FACULTY OF AGRICULTURAL SCIENCES

Institute of Agricultural Sciences in the Tropics

(Hans-Ruthenberg-Institute, 490)

Section: Agronomy in the Tropics and Subtropics (490e)

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UNIVERSITY OF HOHENHEIM

1818

Nitrogen dynamics in organic and conventional farming systems in the sub-humid highlands of central Kenya

Dissertation
Submitted in fulfilment of the requirements for the degree
"Doktor der Agrarwissenschaften"
(Dr.sc.agr. / Ph.D. in Agricultural Sciences)
to the
Faculty of Agricultural Sciences

Presented by

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Stuttgart-Hohenheim, July 2019

This thesis was accepted as a doctoral dissertation in fulfilment of the requirements for the degree "Doktor der Agrarwissenschaften" by the Faculty of Agricultural Sciences at University of Hohenheim by Faculty of Agricultural sciences at the University of Hohenheim, Stuttgart, Germany on 7th February 2016.

Date of the oral examination: 26th June 2019

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Dedication

To God and the Father of our Lord Jesus Christ and to my beloved family Daniel, Mercy, Hope and Praise Musyoka

Acknowledgements

I acknowledge the Lord of all grace for granting me this opportunity to study. He has made everything appropriate in its time (Ecclesiastes 3:11). Oh, the depth of the riches of the wisdom and knowledge of God! How unsearchable His judgments, and untraceable His ways! (Romans 10:33) for by Him I can ran through a troop, by my God I can leap over a wall (2 Samuel 22:30). I am forever grateful to God for enabling me to overcome all the challenges and handles I faced during this period. I am sincerely grateful to Dr. Juan Cobo and Dr. Brigitte Nyambo who encouraged me to apply for this PhD program and planned with *icipe* management for me to be able study and work in the project.

I learnt and gained extensive knowledge from my supervisors; Dr. Noah Adamtey, Dr. Anne W. Muriuki and Prof. Dr. Georg Cadisch. I am indebted to them for all their guidance, constant encouragement; generous inputs to the manuscripts and their continuous interest in the progress of my studies. “For the student is not above the teacher, but everyone who is fully trained will be like their teacher” Luke 6:50. I sincerely appreciate the counsel received from Dr. Anne Muriuki on how to balance work-family-studies to avoid burnouts. I appreciated all the support accorded to me by FiBL through the project “Long-term Farming System Comparisons in the Tropics” funded by Swiss Development Cooperation (SDC), LED, CCOOP Sustainability Fund and Biovision Foundation. I would like to acknowledge *icipe* (implementing agency of the project in Kenya) for the opportunity to carry out my PhD study within the project. I am grateful for the support and guidance accorded to me by Dr. Komi Fiaboe as I discharged my studies and work duties at *icipe*.

I sincerely appreciate the support offered by the SysCom project team during field activities, data collection, soil sampling and all the other activities. I appreciate the immense support offered by Mr. Edward Karanja, the late Mr. Peter Owuor, Ms. Jane Makena and Ms. Felistus

K. Mutua who supported me during all the processes of data collection and transfer of samples to the laboratories.

I am grateful for the KALRO Muguga Soil chemistry laboratory staff led by Mr. Nicholas Kung'u and Peter Wakaba for their support and encouragement during soil and plant samples handling, extraction and analysis process. The support by FiBL international department team and the Hohenheim University, Agronomy in the Tropics and Subtropics team (Institute 490e) is much appreciated. I appreciate the special support given by David Bautze in drawing graphs using Prism software and German translation of my Thesis summary. I sincerely appreciate accommodation offered by Dr. Mary Kamaa and Dr. Esther Muema during my stay at Stuttgart and FiBL guest house team during my stay at FiBL, Frick.

Finally, I wish to extend my deepest and immeasurable gratitude to my beloved husband Daniel M. Nzyuko for his moral support, encouragement, prayers and selfless sacrifice to take care of our daughters as I undertook this study. May the Lord richly bless you and extend your boundaries. I deeply appreciate our daughters Mercy Neema Musyoka, Hope Mwende Musyoka and Praise Muathime Musyoka for their patience, encouragement, love and sacrifice that empowered me to accomplish the task.

Abbreviations and acronyms	
AE	Agronomic efficiency
AEN	Agronomic efficiency of Nitrogen
AEZs	Agro-ecological zones
APSIM	Agricultural Production Systems sIMulator
BNF	Biological nitrogen fixation
C	Carbon
Ca	Calcium
CA	Conservation agriculture
CAADP	Comprehensive Africa Agriculture Development Programme
CAN	Calcium ammonium nitrate
DAP	Di-ammonium phosphate
DAS	Days after sowing
DON	Dissolved Organic Nitrogen
DIN	Dissolved Inorganic Nitrogen
DSSAT	Decision Support System for Agrotechnology Transfer
FAO	Food and Agriculture Organization of the United Nations
FiBL	Research institute of organic Agriculture
ISFM	Integrated Soil Fertility Management
IER	Ion-Exchange Resin
K	Potassium
KALRO	Kenya Agricultural Research Institute
KCl	Potassium chloride
Kg	Kilogram
LEIA	Low external input agricultural
LTE	Long-term experiments
MoA	Ministry of Agriculture
Mg	Magnesium
N	Nitrogen
N_2O	Nitrous Oxide
N, P, K	Nitrogen, Phosphorus and potassium
NH_4^+-N	Ammonium nitrogen
NO_3^--N	Nitrate nitrogen
NHI	Nitrogen harvest Index
NUE	Nitrogen use efficiency
NUpE	Nitrogen uptake efficiency
NUtE	Nitrogen Utilization efficiency
P	Phosphorus
PR	Phosphate rock
SOM	Soil Organic matter
SSA	Sub-Saharan Africa
TSP	Triple superphosphate
WaNuLCAS	Water Nutrient Light Capture

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Executive summary

Nitrogen (N) deficit is one of the limiting factors to food security in most developing countries while the excessive use of N has resulted in environmental contamination. Timely N availability, at the right rate is crucial to improving crop yield and N use efficiency in farming systems. Therefore, understanding nitrogen dynamics under different farming systems is essential to improve N use and recovery efficiencies of crops and in addressing environmental impacts associated with increased use of inorganic and organic inputs. This study focused on N dynamics in conventional (Conv) and organic (Org) farming systems as practiced by small scale farmers (at ~50 kg N $ha^{-1}yr^{-1}$, Low input) and at recommended levels of input (~225 kg N $ha^{-1}yr^{-1}$, High input) for commercial use in the sub humid and humid regions of Central Kenya. Data was collected during three cropping seasons between October 2012 and March 2014 in an on-going long-term trial established since 2007 at Chuka and at Thika sites located in central highlands of Kenya. Mineral N-based fertilizer and cattle manure were applied in Conv-High and Conv-Low while composts and other organic inputs were applied at similar N rates for Org-High and Org-Low. Farming systems were laid down in a randomized complete block design with 4 and 5 replications at Chuka and Thika respectively. The trial follows a 2 season-three-year crop rotation envisaging maize, legumes, vegetables and potatoes.

N mineralization was studied using a modified buried bag approach while N loss was measured using Self-Integrating Accumulator (SIA) cores. N synchrony was assessed using daily N flux differences constructed as daily N release minus daily N uptake at different stages of the crops. N uptake was assessed at various stages of the crop through destructive sampling while nitrogen use efficiency (NUE) was assessed at harvest. Surface N balances were constructed using N applied as inputs, N deposition via rainfall, biological N fixation and crop yield and biomass as outputs.

Out of the total N applied from inputs, only 61, 43 and 71 % was released during potato, maize and vegetable seasons respectively. Farming systems did not show a major impact in their influence on N synchrony, i.e. matching N supply to meet N demand. Rather the N synchrony varied with crop and N demand stages. Positive N flux differences were observed (higher N release compared to N demand) during the initial 20-30 days of incubation for all the farming systems, and negative N flux differences (higher N demand than release) at reproductive stages of the crops.

Nitrogen uptake efficiency (NUpE) of potato was highest in Conv-Low and Org-Low at Thika and lowest in Org-High and Org-Low at Chuka where late blight disease affected potato performance. In contrast, NUpE of maize was similar in all systems at Chuka site, but was significantly higher in Conv-High and Org-High compared to the low input systems at Thika site. The NUpE of cabbage was similar in Conv-High and Org-High while the NUpE of kale and Swiss chard were similar in the low input systems. Potato N utilization efficiencies (NUtE) and agronomic efficiencies of N use (AE_N) in Conv-Low and Conv-High were higher than those from Org-Low and Org-High, respectively. The AE_N of maize was similar in all the systems at Chuka but was higher in the high input systems compared to the low input systems at the site in Thika. The AE_N of vegetables under conventional systems were similar to those from organic systems.

