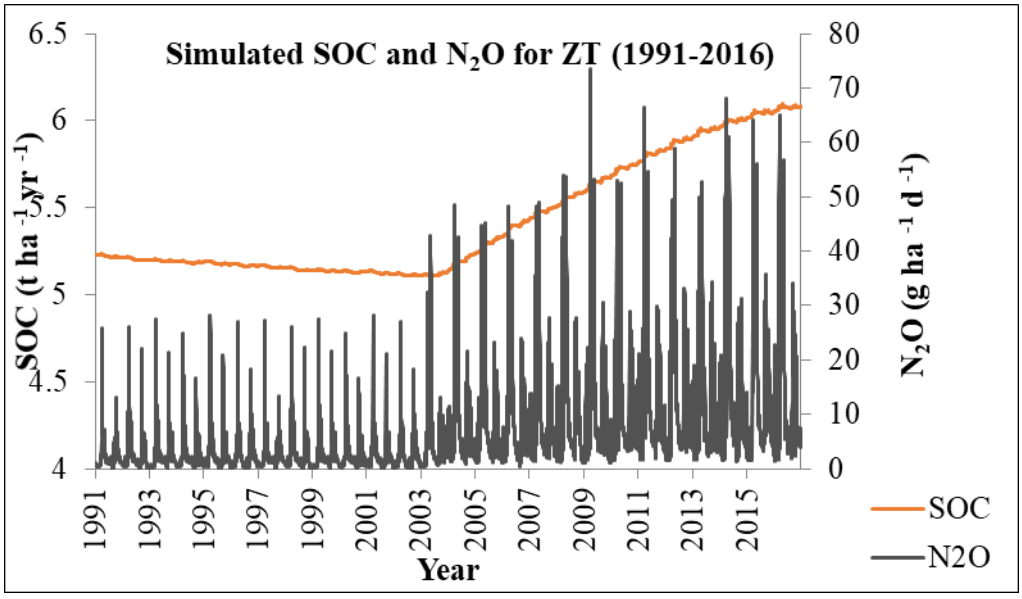

Figure 4.18: DAYCENT simulated N_2O emissions and SOC for reduced tillage (ZT) in Nyabeda (1991-2016)

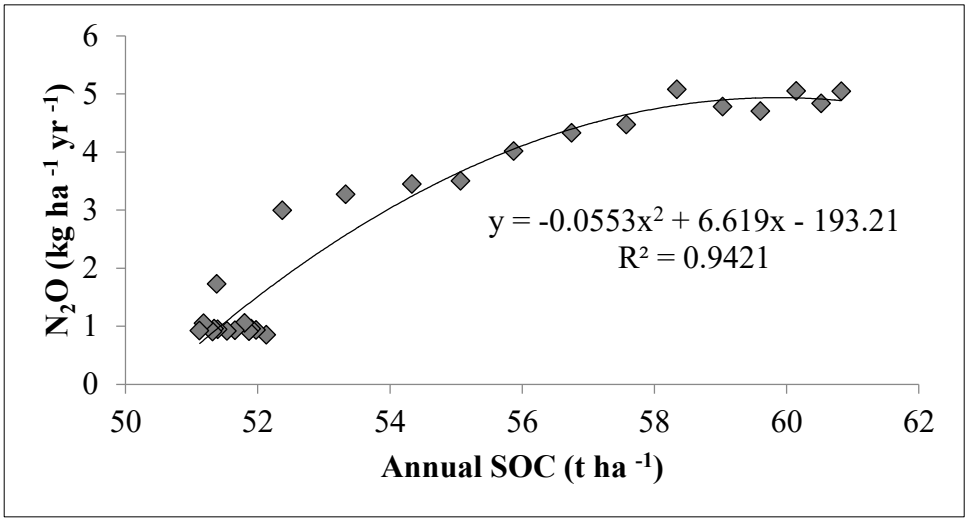

Figure 4.19: Correlation between simulated N_2O emissions and SOC for Nyabeda (1991-2016)

CHAPTER FIVE

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

This chapter highlights the key observations and implication of this study based on the objectives and the hypothesis of this study. It is presented in four sections: section 5.2 summarizes the key results while section 5.3 draws major conclusions from the key results. Section 5.4 gives recommendations from the study based on the results for each objective. Section 5.5 highlights the areas for further research to build on the knowledge in the subject of greenhouse gases and soil carbon in maize-based cropping systems.

5.2 Summary of findings

Results showed that soil mineral N increased soon after fertilizer application during planting and declined about two months after planting. This coincided with a time when crops were too young for N uptake which would encourage losses. Nitrate concentrations were significantly higher in the top soil depth (0-10 cm) under reduced tillage systems with residue and N fertilizer *(*ZT M-S NU and ZT M-S CRU). In the lower soil depth (25-50 cm), conventional tillage with maize – soybean rotation without residues had significantly higher N concentration. Reduced tillage with maize - soybean intercrop without N fertilizer (ZT M/S) had significantly lower N across all soil depths.

In relation to N_2O emissions, Maize-soybean rotation under reduced tillage with Controlled release Urea (ZT+M-S+CRU) had significantly higher N_2O emission

compared to the other treatments in the long rainy season. the emissions reached 30 g N_2O -N ha^{-1} d^{-1} for this treatment, which was double that of the other treatment. Reduced tillage maize- soybean intercrop without N fertilizer recorded significantly lower N_2O emissions than in other treatments. This was attributed to the role of inorganic N in enhancing N_2O emissions

Results on CO_2 emissions indicated there were higher emissions in the beginning of the season but never decreased to zero at any time through the study period. The study observed higher CO_2 emissions under the reduced tillage under maize - soybean intercrop without N fertilizer treatment . This was attributed to the existence of SOM and adequate moisture to facilitate microbial decompositio of residues, and positive relationship between quantity of organic matter and emissions. Methane emissions were generally low throughout the study and in most cases the fluxes were negative.This was attributed to lack of favourable conditions (anaerobic) for methanogesis.

Maize and soybean yield were significantly lower for maize- soybean intercrop under reduced tillage without N fertilizer. All other treatment did not record significant differences in yield, although CT M-S NU had slightly higher yield. This observation was greatly asociated with the important role that N has in crop yield in highly weathered soil low in N.

Results on model simulation indicated that DAYCENT model simulated crop yield, soil carbon well with lower RMSE and RRMSE. The model oversetimated N_2O in the beginning of the season (RMSE = 20 g N ha^{-1} d^{-1}, RRMSE= 35 %) but

simulated emissions were comparable to observed emissions when emissions were low at later stages of the season.

Soil moisture content which is a major driving factor for GHG emissions and was recorded as auxiliary data was highest at the beginning of the seasons (WFPS > 60 %) and decreased as the seasons progressed to as low as 20 %. The soil moisture content did not differ significantly among the tested cropping systems ($p=0.05$). This observation pointed out that the observed trends in both observed and simulated emissions were influenced by soil water, resulting in higher emissions in the beginning of the season

5.3. Conclusions

From the results of this study, the following conclusions were drawn: Reduced tillage with maize residue application reduced N leaching as evidenced by significantly higher concentration of NO_3^- in the top soil layer in ZT systems and higher concentrations in the lower layers in the conventional tillage system. Application of N fertilizer also influenced mineralization of N as observed for reduced tillage maize-soybean intercrop system that had significantly lower N at all depths at different times of the seasons.

N_2O emissions in Siaya County were generally low and the type of N fertilizer seemed to influence the quantities. For instance, the controlled release urea (CRU) triggered significantly higher N_2O emissions in the long rainy season. the treatment that had no inorganic N had significant lower N_2O, leading the study to conclude that inorganic N had an effect on the amount of N_2O emissions.

Intensification of cropping systems did not influence the soil carbon stocks significantly. Addition of maize residues under reduced tillage however recorded slightly higher soil carbon levels as was the case for all treatments apart from CT+ M-S + NU.

CO_2 emissions were mostly influenced by soil organic matter. This conclusion is based on the higher CO_2 emissions occuring under the ZT + M/S which received more crop residues None of the ferterlizer containing N influenced CO_2 emissions as evidenced by insignigicant differences between the ZT+ M-S + NU and ZT+ M-S + CRU. Similarly, tillage did not significantly influence CO_2 emissions following the similar CO_2 emissions between ZT+ M-S + NU and CT+ M-S + NU

There was a high unlikelihood of upland cropping systems as emitters of methane. The very low or negative emissions coupled with the high variability as evidenced by large error bars, and very low R^2 indicated the inability of the chamber method to detect very low methane emissions.

GHG emissions intensities are dependent on the croppping system and the crop yield. N_2O emission intensity was lowest for reduced tillage maize-soybean intercrop without N fertilizer.

The study showed there is a positive corelation between soil carbon, which is a function of soil management, and CO_2 emissions as the system with higher carbon balance had also the highest emissions.

Despite the continous practice of zero tillage and application of crop residue the carbon stocks did not show a build up compared for 10 years (2006-2016). Soil carbon

buld up is a mitigation strategy. There is need to research further on to the possible causes which this study did not focus on.

DAYCENT model the is able predict the impacts of different soil managemnt and cropping systems as evidenced by positive simulations of water, soil carbon and maize yield. The model however overestimated N_2O emissions pointing to a problem with this type of model in tropical soils and conditions.

5.4 Recommendations

Based on the findings, and the conclusions, the following recommendations were made:

- Farmers who practice reduced tillage and incorporate crop residues in their farms should continue and the rest should adapt it to reduce N losses associated with leaching and N_2O emissions
- Controlled release urea (CRU) as a mitigation strategy in the area may not be applicable, as it showed higher N_2O emissions in the long rainy season.
- Zero tillage with maize soybean intercrop (ZT M/S) should be adopted in the light of mitigating GHG emissions and climate change in Siaya.
- DAYCENT model may be used to predict/estimate carbon stocks for different soil management practices.

5.5 Areas for further research

- The controlled CRU needs to be evaluated on how it emits N_2O based on; amount and time of its application, soil type, soil moiture and temperature .This is because this was the first time the fertilizer was being tested for its potential to

mitigate N_2O emissions in the area, therefore the contrasting preliminary results of this study cannot be used to dismiss or accept it.

- Adopting crops with less N requirement in place of maize to test the climate resilience of zero tillage in strengthening the potential shown by ZT M/S treatment.
- More research on site specific model calibration for smallholder systems in tropical agricultural soils is required. This would include denitrification and nitrifictaion limits, and development of intercropping component since intercropping dominates smallholder farming systems in Kenya and SSA at large.