Both conventional and organic systems lost substantial amounts of mineral-N into lower soil horizons before crop establishment (0-26 days). Cumulative NO_3^--N leached below 1 m was similar in all the farming systems but was higher at the more humid Chuka site compared to Thika site during the maize season. Significantly more N was leached during potato season compared to maize and vegetable seasons. When NO_3^--N leached was expressed over total N applied, 63-68% more NO_3^--N was leached from the low input systems compared to the high input systems. Org-High showed a positive partial N balance at both sites and in all the

cropping systems except during the vegetable season at Chuka. All the other systems exhibited negative partial N balances for the three cropping seasons with exception of Conv-High during potato season and Conv-Low and Org-Low during vegetable season at Thika site.

In summary, organic and conventional had similar effects on N release, synchrony and N loss through leaching. Furthermore, more N was leached (when expressed as a fraction of N applied) during potato and vegetables cropping seasons in the low input systems compared to the high input systems. In addition, conventional and organic farming systems had similar effects on NUpE, AE_N, NUtE and NHI for maize and vegetables, while conventional systems improved NUE of potato compared to organic systems. The research therefore concludes that organic and conventional farming systems at high input level are viable options of increasing food security in sub-Saharan Africa (SSA) for maize and vegetables as demonstrated by similar yields, NUE, N supply and loss. Ability to meet food security in conventional and organic system at low input is hampered by high N losses, negative N balances coupled with low productivity due to biotic and abiotic stresses. In both conventional and organic systems, there is a need to reduce N application at planting and increase N applied at reproductive stages to minimize potential loss during the initial 20-30 days after application and improve N supply midseason when crop demand is high. Since organic systems depend on organic inputs, there is a critical need to improve the quality of manure, composts and other organic inputs to improve N supply and availability.

Zusammenfassung

Stickstoff-(N)-Mangel für Kulturpflanzen ist einer der limitierenden Faktoren für die Ernährungssicherheit in den meisten Entwicklungsländern, wohingegen die übermäßige Verwendung von N zu einer Umweltverschmutzung geführt hat. Eine rechtzeitige N-Verfügbarkeit ist entscheidend für die Verbesserung der Ernteerträge und der N-Nutzungseffizienz in der Landwirtschaft. Daher ist ein besseres Verständnis der Stickstoffdynamik unter verschiedenen Produktionssystemen unerlässlich, um die N-Nutzung und die N-Rückgewinnungseffizienz von Nutzpflanzen zu verbessern und die Umweltauswirkungen im Zusammenhang mit der verstärkten Nutzung anorganischer und organischer Betriebsmittel zu verringern. Die vorliegende Studie beschäftigt sich mit der N-Dynamik in konventionellen (Conv) und ökologischen (Org) Produktionssystemen, wie sie von Kleinbauern (~50 kg N ha^{-1} yr^{-1}, Low Input) oder mit den empfohlenen Nährstoffwerten für den kommerziellen Einsatz (~225 kg N ha^{-1} yr^{-1}, High Input) in den subhumiden und humiden Regionen Zentralkenias praktiziert werden. Die vorliegenden Daten wurden während drei Vegetationsperioden zwischen Oktober 2012 und März 2014 in einem seit 2007 laufenden Langzeitversuch an den Standorten Chuka und Thika im Zentralen Hochland Kenias erhoben. In den Produktionssystemen Conv-High und Conv-Low wurden N-basierte Mineraldünger und Rindermist eingesetzt, wohingegen in Org-High und Org-Low Kompost und andere organische Düngemittel mit ähnlichen N-Mengen eingesetzt wurden. Die Anbausysteme wurden in einem komplett randomisierten Blockdesign mit 4 bzw. 5 Replikationen in Chuka und Thika angelegt. Der Versuch folgt einer dreijährigen Fruchtfolge, die Mais, Hülsenfrüchte, Gemüse und Kartoffeln beinhaltet.

Die N-Mineralisierung wurde mithilfe eines modifizierten 'Buried-Bag'-Ansatzes ermittelt, während der N-Verlust mit Hilfe von Selbst-Integrierenden Akkumulatoren (SIA) gemessen wurde. Die N-Synchronität wurde anhand der Differenz der täglichen mineralischen N-

Freisetzung minus der N-Pflanzenaufnahme in verschiedenen Wachstumsstadien errechnet. Die Dynamik der N-Aufnahme während verschiedener Kulturstadien wurde durch destruktive Probenahme ermittelt, während die Effizienz der Stickstoffnutzung (NUE) zum Zeitpunkt der Ernte bewertet wurde. Partielle N-Bilanzen wurden anhand des ausgebrachten N, sowie dem Verlust durch die pflanzliche Biomasse berechnet.

Von dem insgesamt zugeführten organischem N wurden 61, 43 und 71 % während der Kartoffel-, Mais- und Gemüsesaison freigesetzt. Die landwirtschaftlichen Produktionssysteme hatten keinen unterschiedlichen Einfluss auf die N-Synchronität, d.h. die Anpassung des N-Angebots an die N-Nachfrage. Vielmehr variierte die N-Synchronität mit den Kulturstadien und der N-Nachfrage. Es wurden positive Differenzen des N-Fluxes (höhere N-Freisetzung im Vergleich zum N-Bedarf) während der ersten 20-30 Tage der Inkubation und negative Differenzen des N-Fluxes (N-Bedarf höher als Freisetzung) in den Reproduktionsstadien der Kulturen für alle Produktionssystemen beobachtet.

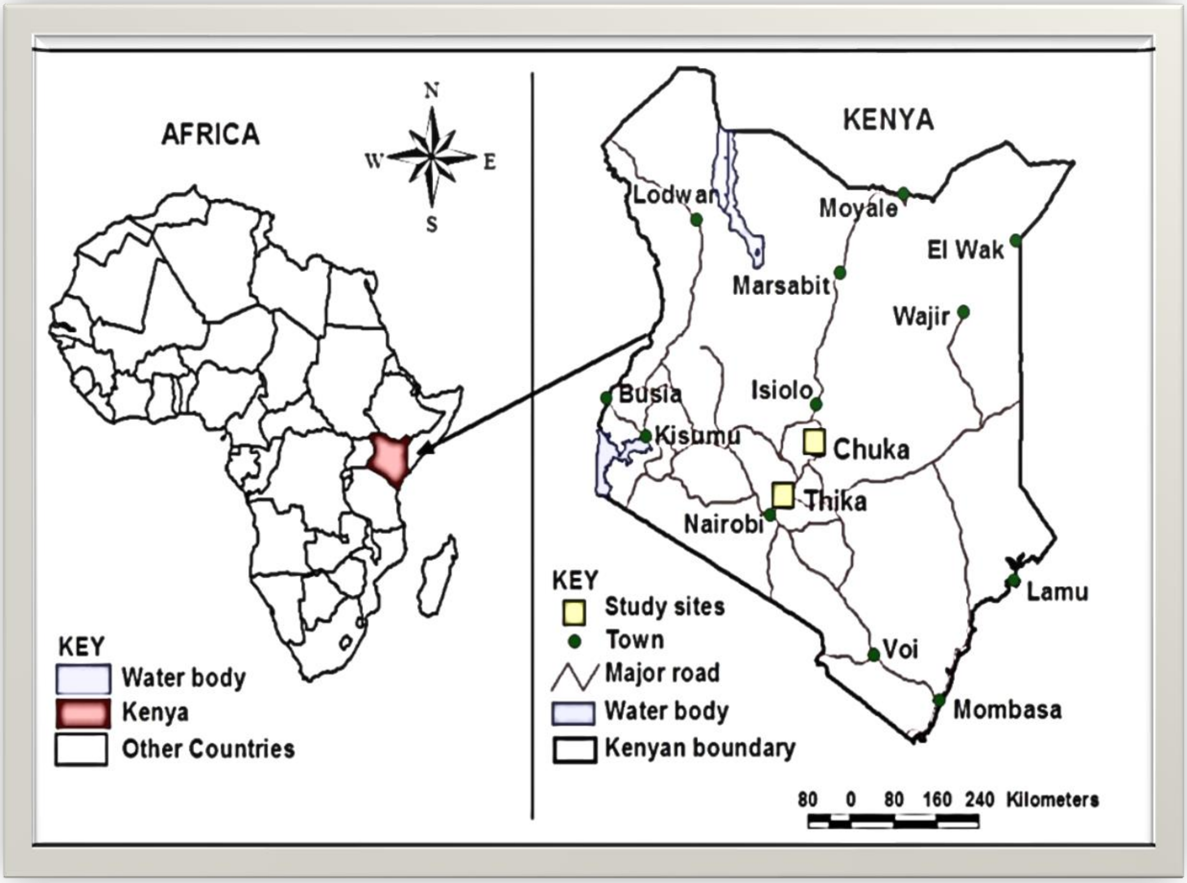
Die Stickstoffaufnahmeeffizienz (NUpE) der Kartoffel war am höchsten in den Produktionssystemen Conv-Low und Org-Low in Thika und am niedrigsten in Org-High und Org-Low in Chuka, wo die Krautfäule die Kartoffelproduktion beeinträchtigte. Die NUpE von Mais war in allen Systemen am Standort Chuka gleich, während sie in Thika für die High-Input-Systemen höher war als in den Low-Input-Systemen. Die NUpE von Weißkohl war in High-Input-Systemen gleich, wiederum war die NUpE von Grünkohl und Mangold nur in den Low-Input-Systemen gleich. Die N-Nutzungseffizienz der Kartoffel (NUtE) und die agronomische Effizienz der N-Nutzung (AE_N) in den Produktionssystemen Conv-Low und Conv-High waren höher als die in Org-Low bzw. Org-High. Die AE_N von Mais war in allen Systemen in Chuka vergleichbar, war aber in den High-Input-Systemen höher als in den Low-Input-Systemen in Thika. Die AE_N von Gemüse in den konventionellen Produktionssystemen war vergleichbar mit denen aus ökologischen Systemen.