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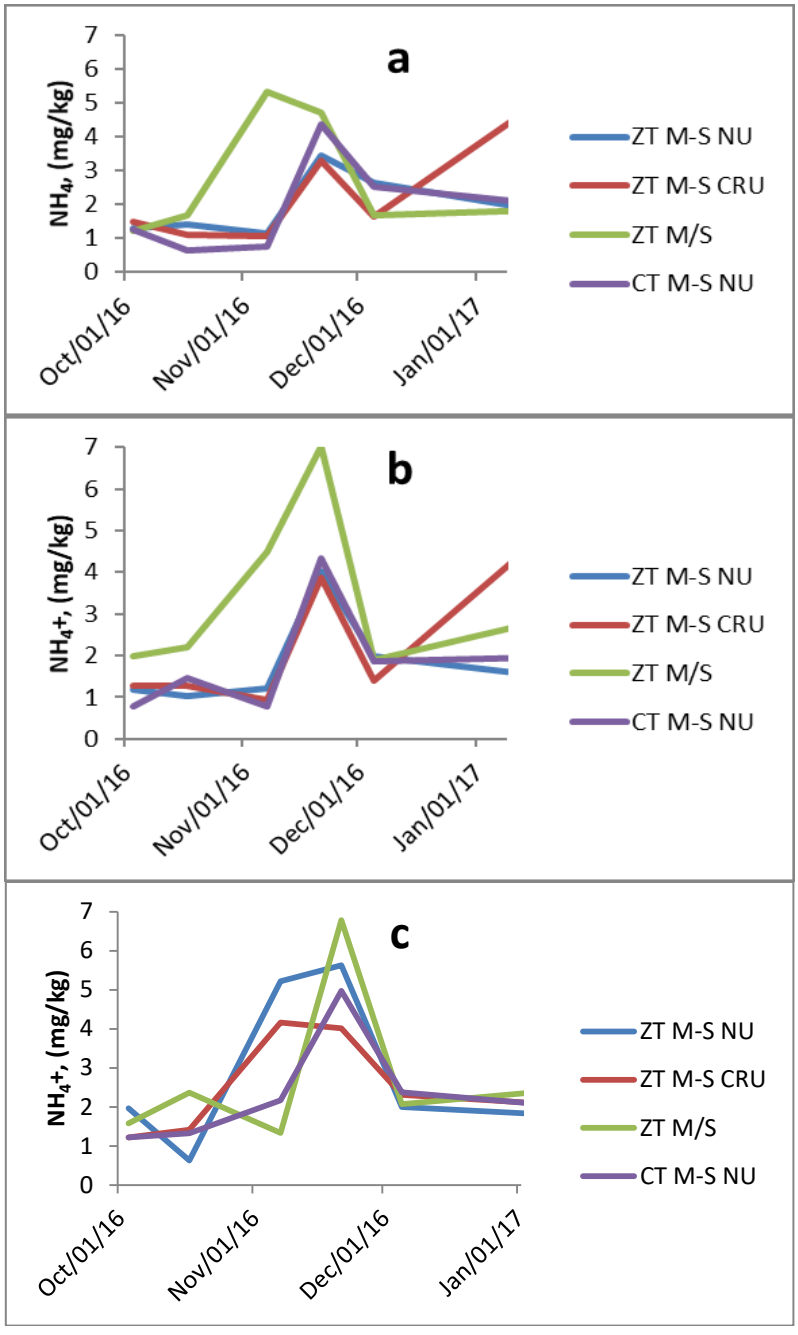
APPENDICES

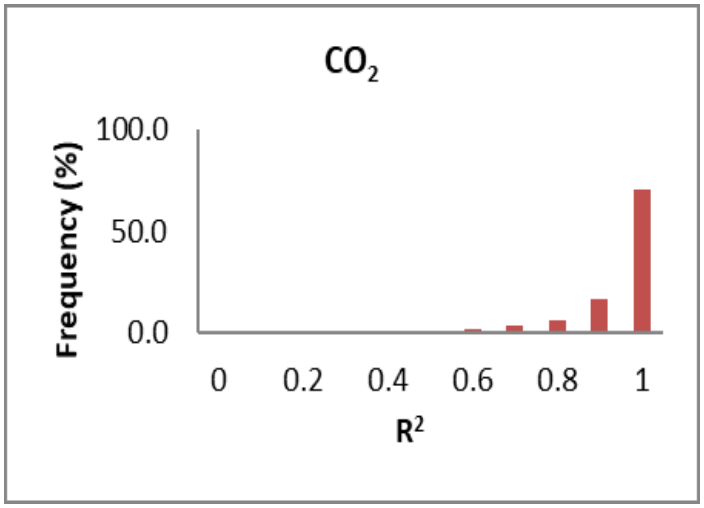
Appendix I: Initial soil status at the start of the experiment

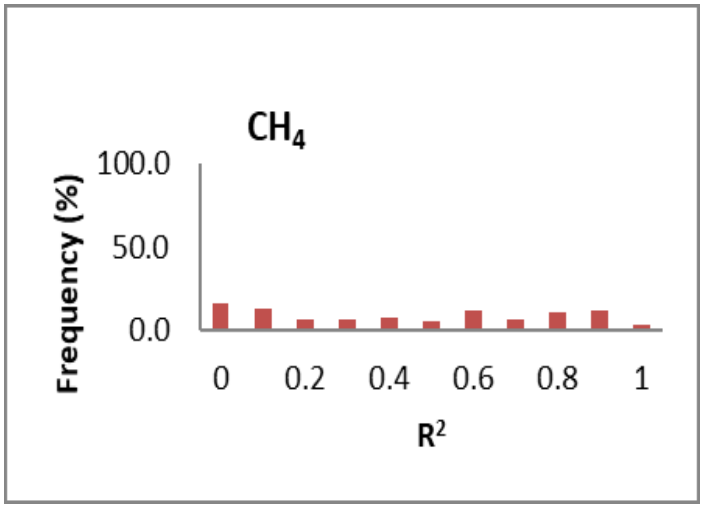
Treatment	pH	% C	% N
ZT M-S NU	4.7	1.9	0.17
ZT M-S CRU	4.7	1.9	0.17
ZT M/S	5.2	1.9	0.17
CT M-S NU	4.9	1.9	0.17

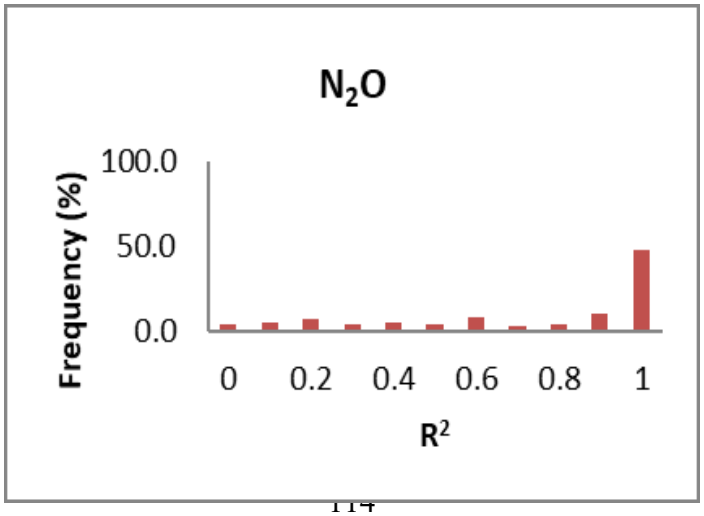
Appendix II: Concentration of nitrate at different weeks after planting (WAP) during 2016 short rains in Nyabeda



Appendix III: Frequecies of R^2 used for detection limits for GHG







Appendix IV: Daily N_2O emissions for Long rain 2016

Treatment	Daily N_2O fluxes for LR 2016 (g ha^{-1} d^{-1})															
	7-Apr-16	9-Apr-16	11-Apr-16	14-Apr-16	18-Apr-16	21-Apr-16	26-Apr-16	3-May-16	9-May-16	18-May-16	27-May-16	9-Jun-16	20-Jun-16	5-Jul-16	16-Jul-16	Total fluxes
ZT M-S NU	2.23	14.6	9.07	7.93	13.31^{a}	15.4^{b}	3.41^{b}	4.44^{b}	4.56^{b}	3.37^{b}	0.53	-0.09	1.35	2.18	0.7	83.0^{b}
ZT M-S CRU	2.91	11.4	9.98	9.21	14.02^{a}	26.04^{a}	8.49^{a}	15.21^{a}	20.01^{a}	6.23^{a}	4.18	-0.51	3.17	0.94	0	131.3^{a}
ZT M/S	1.5	9.1	7.49	7.19	3.81^{b}	10.67^{b}	1.38^{b}	2.24^{b}	1.46^{b}	0.38^{c}	1.61	1.7	0.8	0.92	0.2	50.5^{b}
CT M-S NU	1.86	9.4	5.34	7.09	18.11^{a}	10.41^{b}	2.28^{b}	3.88^{b}	4.99^{b}	3.92^{b}	1.25	1.41	1.61	2.49	0.48	74.5^{b}
p value	0.31	0.53	0.19	0.85	**0.01**	**0.027**	**0.002**	**<.001**	**0.004**	**0.003**	0.25	0.15	0.22	0.33	0.97	**0.02**
esd	0.69	3.95	1.95	2.69	2.73	4.08	1.07	1.16	3.09	0.86	1.67	0.96	1.02	0.98	1.46	17.20
lsd	1.69	9.66	4.77	6.57	6.67	9.99	2.61	2.85	7.57	2.10	4.09	2.34	2.50	2.39	3.56	42.09

Appendix V: Daily N_2O emissions for short rain 2016

Treatment	Daily N_2O fluxes for SR 2016 (g ha^{-1} d^{-1})																
	12-Sep-16	14-Sep-16	20-Sep-16	24-Sep-16	27-Sep-16	3-Oct-16	10-Oct-16	17-Oct-16	24-Oct-16	31-Oct-16	7-Nov-16	15-Nov-16	21-Nov-16	12-May-16	14-Dec-16	17-Jan-17	Total fluxes
ZT M-S NU	4.6	8.1	-0.1	8.0	1.3	4.6	0.3	0.4	1.7	0.8	1.5	7.1	4.6	4.8	1.8	-0.2	49.3
ZT M-S CRU	0.9	10.2	1.4	7.8	7.1	9.0	0.9	0.5	3.0	3.6	1.5	4.3	5.7	1.9	0.3	2.0	60.1
ZT M/S	5.1	7.4	0.2	8.9	1.4	3.3	0.6	0.1	3.4	0.8	1.1	-0.1	0.6	2.3	0.0	0.5	35.3
CT M-S NU	3.8	1.9	1.7	1.5	3.4	3.0	1.3	0.1	1.3	1.9	1.3	1.1	9.0	1.0	0.6	0.3	33.2
p value	0.5	0.154	0.43	0.311	0.202	0.332	0.406	0.812	0.88	0.275	0.467	0.095	0.074	0.348	0.197	0.41	0.24
esd	2.9	3.1	1.2	3.9	2.7	3.3	0.6	0.5	3.0	1.4	0.3	2.5	2.5	2.0	0.8	1.2	13.22
lsd	7.1	7.7	3.0	9.6	6.5	8.1	1.4	1.2	7.4	3.5	0.8	6.1	6.1	4.9	1.9	3.0	32.34