Sowohl konventionelle als auch organische Produktionssysteme verloren erhebliche Mengen an mineralischen N in die unteren Bodenhorizonte bereits vor dem Auflaufen der Kulturen (0-26 Tage). Die kumulative Nitrat-N Auswaschung unter 1 m war in allen Anbausystemen gleich, lag aber am feuchteren Standort Chuka höher als am Standort Thika während der Maissaison.

Deutlich mehr N wurde in der Kartoffelsaison ausgewaschen als in der Mais- und Gemüsesaison. Wenn das ausgewaschene Nitrat-N im Verhältnis zur eingesetzten Gesamtmenge N ausgedrückt wurde, wurden 63-68 % mehr Nitrat aus den Low-Input-Systemen ausgewaschen als aus den High-Input-Systemen. Org-High zeigte eine positive partielle N-Bilanz an beiden Standorten und in allen Produktionssystemen mit Ausnahme der Gemüsesaison in Chuka. Alle anderen Systeme wiesen für die drei Vegetationsperioden mit Ausnahme von Conv-High während der Kartoffelsaison und Conv-Low und Org-Low während der Gemüsesaison am Standort Thika negative partielle N-Bilanzen auf.

Zusammenfassend lässt sich sagen, dass ökologische und konventionelle Produktionssysteme ähnliche Auswirkungen auf die N-Freisetzung, die Synchronität und den N-Verlust durch Auswaschung hatten. Darüber hinaus wurde während der Kartoffel- und Gemüsesaison in den Low-Input-Systemen relative mehr N ausgewaschen (ausgedrückt als Anteil des eingesetzten N) als in den High-Input-Systemen. Zudem hatten konventionelle und ökologische Produktionssysteme ähnliche Auswirkungen auf NUpE, AE_N, NUtE und NHI für Mais und Gemüse, während konventionelle Systeme die NUE von Kartoffeln im Vergleich zu ökologischen Systemen verbesserten. Die Studie kommt daher zu dem Schluss, dass ökologische und konventionelle Anbausysteme auf hohem Inputniveau für Mais und Gemüse eine tragfähige Option zur Erhöhung der Ernährungssicherheit in Subsahara-Afrika (SSA) sind, wie ähnliche Erträge, NUE, N-Versorgung und Verluste zeigen. Die Fähigkeit, die Ernährungssicherheit im konventionellen und ökologischen System mit niedrigem Input zu gewährleisten, wird durch hohe N-Verluste, negative N-Bilanzen und geringe Produktivität aufgrund biotischer und abiotischer Belastungen eingeschränkt. Sowohl in konventionellen als auch in ökologischen Produktionssystemen besteht die Notwendigkeit, den Einsatz von N bei der Aussaat zu verringern und andererseits die N-Düngung in der reproduktiven Phase zu erhöhen, um die potenziellen Verluste während der ersten 20-30 Tage nach der Aussaat zu minimieren und das N-Angebot in der Hauptwachstumsphase zu verbessern. Da ökologische Produktionssysteme von organischen Inputs abhängen, ist es dringend notwendig, die Qualität von Mist, Kompost und anderen organischen Inputs zu verbessern, um die N-Versorgung und Verfügbarkeit zu verbessern.

CHAPTER 1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Thika
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Mombasa
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Study sites
Town
Major road
Water body
Kenyan boundary
80 0 80 160 240 Kilometers

1.0. Introduction to the thesis

1.1. Background and rationale

Farming systems in the tropics are often associated with outflows of major nutrients that far exceed inflows (Smaling, 1993; Gachimbi et al., 2005; Onwonga and Freyer, 2006; Cobo et al., 2010). Due to this soil mining, per capita food production in most sub-Saharan Africa has declined. However, extensive research on different technologies that includes use of mineral fertilizers, organic resources such as manure, green manure legumes, agroforestry prunnings and composts, integrated use of both organic and mineral sources as well as the use of phosphate rocks (PR) has been conducted. A major focus has been on nitrogen (N) and phosphorus (P) which are the key limiting nutrients (Okalebo et al., 2006; Tittonell et al., 2007b; Gentile et al., 2009; Vanlauwe et al., 2011). Previously, conventional farming systems mainstreamed in most Sub-Saharan Africa (African countries south of the Sahara, SSA) by agricultural extension systems, have been associated with increased food production; but costs of production in these systems are generally very high and out of reach to the resource-poor farmers who dominate in Sub-Sahara Africa (Sanchez et al., 1997; Mateete et al., 2010; Vanlauwe et al., 2011). Further, due to continuous cropping, mechanical tillage and continuous use of pesticides in conventional farming, the system is often associated with a decline in soil productivity such as loss of soil organic matter and soil erosion (Tisdale and Nelson, 1993; Balota et al., 2004), loss of biodiversity, resistance of many pests to pesticides (Bellinger, 1996), and contamination of food and the environment (Pacini et al., 2003; Fließbach et al., 2007; Hathaway-Jenkins et al., 2011). On the other hand, long-term application of animal manures and other organic amendments can increase soil total and available nutrients in both surface and subsurface horizons (Mando et al., 2005), reduce soil P adsorption capacity (Kifuko et al., 2007), and increase soil organic matter (Mando et al., 2005) content due to stimulation of microbial and enzyme activities (Tiessen et al., 1994; Fließbach et al., 2007). However, when manures and low quality organic residues (<2.5% N lignin >14%, polyphenol >4%) are incorporated into the soil, only a small fraction of plant nutrients are released in the short term and are available to crops while the remaining fraction is retained in various soil pools and may be available in the long term to subsequent crops or lost to the environment. Thus, organic farming systems can act as nutrient sinks and can be very critical in contributing to nutrient losses into underground water reserves. In addition, currently promoted integrated soil fertility management approaches that embrace improved biological, chemical, physical, social economic, health and nutrition approaches need to be assessed in the long-term.

Nitrogen is of special interest in both organic and conventional farming systems. Most of the N is held in the soil as stable organic matter with up to 95% of N in organic forms in some soils (Bingham and Cotrufo, 2016). Its transformation is microbial mediated, and the processes are affected by many system specific factors such as management practices (e.g. tillage, previous fertilization intensity, cropping patterns), soil (chemical, physical, biological) characteristics, climate (soil moisture and temperature) and biotic factors (St. Luce et al., 2011). Nitrogen transformation processes that are dominant in the soil ecosystem are decomposition, mineralization and nitrification.

Nitrogen mineralization (release of NH_4^+) or immobilization (microbial assimilation of NH_4^+ and NO_3^-) occurs in farming systems depending on type of substrate (organic matter) or carbon content and nitrogen availability for utilization by microbes (Murphy et al., 2003). In high quality (materials with N >2.5%, lignin <15% and polyphenols<4%) residues nutrients are released rapidly during the initial stages (Gentile et al., 2009) and these could be in excess of nutrient demand by crops resulting in nutrient losses. Similarly, residues containing low N (<2.5%) and high lignin (>15%) may result in N immobilization in the first few weeks (Yadvinder et al., 2005; Gentile et al., 2009) such that crops planted after these residue application may suffer from deficiency of plant available N.

Nitrification is the constant transformation of relatively immobile NH_4^+ to more mobile form NO_3^- (Subbarao et al., 2006; Norton and Stark, 2011). The mobile NO_3^--N is made available for plant uptake and is also exposed to losses in gaseous forms as well as leaching and denitrification (Stange and Neue, 2009). The process of nitrification is affected by numerous factors such as soil moisture, temperature, soil oxygen concentration, SOM content, NH_4^+ availability and pH (Stange and Neue, 2009). Knowledge of N dynamics during crop development is therefore essential in ensuring N synchronization (the extent to which N supply match crop N uptake), improving nitrogen use efficiency (NUE) and mitigating potential losses to the environment (St. Luce et al., 2011).