Appendix VI: Daily CO_2 emissions for long rains 2016

Treatment	Daily CO_2 fluxes for LR 2016 (kg ha^{-1} d^{-1})															
	7-Apr-16	9-Apr-16	11-Apr-16	14-Apr-16	18-Apr-16	21-Apr-16	26-Apr-16	3-May-16	9-May-16	18-May-16	27-May-16	9-Jun-16	20-Jun-16	5-Jul-16	16-Jul-16	Total fluxes
ZT M-S NU	19.5	28.9	23.1	22.1	28.7	33.3	26.5	26.1	21.7[b]	32.5	34.0	20.1	31.6	20.9	16.5	385.5
ZT M-S CRU	19.4	28.6	25.4	20.2	23.6	32.8	23.9	23.4	40.6[a]	38.9	36.9	26.5	36.1	18.2	17.0	411.4
ZT M/S	16.7	25.0	28.4	22.6	24.3	37.3	26.3	24.3	17.7[b]	27.4	41.5	34.2	34.4	21.6	25.1	406.9
CT M-S NU	15.7	30.6	17.1	1.0	33.7	22.6	19.6	21.1	39.5[a]	28.6	33.7	22.0	29.9	17.1	9.4	362.7
p value	0.149	0.515	0.129	0.22	0.142	0.139	0.289	0.845	**0.003**	0.13	0.85	0.154	0.812	0.896	0.22	0.54
esd	1.7	3.6	4.1	5.8	4.1	5.4	3.6	5.6	4.3	4.4	9.9	5.6	6.9	6.8	6.4	35.7
lsd	4.2	8.9	9.9	14.1	9.9	13.2	8.8	13.8	10.5	10.7	24.3	13.6	0.2	16.7	15.7	87.2

Appendix VII: Daily CO_2 emissions for short 2016

Treatment	Daily CO_2 fluxes for SR2016 (kg ha^{-1} d^{-1})																
	12-Sep-16	14-Sep-16	20-Sep-16	24-Sep-16	27-Sep-16	3-Oct-16	10-Oct-16	17-Oct-16	24-Oct-16	31-Oct-16	7-Nov-16	15-Nov-16	21-Nov-16	12-May-16	14-Dec-16	17-Jan-17	Total fluxes
ZT M-S NU	18.6	22.6	6.6	9.2	9.0[b]	9.2	6.0	6.3	9.6	7.9	29.8	26.4	21.6	32.9	15.1	7.4	239.0
ZT M-S RU	23.4	25.2	12.5	22.6	15.1[a]	8.1	9.1	8.5	7.5	9.6	28.3	20.3	18.8	27.7	16.3	5.7	258.7
ZT M/S	16.2	21.7	8.1	15.1	9.8[b]	12.1	6.0	7.1	27.7	9.2	29.5	25.9	26.7	23.5	22.6	11.3	272.3
CT M-S NU	18.6	13.8	7.9	9.0	6.6[b]	10.5	7.5	6.8	11.5	15.0	21.1	17.3	21.4	18.1	13.2	11.3	209.6
p value	0.31	0.076	0.363	0.128	**0.006**	0.915	0.523	0.853	0.25	0.188	0.576	0.341	0.708	0.542	0.319	0.18	0.51
esd	3.5	3.6	3.2	5.4	1.4	5.9	2.3	2.6	9.7	3.0	6.9	5.3	6.7	10.0	4.8	2.6	41.50
lsd	8.6	8.7	7.8	13.2	3.5	14.3	5.7	6.4	23.8	7.3	16.8	13.1	16.4	24.4	11.7	6.5	101.50

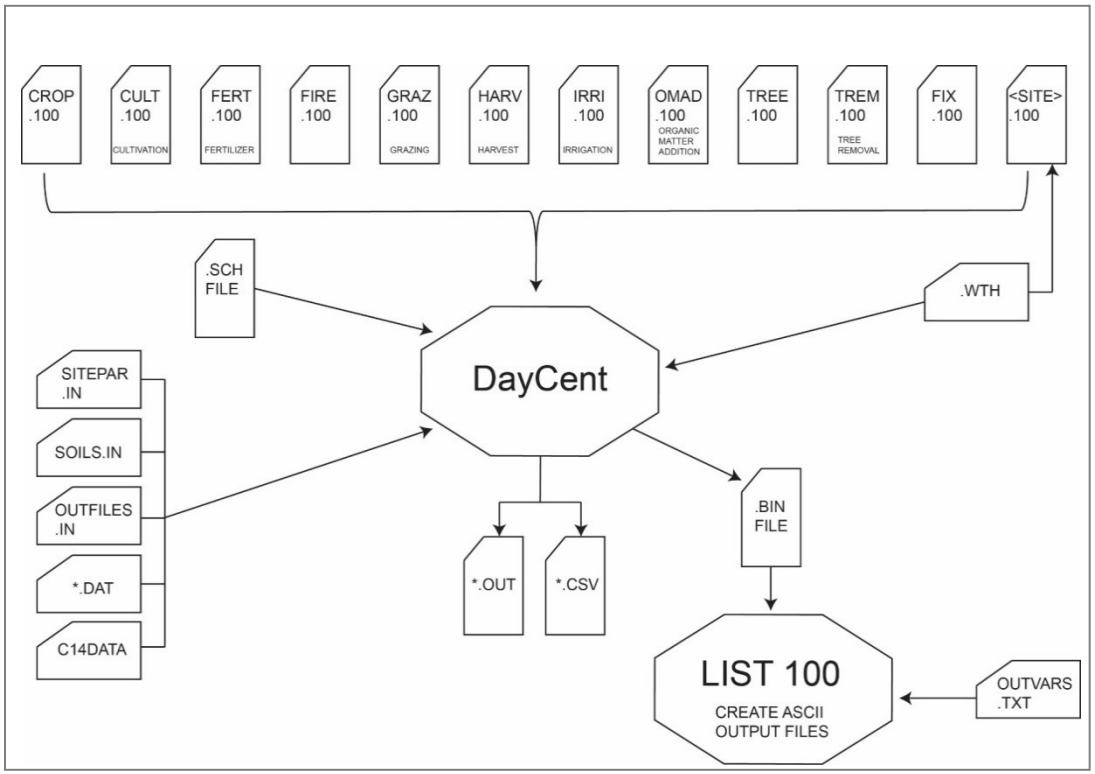
Appendix VIII: Daily CH_4 emissions for long rains 2016

Treatment	Daily CH_4 fluxes for LR 2016 (g ha^{-1} d^{-1})															
	7-Apr-16	9-Apr-16	11-Apr-16	14-Apr-16	18-Apr-16	21-Apr-16	26-Apr-16	3-May-16	9-May-16	18-May-16	27-May-16	9-Jun-16	20-Jun-16	5-Jul-16	16-Jul-16	Total fluxes
ZT M-S NU	-0.5	0.8	-5.5	4.2	1.5[a]	1.2	-0.3	-2.1	-5.3	0.5	-0.2	-4.2	4.5	-5.1	-4.5	-15.0
ZT M-S CRU	0.7	1.9	7.6	-2.4	2.0[a]	-7.1	-0.7	-1.2	-3.3	-2.7	1.4	-3.9	2.0	-2.2	0.9	-7.0
ZT M/S	0.6	-2.6	0.8	1.4	0.4[a]	-2.5	-1.2	-1.9	-5.0	0.9	-1.0	-6.6	-9.8	-4.5	-8.5	-39.5
CT M-S NU	-0.8	0.0	0.3	-3.5	-1.8[b]	-5.8	-2.6	2.7	-0.7	-3.7	-5.4	-3.1	-10.6	-4.0	-1.6	-40.7
p value	0.92	0.75	0.46	0.15	0.02	0.34	0.52	0.81	0.72	0.32	0.50	0.94	0.43	0.53	0.25	0.46
esd	2.8	4.2	7.6	3.1	0.8	4.5	1.5	5.5	4.4	2.7	4.4	5.8	10.7	2.0	4.3	24.2
lsd	6.8	10.3	18.7	7.6	2.1	11.0	3.7	13.6	10.7	6.6	10.6	14.2	26.3	4.9	10.5	59.3

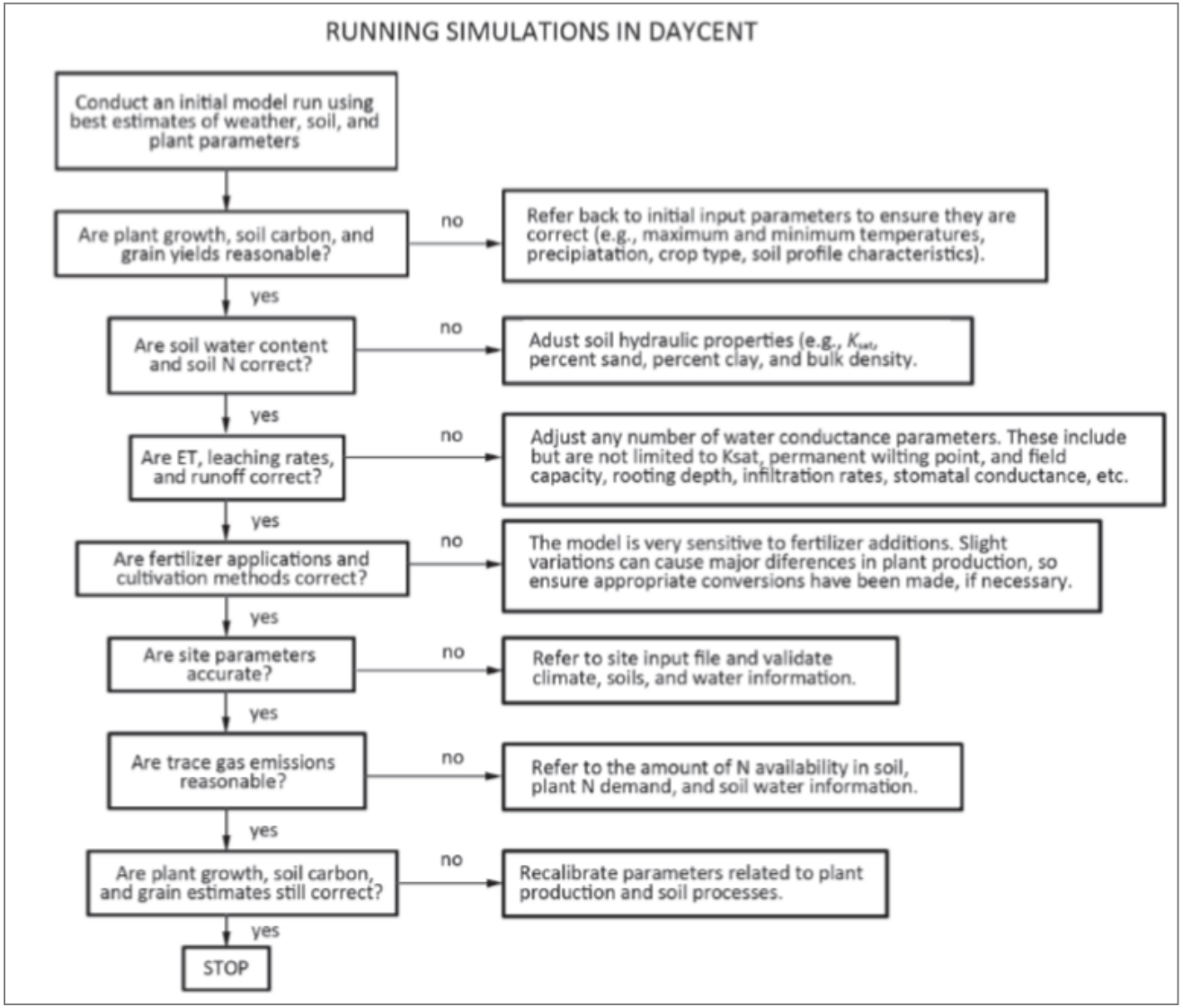
Appendix IX: Daily CH_4 emissions for short rains 2016