1.2. Food security and N dynamics

Nitrogen plays a crucial role in food, feed and fibre production. Use of N has resulted in tripling of per capita food production in the last 50 years (Mosier et al., 2004; Prasad, 2013). However, pursuit of food production has encouraged adoption of technologies such as mono-cropping that has led to soil depletion (Altieri et al., 2017). In addition, achieving food security through agricultural intensification in densely populated and small holder farming systems has remained a challenge due to lack of supporting polices in most SSA countries (Palm et al., 2010). On-going research in Malawi reveals the impact of improved government policies in intensifying agricultural systems through subsidies to mineral fertilizers and hybrid maize seeds (Mungai et al., 2016). One of the major challenges in food production is ameliorating degraded soils while increasing the productivity and supply of ecosystem services (Power, 2010). In this case SOM and nitrogen become very critical. Thus, to be able to develop sustainable and environmentally friendly farming systems, research is required at different scales to assess N supply vs demand by crop (Spiertz, 2010). Increase in crop yield has been based on improved genetics, nutrient and water use efficiency (Sinclair and Rufty, 2012). Thus, improving NUE efficiency (defined as the ratio of N output and input in farming systems, (Fageria and Baligar, 2005) in different farming system would help improve food security as well as reduce environmental pollution (Luis et al., 2016). In SSA, most farming systems are characterized by low N input, N depletion, high N loss through erosion and leaching and low N use efficiency (Masso et al., 2017). N application rates in most SSA countries are still very low even after the commitments by Heads of African states government to raise nutrient application rate to 50 kg ha^{-1} Comprehensive Africa Agricultural Development Programme (CAADP, 2006 Abuja declaration) resulting in large yield gaps compared to the rest of the continents (Masso et al., 2017). Thus, research targeted at improving food security especially in SSA should target improving soil fertility, N use and supply and reduction of N loss into the environment as outlined in the Kampala statement of action on reactive N (INI, 2013; Stefan et al., 2016). Most of the common practices of improving soil fertility in SSA are associated with use of manure and other organic resources in addition to low amounts of mineral fertilizers. Research should thus also target on improving manure and mineral fertilizer quality (Diogo et al., 2013; Bold et al., 2015). N use efficiency improvement through crop management should embrace the 4R principles of the right source, right rate, right timing of application and right placement (Majumdar et al., 2016; Masso et al., 2017). In SSA low rates and inappropriate management of N application have resulted in low yields and hence food insecurity. Further, additional studies should incorporate profitability of the farming systems to improve productivity and hence improve food security (Masso et al., 2017). Nitrogen use efficiency also play a critical role in this process as low NUE may be caused by insufficiency of other nutrients (Mosier et al., 2004) such as P, K and micronutrients. Thus, adoption of different technologies such as use organic resources and integrated use of mineral fertilizer together with organic inputs may result to improved NUE and thus improve food security (Kihara et al., 2015; Masso et al., 2017). Significant improvement on NUE must be made in order to feed the world and avert the negative environmental impacts associated with surplus N (Balasubramanian et al., 2004).

1.3. Organic and conventional farming systems in the tropics

1.3.1. Development of organic farming systems in the tropics

Organic agriculture in the tropics has been viewed as a development from traditional farming fused with modern farming systems since most of the applied principles rely on indigenous knowledge (Guarino, 1995). In Africa, organic farming was initiated by non-governmental organizations and private institutions agitating against externalities associated with the green revolution (Kimemia and Oyare, 2006). For example, in Kenya, organic farming was initiated by Kenya institute of Organic Farming (KIOF) in 1986 (Kledal et al., 2009). Later, organic farmers trained by KIOF with the support of NGO's formed Kenya Organic Farmers Association (KOFA) and this later culminated to the formation of Kenya Organic Agriculture network after KOFA merged with Kenya Organic Producers association (KOPA) in 2005. Formation of national organic bodies has played a major role in the development of the organic sector in Africa (Kimemia and Oyare, 2006). Some of the major challenges in the development of organic farming systems has been the lack of legislation and government policy to support the development of the sector (Kledal et al., 2009). In Kenya, progress has been made on this front and a policy paper has been developed and is pending presentation to the law makers before it is passed as an act of parliament (Wanjiru Kamau, *personal communication*). Further, growth of organic farming has been facilitated by demand of certified organic produce by developed countries. Thus, certification processes in the tropics has been dominated by international certification bodies from countries with organic market niche (Kimemia and Oyare, 2006). In Kenya, certification bodies such as Ecocert (France), Institute of Market-Ecology (IMO, Germany), Bio Sussie (Switzerland) and Ceres (USA) have been active in the sector and hence organic farming has been driven by demand of organic products in developed countries. However, organic farming is practiced as certified and uncertified form. Although awareness of organic farming is still low with 13, 44 and 57 % of the population still not informed about organic farming in Uganda, Kenya and Tanzania (Ndungu, 2006) there has been significant progress in the organic sector. In 2007, East African Organic Products Standard (EAOPS) were developed and have been used as a basis for organic product certification in the region. By 2015, there were 1.7 million hectares of land under organic farming in Africa with 719000 producers involved (Niggli et al., 2017). The major organic products grown and sold in Africa include coffee, cocoa, olive oil and oil seeds which were grown mainly for export (UNEP-UNCTAD Capacity Building Task Force on Trade, 2010; Niggli et al., 2017). Data on productivity and profitability of organic systems is often lacking (Niggli et al., 2017) while progress in the organic sector has also been limited by lack of organic seeds, bio-pesticides and other inputs (Niggli et al., 2017). Further the sector faces challenges of being dependent on external market and hence more research needs to be done on organic food systems and their sustainability. The question on whether organic can feed the world lingers even though there are claims that organic farming systems improves food security as minimal research to deduce this has been conducted. Where research has been done, it is scattered in most African countries and this has resulted to the formation of Organic Research Centres Alliances by FAO to empower existing research centres to be centres of excellence (Bouagnimbeck, 2010).

1.3.2. Suitability in the tropics

There is currently a major debate on whether organic farming system can feed the world due to the yield gap observed between organic and conventional farming systems. Organic farming systems have been shown to yield about 80% of conventional systems (de Ponti et al., 2012) while in the tropics yields of organic systems have been found to be similar to those conventional systems after a three year conversion phase (Adamtey et al., 2016). This has been shown to differ between crops and regions (de Ponti et al., 2012). Suitability of farming systems is associated with yield stability over adverse climatic conditions as well as impact of the systems on soil ecology and environment. In addition, suitability of most ecological farming systems is site-specific and is dependent on natural, economic and social cultural conditions (Kotschi, 2013). In the recent past, organic agriculture production systems have increased with approximately 12 million ha of land under organic farming in developing countries being a positive indication of the performance of these systems (Rosinger, 2013). Long-term trials in Rodale Institute (United States of America) have shown that organic farming performed better that conventional farming systems under extreme weather conditions (Lotter et al., 2003). Further comparison between conventional and organic farming systems in the sub-Tropics have shown that organic systems performed better than conventional and that yield increases in organic cropping systems were achieved in less developed countries, and in arid regions (Te Pas and Rees, 2014). This is mainly due to improved water holding capacity as soil organic carbon may be higher in organic systems than in conventional ones. This makes organic farming suitable in the tropics where moisture stress is common. Further, use of *Tithonia* biomass transfer at Chuka (Tharaka Nithi county, central highlands of Kenya) has been found to yield highest grain yield compared to when combined with inorganic fertilizers while at Embu, after 11 years of application of *Leucaena* and *Calliandra* biomass transfer combined with half of the recommended inorganic fertilizer gave highest yields (Mugendi et al., 2007). In Long-term trails at Kabete (Kiambu County, Central highlands of Kenya), cumulative use of farm yard manure gave better yield than N and P fertilizer application alone (Kibunja et al., 2012). It is therefore noted that use of organic and integrated farming systems significantly increase productivity in the tropics. Consequently, the Sub-Saharan Africa Challenge Programme has developed a strategy to build on integrated soil fertility approach to increase productivity (Von Kaufmann, 2007). In addition, Africa under the Comprehensive Africa

Agriculture Development Programme (CAADP) has devised a plan to intensify agricultural production through adoption of suitable technologies such as ecological, organic and integrated farming systems in a bid to increase food production on a sustainable basis to match population increase (Robinson et al., 2015).

1.3.3. Challenges and comparisons

Some of the major challenges faced by small scale farmers are associated with adaptation to climate change impacts and lack of access to credit facilities making farmers more vulnerable to impacts of climate change (Bationo and Waswa, 2011). In addition, most of the agricultural systems are rain-fed and operate under inconsistent agricultural policies (Makonese and Sukalac, 2011). Organic and ecological farming systems also face challenges of government subsidies on mineral fertilizer to enable farmer's access to fertilizer inputs in SSA (Kotschi, 2013). This has a direct impact on soil productivity in the long-term for conventional systems while fertilizer subsidy by governments can attract more farmers and hence hamper adoption of organic farming given that organic and ecological systems require a lot of labour for compost preparation and application. Economic viability of use of inorganic fertilizers has been found to shrink over time (Kotschi, 2013) and any improvement must be by adjusting food prices to match the cost of fertilizers (Kotschi, 2013). The other challenge associated with most farming systems relates to reduction in soil organic matter. Most of the farming systems in the tropics have been shown to reduce SOC possibly due to the high temperatures that increases microbial activity resulting in rapid decomposition of applied organic matter (Kotschi, 2013). Thus, under FiBL LTE trials in Central Kenya, SOC has been shown to decline over the last seven years with a significant higher decline under conventional compared to organic high input systems (Adamtey et al., 2018) . On the contrary, a literature review comparing conventional and organic farming has shown that organic systems had 53% higher SOC compared to conventional systems (Te Pas and Rees, 2014). Organic farming is knowledge intensive as producers have to understand the farming practice, certification process (Seufert, 2012) and also market information (Bello, 2008b) In addition, organic farming systems in the tropics are associated with high risks of pests, poor soils and erratic rainfall which lower crop yields (Halberg et al., 2006). Crop diversity in organic and ecological farming systems reduces consequences of erratic rains (Halberg et al., 2006). Organic systems are also dependent on external markets to achieve premium prices as local markets may not be well developed (Seufert, 2012). In most SSA countries only minimal breeding efforts for organic crops have been done thus the system depends on conventionally bred crops and traditional (unimproved) crop varieties and this may be a major setback as these crops are bred for specific conditions.

Comparing organic and conventional farming systems is challenging due to differences in crop rotations. Research has reported that organic systems have more diversified cropping systems as a way of controlling weeds, pests and diseases and as a buffer against abiotic stress and climate change (Barbieri et al., 2017) while conventional farming systems have high value crops in the rotations (Nemes, 2009). There is therefore a difficulty in designing identical crop rotation in organic and conventional farming systems as organic systems depends on cover crops and legume based crop rotations to supply N to the preceding crop (Kirchmann et al., 2016). Further, to compare the two systems an entire crop rotation needs to be considered as the effect of the rotation, especially in organic systems, is felt in much later years and hence a multi-year comparison is required (Nemes, 2009). This must take into consideration periods in the crop rotation when only green manure was grown (Nemes, 2009; Kirchmann et al., 2016). The effect of use of green manure crops in organic systems and not in conventional systems may also hinder the comparison of the systems as this may be an indication of error in design and these non-system specific biases need to be avoided (Kirchmann et al., 2016). In addition, the indicators used for comparison of organic and conventional farming systems (e.g. gross margins, yield etc.) may result to biases as they may ignore key interactions in the system and hence a farming system approach may be crucial in comparison (Nemes, 2009). For example, comparing yields in organic systems reveals that their yields may be lower than in conventional systems even though organic systems may have other beneficial environmental services (Nemes, 2009). Soil quality often improves over time in organic systems while pests, diseases, weed pressure reduce over time and hence any comparison between organic and conventional farming systems are best in long-term trials to capture these dynamics (Nemes, 2009). The agro-ecosystems and the crops grown in conventional and organic systems should also be considered in such comparisons as organic systems have been shown to perform better than conventional in drier areas compared to conventional (Diebel et al., 1995). The comparisons of conventional farming systems should also consider government subsidies on fertilizer and seeds which is not commonly given to organic farmers (Nemes, 2009). Due to the differences in the form in which nutrients are applied, there is need to understand the synchrony of N release and crop N demand which has a major effect on N loss through leaching, as N may be released at a time when there is no crop or when crop N demand is low (Kirchmann et al., 2016). N input intensities between the two systems may also differ due to N fixation by legume crops in the organic rotation compared to conventional and hence strategies to correct for this may be needed (Kirchmann et al., 2016). Therefore, for favourable comparisons of the systems conditions such as i) similar soil fertility status at the start of the comparison, and ii) same type of crop production among others needs to be considered (Kirchmann et al., 2016).

1.3.4. High and low input systems in the tropics

Common practice of resource poor farmers is to use low levels of inputs (both manure and fertilizers). Low external input agricultural (LEIA) systems have been proposed as a sustainable option that is accessible to resource-poor farmers (Liebman and Davis, 2000). However, a case study where LEIA was compared with conventional farming in the Machakos dry land region of Kenya revealed that both systems resulted in severe nutrient mining with

60-80% of the farm income based on nutrient mining (De Jager et al., 2001; Tripp, 2006). On the contrary, research done in more humid regions of western Kenya, revealed that embracing LEIA resulted to increased production with a positive N balance (Tambang and Svensson, 2008). In Madagascar, a rice intensification system (an LEIA technology) resulted in a dramatic yield increase but there were technical problems associated with extra labour at a time when income was low (Moser and Barrett, 2003). Population outburst has led to more intensive high input farming systems to match food production to population increase (FAO, 2011). However, this intensification has led to land degradation and dependency on external inputs rendering the systems to be unsustainable (Altieri et al., 2017). High external input farming systems common with large scale farmers and developed countries are highly mechanized characterized by monoculture and mainly rely on fertilizers, pesticides, hybrid seeds (including genetically modified seeds (GM)) and irrigation among others (Stinner and Blair, 1990). Under these systems, yield decline and negative environmental impacts may be masked by high input levels applied (Bello, 2008a). Technologies such as micro dosing of mineral fertilizer and conservation agriculture have been promoted as promising approaches to sustainable agricultural intensification (Aune and Coulibaly, 2015). In low input systems that are rain-fed, increasing N application rates to match current season rainfall amount may be required to improve yields and yield stability (Chikowo et al., 2015) while under high input systems, the focus should be to produce more yield with lower N supply (Spiertz, 2010). Technologies such as conservation agriculture that have been tested in SSA have resulted in very low adoption possibly due to the high labour demand as well as competing use of crop residues (Giller et al., 2009).

1.3.5. Organic resources in the tropics

Organic resources play a major role in short term supply of nutrients as well long-term build-up of SOC (Palm et al., 2001). Their use as a nutrient source depends on availability (quantity) and quality (chemical composition) (Palm et al., 2001). Organic resources such as crop residues green manure, biomass transfer, agroforestry prunnings, use of fallows have been intensely assessed in the tropics (Sanginga and Woomer, 2009). Crop residues are usually available at harvest and the quantity is dependent on crop yield (harvest index). The residues are mainly used as trash lines to control erosion or may be ploughed back into the soil before planting the crop (Sanginga and Woomer, 2009). In addition, crop residues are fed to livestock and the collected animal manure is recycled back to the farms (Sanginga and Woomer, 2009). Most crop residues are, however, low in nutrients and have competing alternative uses such as feed and fuel (Sanginga and Woomer, 2009). Green manures on the other hand have been very beneficial due to their high biomass and nutrient content; they are useful in nutrient uptake from deep soil layers making them available to the crop once they are incorporated (Fageria, 2007). However, green manures are seldom adopted by resource-poor farmers mainly due to small land holdings and high labour requirement (Sanginga and Woomer, 2009). Manure is a key source of nutrients to crops among resource poor farmers and most of the farming systems in SSA revolve around manure use and management (Rufino et al., 2007; Zingore et al., 2008). However, the quality of manure is low due to poor animal housing and manure storage while in pastoral areas, collection and transportation is a major hindrance to manure use (Lekasi et al., 2003; Muriuki et al., 2013). Thus focus on improving the quality of manure would be an appropriate intervention to improve nutrient content (Harris, 2002). Agro-industrial by products such as coffee husks, sugarcane bagasse, rice husks have also been tested for their use as sources of nutrient (Kifuko et al., 2007; Sanginga and Woomer, 2009). Their use is, however, limited by transportation to farms due the associated distance (Sanginga and Woomer, 2009). Use of organic resource in SSA is faced with the challenge of alternative competing use of the resource, short supply and labour requirements (Sanginga and Woomer, 2009; Rufino et al., 2011; Vanlauwe et al., 2014). In addition most of the organic resources available to farmers have low nutrient content and hence may not sufficiently supply the nutrients required by the crop (Vanlauwe and Giller, 2006; Vanlauwe et al., 2006). Therefore, adoption of some of these technologies, such as green manure crops, has had very low impact due to the intensive labour, and competing uses of land resources (Sanginga and Woomer, 2009; Vanlauwe et al., 2014).

1.4. Study sites generic farming systems and climatic conditions

The Central highlands of Kenya lie between Nairobi and Mt Kenya region (1500-2000 m.a.s.l) and are endowed with a high potential for agricultural production due to the abundant rainfall (1000-2000 mm) and potentially fertile soils (mainly nitisols) that can support a range of crops (in two cropping season) and livestock (Place et al., 2006a). However, a large population (average of 500 persons km^{-2}) has put pressure onto the resource base resulting in continuous cropping and sub-division of land (0.5-2 ha) leading to reduction of land productivity and hence food insecurity (Place et al., 2006a). Approximately 75% of rural population is engaged in agricultural and livestock production (Place et al., 2006b). Most of the farmers in these regions have mixed cropping systems for subsistence with main crops grown being maize, beans, bananas, potatoes and perennial crops such as macadamia, bananas, avocado, mango, tea, passion fruit, coffee and tea (Place et al., 2006a). Surveys in these regions have shown that more than 90 % of farmers use fertilizer in their maize farms (Ariga et al., 2008). This improvement could have been due to fertilizer and seed subsidy as well as training that has been initiated by the government of Kenya based on the National Accelerate Agricultural Input Access program (NAAIAP) with a focus on improving food security (Robert and Nie, 2015). Average N application rates to maize in this region have been reported to be 143 kg ha^{-1} (58 kg acre^{-1}, (Ariga et al., 2008). The common form of fertilizer used are compound fertilizers, that supply N, P, and K such as 17:17:17 and di-ammonium phosphate (DAP) while calcium ammonium nitrate (CAN) is mainly used for topdressing (Musyoka, 2007), in addition to N fixation by crops such as beans and cowpea, farm yard and animal manure (Ngetich et al., 2012). Most farmers grow an average of 6 crops in their farm (Njuki and Verdeaux, 2001) with the focus on maize and beans. In these areas crop rotation involves maize, beans and potatoes (Musyoka, 2007). Vegetable crops such as kales, tomatoes, cabbage are grown near the river catchments (Place et al., 2006b). Manure production in this area range from 4-13t yr^{-1} (fresh weight) with each household having an average of 2.3 cows (Place et al., 2006a). In these areas, most of the farmers feed their livestock with crop residues in addition to weeds and nappier grass harvested from the farms (Mairura et al., 2007). Trees are mainly planted to demarcate boundaries while fruit trees are planted at random in the farms (Njuki, 2001; Place et al., 2006a). Common farmers practice in nutrient management is mainly integrated use of mineral fertilizers combined with use of fresh manure (Mucheru-Muna et al., 2007; Musyoka, 2007).