Treatment	Daily CH_4 fluxes for SR 2016 (kg ha^{-1} d^{-1})																
	12-Sep-16	14-Sep-16	20-Sep-16	24-Sep-16	27-Sep-16	3-Oct-16	10-Oct-16	17-Oct-16	24-Oct-16	31-Oct-16	7-Nov-16	15-Nov-16	21-Nov-16	12-May-16	14-Dec-16	17-Jan-17	Total fluxes
ZT M-S NU	-0.2	-2.2	-6.4	-5.3	-2.5	3.9	3.6	-1.8	-0.8	-0.3	-1.9	-2.1	0.2	-4.0	0.8	2.8	**-25.9**
ZT M-S CRU	-6.5	-1.1	0.3	-3.8	4.0	-1.6	-4.7	-0.4	-1.5	0.8	-2.8	1.8	0.1	-0.9	-1.3	-0.8	**-18.3**
ZT M/S	-0.2	-2.5	-5.8	-12.3	2.3	1.3	6.9	7.0	-0.9	-1.8	-1.7	-4.8	-4.4	-1.1	1.3	-1.6	**-18.5**
CT M-S NU	-3.1	2.3	-1.9	-5.5	1.2	1.8	-5.1	-2.8	-3.5	-2.0	-3.5	-3.1	1.7	-3.3	-1.8	-6.0	**-34.5**
p value	0.69	0.41	0.65	0.75	0.89	0.86	0.14	0.27	0.91	0.28	0.94	0.35	0.33	0.31	0.78	0.13	0.75
esd	5.1	2.9	6.0	8.3	8.8	6.5	5.2	4.8	4.3	1.4	3.2	3.5	3.2	1.8	3.6	1.9	16.80
lsd	12.6	7.1	14.6	20.3	21.6	15.9	12.8	11.8	10.5	3.5	7.8	8.5	7.7	4.4	8.7	4.7	41.11

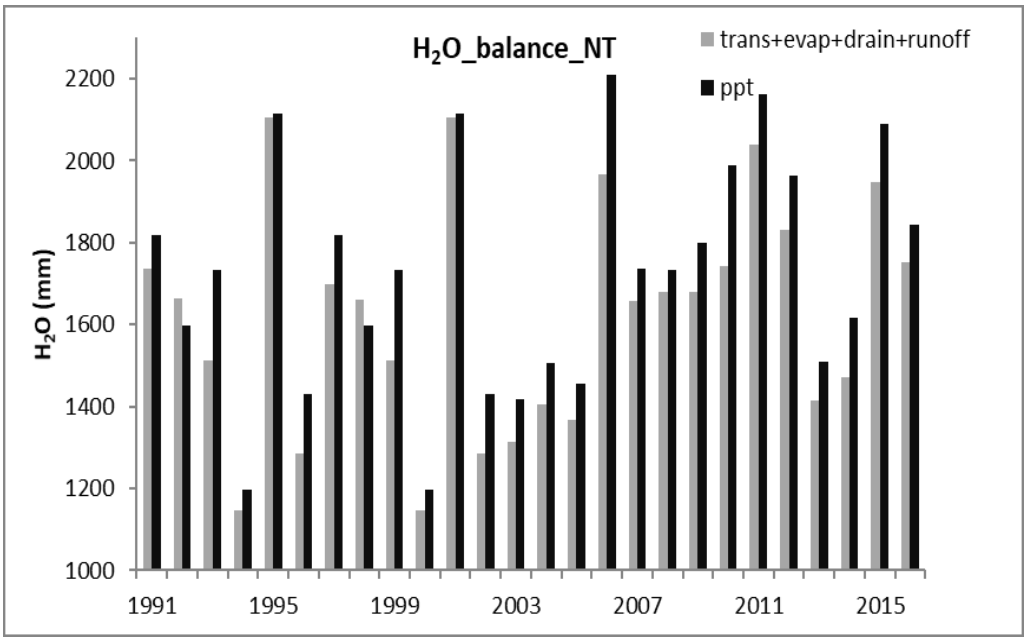
Appendix X: Schematic summary of DAYCENT model showing all the files for running the simulations. (Source: Del Grosso, 2001)