1.5. Long-term trials in these areas

Short-term experiments are common in research to address how systems are regulated over time and space (Knapp et al., 2012). Short-term research differ from long-term experiments (LTE) in that LTE's are able to provide insights on causes of the changes in the slope of response and the magnitude of the long-term change while short-term research only focus on the initial trajectories (Knapp et al., 2012). The importance of Long-term experiments (LTE) in soil and environmental research cannot be underestimated. Long-term experiments are essential in assessing the impact of management systems on environment and biological processes (George et al., 2014). LTE's are experiments with permanent plots that can be sampled over decades of time scale with sample archives that can be analyzed periodically long after the sampling was done (Richter et al., 2006). This provides the necessary platform for assessing long-term trends on how farming systems respond to environmental fluxes (George et al., 2014). Complex systems with multiple components operating at different time scales of response may be interpreted under LTE's (Knapp et al., 2012). In addition, LTE's provides results on changes in soil physical, chemical and biological properties across time (Richter et al., 2006). LTE's also provide critical data for biological, biogeochemical, farming systems sustainability, soil productivity and nutrient cycling (Richter et al., 2006; Knapp et al., 2012). Long-term experiments (LTE) such as those at Rothamsted research station (England) play crucial roles in shaping up soil fertility management in the long-term. These trials are of great importance as they allow monitoring of soil chemical, physical and biological changes over a long period of time which is not possible with short-term experiments (Kibunja et al., 2012). However, such experiments are rare in SSA, and where they exists, data are scattered and inconsistent due to poor long-term donor support (Bationo et al., 2012). LTE's in Africa are mainly affected by lack of funding support to maintain such trials and hence have phases of low data collection that hampers the quality of outputs (Bationo et al., 2012). In Kenya, a few LTE trials exist in the Central highlands of Kenya as well as in Western Kenya. One of the well-known long-term trails is based at Kenya Agricultural and Livestock Research Organisation (KALRO) Kabete and was started in 1976. Results from these trials indicate that use of manure and manure combined with mineral fertilizer has consistently performed better than mineral fertilizer alone in 30 years of cropping (Kibunja et al., 2012). Further, the trial shows that use of mineral fertilizer resulted in acidification of the soil while organic carbon declined in all the systems. Soil microbial populations were highest in integrated treatments (Kibunja et al., 2012). On a drier semi-humid zone, Machang'a long-term trials (started in 1988), showed increase in soil organic carbon in soil treated with 5 and 10 t ha^{-1} of manure (Kihanda and Warren, 2012). Changes in soil physical, chemical and biological characteristics take time depending on the soil type and it is important to verify different technologies suitable to improve different aspects of the soil in long-term field experiments (Körschens, 2006). Long-term trials are therefore essential in assessing sustainability of production systems and hence advising farmers, agronomists as well as policy makers (Poulton, 1995). In addition, effects of crop rotations on crop yields, climatic changes on soil properties, nutrient balances and effects of management systems on ecological soil functions are best studied under long-term field trials (Körschens, 2006). LTE's may play a crucial role in shaping the rates and types of fertilizers required for crop nutrition (George et al., 2014) and in the long run assess accumulation of heavy metals that are detrimental to crops. There is a need to assess the effects of farming systems on food security, biodiversity and sustainability and this can be assessed under LTE trials (George et al., 2014). Some of the major challenges associated with long-term trials are associated with the choice and changes of treatments as well as modifications of experimental designs over time.

1.6. Nitrogen availability

Nitrogen is one of the major limiting elements to primary productivity of plants (Vitousek and Howarth, 1991). N availability in tropical soils is usually very low due to highly weathered soils with low soil organic matter (Sanchez and Logan, 1992). Major sources of N in most SSA countries are mainly from manure, fertilizer, N fixation by legumes and from crop residues with low N content. Eighty percent of farms in highlands of central Kenya have been found to be N deficient (<0.2%N in soil) (Mugwe et al., 2007). Deficiency of N is mainly associated with its mobility and its biochemistry (Vitousek and Howarth, 1991). N from fertilizers is readily recovered by the crop but is unaffordable to resource poor farmers who form the majority of the farming community in SSA (Crews and Peoples, 2005). N from organic sources such as manure, green manure legumes, crop residues among others is mainly retained in the soil and may be available to preceding crops over time (Kumar and Goh, 1999; Crews and Peoples, 2005). The release of nutrients from these organic sources is regulated by their quality and chemical composition (Palm et al., 2001; Chikowo et al., 2006). N and P content, lignin, polyphenols are some of the key chemical compositions that affect N availability from organic resources (Palm et al., 2001; Vanlauwe, 2004). Thus, Mutambanagwe et al. (2007) found that combining organic resources of diverse quality and mineral fertilizer resulted in 24-104%

increase in maize yield. Maize biomass at two weeks after emergence was found to correlate with final maize grain yield, an indication that early season N availability is critical to maize productivity (Mtambanengwe et al., 2007). N availability in the tropics fluctuates over time in response to soil water, N inputs, uptake by crop, immobilization by microbes, leaching and loss through other pathways (Wong and Nortcliff, 1995). Highest N availability is mainly observed during the translation between dry and wet season possibly due to the "Birch effect" (Wong and Nortcliff, 1995). Crop uptake and N losses reduce N availability during wet seasons.

1.7. N uptake and use efficiencies

Nitrogen use efficiencies (NUE) have been defined as the ratio of N output (total plant N, grain N, biomass yield, grain Yield) and input (total N, soil N or N-fertilizer applied) (Dawson et al., 2008; Masclaux-Daubresse et al., 2010). Nitrogen use efficiencies have two components namely the efficiency of absorption or uptake and the efficiency in which the nutrients absorbed is used to produce grain. Nitrogen use efficiency is largely based on measurements at harvest. For crops, NUE is calculated as the grain yield per unit of nitrogen available from the soil (Masclaux-Daubresse et al., 2010). Calculating NUE at one point rather that at different growth stages may not reflect the complete picture of N dynamics (Dawson et al., 2008). Thus, NUE is the product of N uptake efficiency and nitrogen utilization efficiency (Masclaux-Daubresse et al., 2010) over the growing season. Cassman et al. (2002) defines NUE of a cropping system as the proportion of all N inputs that are removed in harvested crop biomass, contained in recycled crop residues, and incorporated into soil organic matter and inorganic N pools.

Nitrogen management may improve nitrogen uptake and use efficiencies. Nitrogen use efficiency can be improved by i) reducing the soil acidity which is a major constraint to crop production; ii) by use of slow release fertilizer e.g. with NO_3/NH_4 inhibitors; iii) by adopting appropriate soil management practices such as use of manure, rate and timing of application and conservation tillage; and iv) water management as moisture is crucial for crop development

(Fageria and Baligar, 2005). Soil acidity may cause toxicity or deficiencies of certain nutrients in the soil resulting to reduced crop growth and N use efficiency (Tisdale and Nelson, 1993). Soil acidity may also affect mineralization, nitrification and nodulation (Fageria and Baligar, 2005). Use of slow release fertilizers and nitrification inhibitors may improve N uptake and minimize losses (Tisdale and Nelson, 1993). Rate and timing of application of organic and inorganic fertilizers is vital in improving crop uptake and hence NUE. This relates to matching N supply to crop demand to minimize losses (Ladha et al., 2005). Application of manures, composts and crop residues improves the SOM and hence N reserves of the soil (Tisdale and Nelson, 1993). Vanlauwe et al. (2011) in a meta-analysis of N agronomic efficiency in SSA found that combining mineral fertilizers with manure or compost resulted in a higher N agronomic effectiveness compared to mineral fertilizer alone, while application of organic inputs of high quality (e.g. *Tithonia diversifolia*) and those with high C:N ratio (e.g. *Siena siamea*) and high lignin content (e.g. sawdust) did not affect the N agronomic use efficiency (Vanlauwe et al., 2005; Vanlauwe et al., 2011). Water management during crop growth is very critical. Water deficit may limit N mobility and hence reduce uptake while excess moisture may result to N loss through leaching and denitrification (Fageria and Baligar, 2005). Crop management aspects may also improve NUE. These aspects include i) control of pests and diseases that may lower the ability of the crop to take up N, ii) crop rotation which allows efficient use of resources, iii) use of cover crops that reduce erosion and acts as a fallow to supply nutrient to subsequent crops, iv) use of crop residues to build up soil organic matter and supply nutrients to crop, and v) the use of N efficient genotypes (Fageria and Baligar, 2005; Ladha et al., 2005). Worldwide NUE of cereals is estimated to be about 33% while the rest is unaccounted for (Raun and Johnson, 1999). Thus, improving NUE of conventional and organic systems is important and will reduce environmental contamination (Masclaux-Daubresse et al., 2010).

Different formulas have been used to calculate NUE of crops. These include agronomic efficiencies (ratio of grain yield i.e. fertilized minus unfertilized to N supply) (Ladha et al., 2005); recovery efficiencies (ratio of plant N to N supply (Dawson et al., 2008)); physiological use efficiencies (ratio yield to plant N) and utilization efficiency (ratio of grain weight to N supply) (Good et al., 2004). The NUE of grain can be measured as increase in grain per unit of N supplied as described by Good et al. (2004). This has an advantage in that it describes increase in yield per unit of N applied and does not require yields from an unfertilized plot.

1.8. Synchrony of N availability and crop demand

Nitrogen-efficient systems have available N matched with crop demand to minimize potential losses (Robertson, 1997). Stute and Posner (1995) reported similar N release patterns from legume cover crops and conventional fertilizer and in synchrony with maize N uptake. Other researcher have found better nutrient synchrony in conventional fertilizer than in legume systems (Crews and Peoples, 2005). However, in most systems there occurs a period of asynchrony during periods when soils are not cropped (Crews and Peoples, 2004). In addition, most organic sources N usually supply nutrients within a short period of time or may result to N immobilization consequently resulting to asynchrony with N uptake by the crop (Gaskell and Smith, 2007). Further, there is continuous release of inorganic N from soil organic matter throughout the year, whether there is a crop or not while highest crop demand is concentrated in windows of 4-8 weeks (Crews and Peoples, 2005). Various management systems have been proposed to improve synchrony in organic, integrated and conventional farming systems. Some consider controlling N availability through mixing of organic materials of different quality or use of controlled release fertilizers while others focus on improving crop N uptake (Crews and Peoples, 2005). Other strategies use catch crops between the cropping seasons to capture N from lower soil profiles (Sapkotaa et al., 2012). In addition, estimation of in-season N requirement by the crop using leaf colour charts, chlorophyll meters and optical sensors has been proposed to ensure that only N required by the crop is supplied (Yadinder and Bijay, 2008). Modelling may also be a key tool of identifying potential areas improvement of different farming systems (Laurie Boithias et al., 2012)

1.9. N movement and leaching

The impacts of agricultural systems management on the environment has resulted to rethinking of better ways to increase yield with a shift to ecological and climate smart approaches to agro-ecosystem management (Drinkwater and Snapp, 2007). Since nitrate is mobile, its downward movement increases after a heavy rainfall resulting to N loss beyond the rooting zone and into the ground water aquifers (Krishna, 2013). Nitrate is a negatively charged ion and hence it is repelled by negatively charged clay soil surfaces and hence it is the primary form of N that is lost through leaching (Follett, 1995). Nitrate movement is influenced by soil water content above field capacity, soil texture resulting to high infiltration rate in sand soils and low nutrient retention capacity, low activity clays and low soil organic matter among other factors (Lehmann and Schroth, 2003), crop growth and N uptake rate, climatic conditions and management such as irrigation (Gheysari et al., 2009), N application rates (Askegaard et al., 2011), and location and use of catch crops (Jabloun et al., 2015). Nutrient release from organic inputs are more difficult to predict compared to conventional systems since nutrient release for the organic inputs could continue even at a time when there is no crop (Lehmann and Schroth, 2003). In addition, if the rate of N uptake by the crop is lower than the rate of N supply, NO_3^--N may accumulate in the rooting zone and may be prone to loss through leaching. Some of the possible ways to reduce this N movement is to apply only what the crop needs, match N supply and N demand and split N application (Krishna, 2013).

1.10. N balance

Nitrogen balance is the difference between inflows and outflows of N in a system. It is a good indicator of the system efficiency and potential land degradation (Cobo et al., 2010). The N balances can be negative indicating nutrient mining or depletion from the system or they can be positive indicating build-up of the soil nitrogen reserve with possibility of loss to the environment.

Accounting for nutrient input is of great significance to avoid nutrient loss or accumulation in agro-ecosystems. Nutrient mining occurs when nutrient output exceeds input while farming systems are considered sustainable if nutrient output and input are balanced and at optimal crop productivity (Alley and Vanlauwe, 2009). Review of nutrient balances in East Africa showed that more than 75% of the reviewed studies had a balance below zero for N and K (Cobo et al., 2010). In addition, it has been shown that N balances are higher for wealthy farmers than for poor farmers (Cobo et al., 2010).

Nitrogen balances in small scale farms vary based on resource endowment with positive balance associated with high resource endowment and negative balances associated with medium to low endowment famers (Tittonell et al., 2007a). Thus, plot scale N balances ranging from +20 to −18 kg ha^{-1} yr^{-1} of N have been reported in western Kenya (Tittonell et al., 2007a) while N balance of between -42 to -117 kg N ha^{-1} yr^{-1} have been reported in Nakuru district Rift Valley, Kenya (Onwonga and Freyer, 2006). In the semi-arid regions of Kenya N balances of +2 to -21 kg N ha^{-1} yr^{-1} have reported (Gachimbi et al., 2005). Research on some alley cropping systems have revealed negative nutrient balances (Radersma et al., 2004). In China, Wang et al., (2008) found positive N and P balances in vegetable cropping systems where different organic and inorganic fertilizers were applied. Nutrient balances varied across socio economic groups with N depletion being higher for rich farmers in the highlands than poor farmers in the lowlands. Further, nutrient balances are affected by annual variations in soil water as well as rainfall during the growth period (Wang et al., 2007). Understanding nutrient balances of different systems and different scales is critical in the sustainable management of the farming system in the long-term and for policy recommendations (De Jager, 2005).

1.11. Justification

N is critical in production of food, feed and fibre with the current agricultural intensification to feed the world. N poses one of the major management challenges in most farming systems due to its mobility and loss from agricultural systems. Therefore, N management techniques are essential to improving yields, reduce cost of production, and improve the economic sustainability of most farming systems (Van Eerd, 2005; Garnett et al., 2009). Conventional farming systems mainstreamed in most government extension service system in SSA has been shown to increase food production in the short term. Concern has, however, been raised on their impact on soil acidity (Tully et al., 2015), soil organic matter, soil biology (Bossio et al., 2005) as well as to the environment (Bello, 2008a). Thus, ‘best bet’ and ‘best fit’ technologies have been developed and recommended for specific agro-ecological zones to improve N supply in order to increase food production in SSA. Such technologies include climate smart systems such as conservation, ecological, organic and integrated farming systems. Thus, to increase soil N supply in these farming systems, use of synthetic fertilizers combined with organic inputs, N_2 fixation by legumes, use of green or animal manures, crop residues and composts have been recommended (Buresh and Tian, 1998; Gachene and Wortmann, 2004; Ladha et al., 2005; Vanlauwe et al., 2006; Odhiambo, 2011). N availability in organic systems is dependent on microbial transformation with phases of N build up followed by N consumption (Berry et al., 2002). Further, only a fraction of N applied in organic form is available to the current crop, and hence the crop additionally relies on previous fertilization regimes (Al-Bataina et al., 2016). Thus, to achieve synchrony of N release and N demand in these systems poses a major challenge. While organic and integrated systems have been shown to improve crop yields in the short term (Gentile et al., 2008; Chivenge et al., 2011; Odhiambo, 2011), little is known of the impact of these farming systems on synchrony of N released to crop demand, NUE and loss to environment in the long term and how these systems compare to conventional farming systems, in Sub Saharan Africa. Improved understanding of the influence of organic and integrated farming systems on N supply is critical for N synchrony and NUE but few studies have been done to assess the effects of the different farming systems on N supply, synchrony and NUE compared to conventional farming systems.