Appendix XI: Steps for calibrating DAYCENT Model
(Source: Del Grosso et al., 2001)

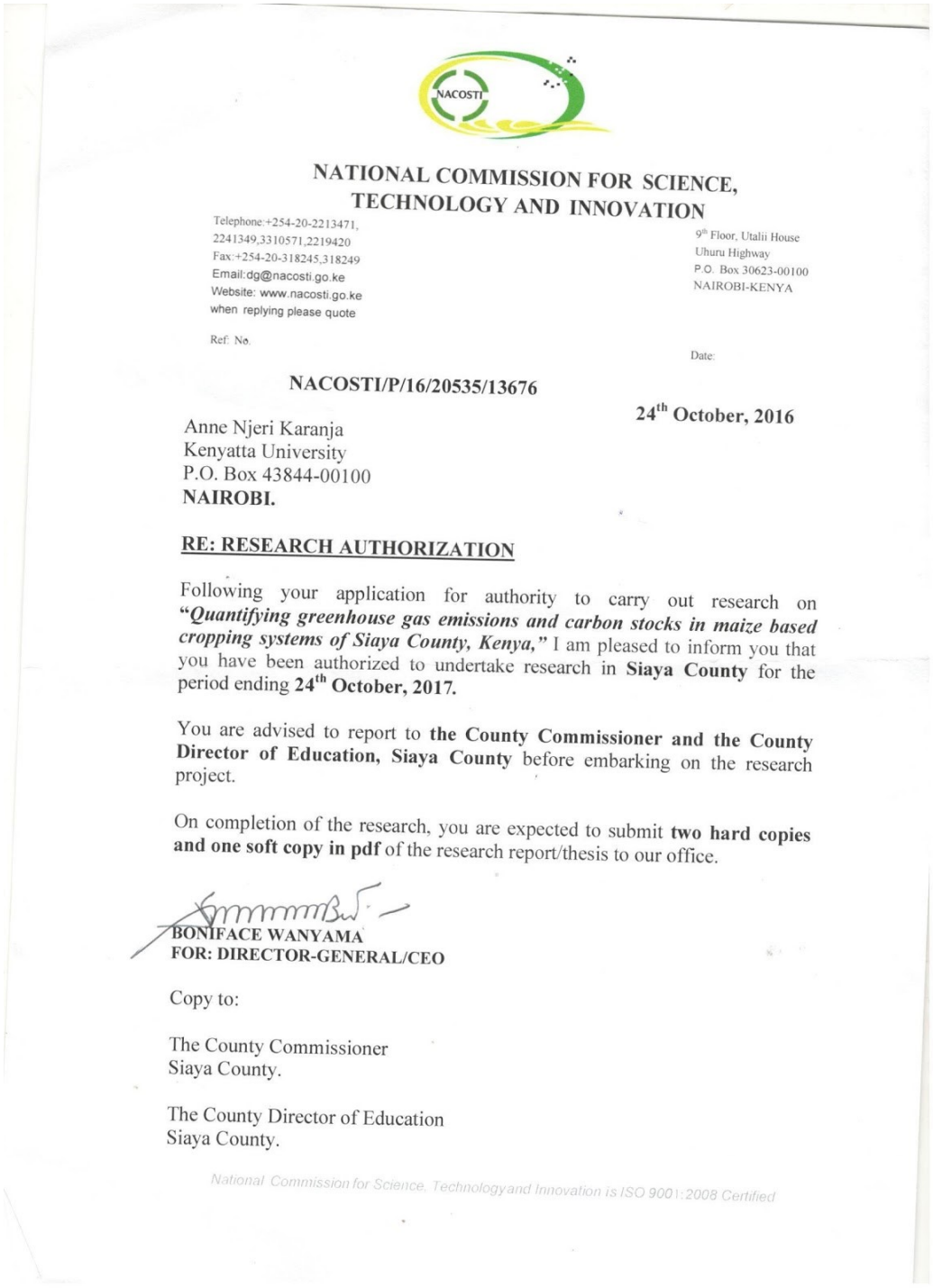


Appendix XII: Model Simulated water balances



The model simulated precipitation to be higher than water the combined total of transpiration, evaporation, drainage and runnoff. This is one of the basic conditions to check if the model is simulating correctly.

Appendix XIII: NACOSTI research authorization letter



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Ref: No.

Date:

NACOSTI/P/16/20535/13676

24th October, 2016

Anne Njeri Karanja
Kenyatta University
P.O. Box 43844-00100
NAIROBI.

RE: RESEARCH AUTHORIZATION

Following your application for authority to carry out research on ***"Quantifying greenhouse gas emissions and carbon stocks in maize based cropping systems of Siaya County, Kenya,"*** I am pleased to inform you that you have been authorized to undertake research in **Siaya County** for the period ending **24th October, 2017.**

You are advised to report to **the County Commissioner and the County Director of Education, Siaya County** before embarking on the research project.

On completion of the research, you are expected to submit **two hard copies and one soft copy in pdf** of the research report/thesis to our office.

BONIFACE WANYAMA
FOR: DIRECTOR-GENERAL/CEO

Copy to:

The County Commissioner
Siaya County.

The County Director of Education
Siaya County.

National Commission for Science, Technology and Innovation is ISO 9001:2008 Certified