Agricultural intensification without adequate and appropriate restoration of soil fertility may threaten the sustainability of most farming systems. Organic farming systems have been promoted as a better option of reducing negative externalities associated with conventional systems with some researchers reporting less N loss (Stopes et al., 2002; Kimetu et al., 2004; Carneiro et al., 2012), higher microbial activity and diversity (Fließbach et al., 2007; Tuomisto et al., 2012) compared to conventional systems possibly due to application of organic inputs. On the hand, organic farming in Europe has been associated with low NUE due to low N availability possibly due to low mineralization (Kirchmann and Ryan, 2004; Bergström et al., 2008a; Alaru et al., 2014). In the tropics, very little research has been done on the impact of organic systems on soil fertility, biology and impact to the environment and how this compares to conventional systems. Further, minimal research has been done to compare the impact of conventional and organic systems at high and low N rates. Use of organic inputs, crop rotations, catch crops, crop residues to improve N availability (Balota et al., 2004; Danga et al., 2009) and coupled with improved crop genotypes have been shown to improve nitrogen retention, recovery and use efficiencies (Hirel et al., 2011). Rate and timing of N application has also been shown to have an impact on NUE (Fageria and Baligar, 2005; Ghosh et al., 2015; Kumar et al., 2015). While N supply under conventional systems is easy, ensuring adequated N supply and in synchrony with crop demand in organic farming systems is a major challenge as N supply is dependent on the quality of organic inputs (Diogo et al., 2013). In addition, N loss associated with application of easily available N applied in conventional systems has a major implication on NUE (Chien et al., 2009; Hirel et al., 2011). In low input farming systems, nutrient supply relies on manure supplied from livestock, N_2 fixation by legumes and agroforestry trees as well as minimal synthetic fertilizers. In addition, these systems are associated with poor agronomic practices resulting to poor yields and low NUE (Snapp et al., 2014). Thus, due to differences in farming systems management intensities, N rate and form of application, organic and conventional systems may have different impacts on N availability, synchrony, uptake, use efficiencies and N loss and hence it is of great importance to assess the impact of conventional and organic systems at high and low input systems on N release, synchrony, NUE and loss under tropical conditions.

Nutrient balances of most African farming systems are negative (Smaling, 1993; Gachimbi et al., 2005; Onwonga and Freyer, 2006; Cobo et al., 2010). However, information on the state of plant nutrient depletion from soils under organic and conventional at recommended and low input farming systems in the long term is not available. Quantitative estimation of plant nutrient depletion from soils under such farming systems is useful for comprehending the state of soil degradation and for devising corrective measures. Nutrient-balance measurement serves as instruments to provide indicators of the sustainability of farming systems. With increase in fertilizer use in Africa coupled with erratic rainfall, leaching and denitrification losses are also expected to increase. There is therefore the need to investigate the effect of organic and conventional farming systems on N balances in a bid to reduce negative environmental effects as well as improve NUE.

1.12. Objectives and hypothesis

Overall objective

The main objective of the PhD study was to quantify and compare N dynamics in conventional and organic farming systems managed at low and high N input levels in the sub humid highlands of Central Kenya.

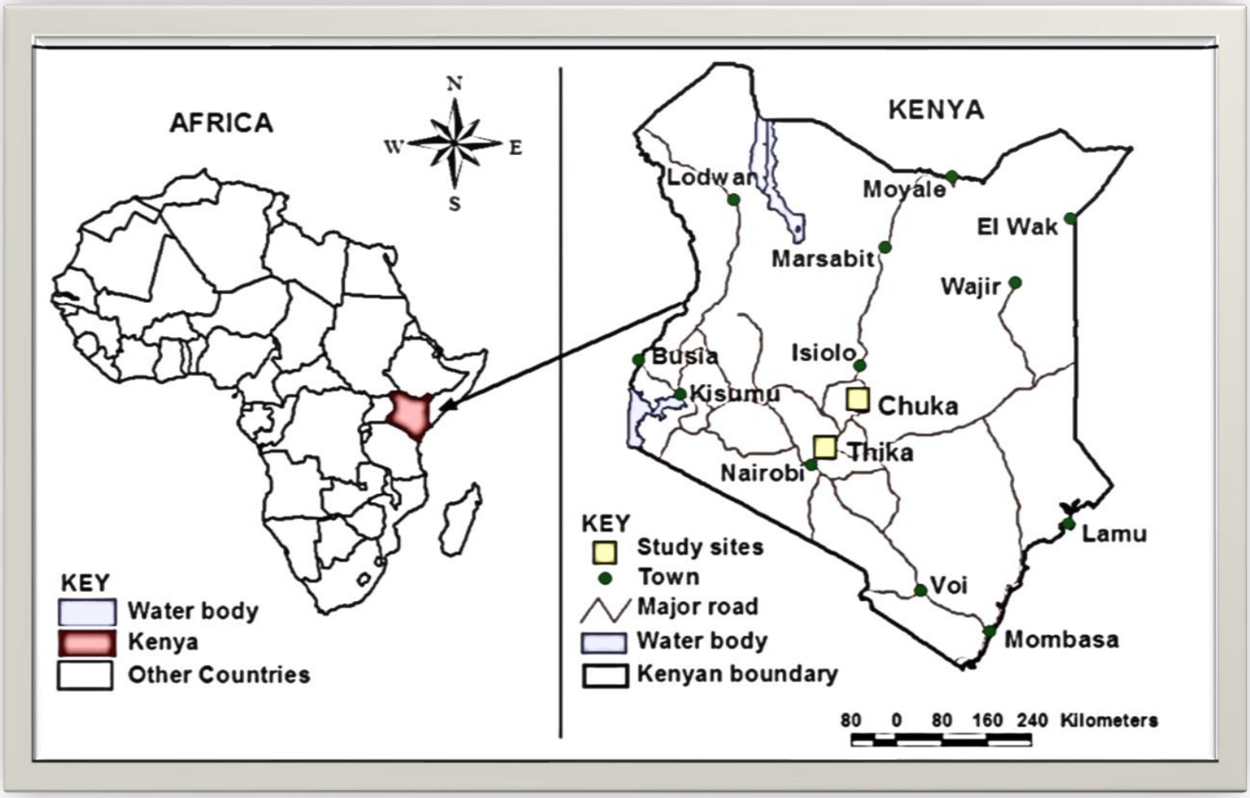
Specific objectives

1. To determine impact of conventional and organic farming systems at two input levels on i) N mineralization dynamics and rates, ii) amount of N released, and iii) the synchrony of soil mineral N released and crop N-uptake patterns under different crops and sites in the Central Highlands of Kenya;
2. To determine the effect of conventional and organic farming systems managed at low and high input levels on N-uptake, NUE (i.e. N uptake efficiency, N utilization efficiency, agronomic efficiency of N use, N-harvest index) in potato, maize and vegetable systems in two agro-ecological zones in the central Highlands of Kenya;
3. To assess the effect of conventional and organic farming systems on the total amount of mineral N leached beyond crop root zone and partial N balances under high and low N input levels and in different cropping systems in the Central Highlands of Kenya.

Hypothesis

1. N release, rate of mineralization and synchrony of N release to crop N demand in conventional systems could differ from that of organic systems due to previous fertilization regimes, type and rate of organic inputs applied versus use of soluble fertilizer in conventional systems.
2. Organic farming systems may promote plant nutrient uptake comparable to conventional systems due to build-up of soil organic N from previous fertilization regimes but differ in the effect on crop NUE due to the type of organic input applied compared to soluble fertilizers used in conventional systems.
3. Higher leaching and negative partial N balances could occur in conventional farming systems compared to organic farming systems due to type of fertilizer applied and higher N removal through crop and biomass.

CHAPTER 2



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Study sites
Town
Major road
Water body
Kenyan boundary
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2.0. Nitrogen release and synchrony in organic and conventional farming systems of the Central Highlands of Kenya[§]

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2.1. Abstract

To match Nitrogen (N) supply to crop N demand, it is essential to understand N release and uptake patterns in different farming systems and crops. To assesses the dynamics of N released in organic and conventional systems and potential synchrony and asynchrony in crop N uptake, trials were conducted over three cropping seasons (potato, maize and leafy vegetables) at two sites in the Central Highlands of Kenya. Mineral-N release and synchrony were monitored in conventional and organic systems at high (recommended N, P, pesticides and irrigation) and low input (low N, P, pesticide use and rainfed) systems. Mineral-N release was assessed using *in situ* buried bags and N synchrony was measured by the daily differences in N fluxes. The

[§]*Published with kind permission of Springer. The original article appeared in the journal Nutrient Cycling in Agroecosystems Vol. 113 No. 3 pp 283-305 which can be found in the link https://link.springer.com/article/10.1007/s10705-019-09978-z*

percentage of N applied released during potato (38%) and vegetable (44%) cropping seasons were similar between systems. However, under maize strong temporal N immobilization from inputs occurred, particularly at Thika, related to the poor quality of manure and compost (lignin:N ratio >13). In all systems, excess-asynchrony of available N was pronounced during vegetative stages and at harvest, while insufficient-asynchrony occurred at reproductive stages. During potato cropping season at Thika, Org-High showed highest positive N fluxes (>20 kg N $ha^{-1}day^{-1}$) at planting and tuber bulking stage. At early stages of maize and vegetables Org-Low and Org-High experienced up to 5 times larger negative N fluxes (insufficiency) compared to conventional treatments at Chuka site. The study recommends reducing N applications at planting and increasing N dosages at reproductive stages of crops.

Key words: Incubation, mineralization, Apparent N, synchrony, organic input quality

2.2. Introduction

Most soils in sub-Saharan Africa are highly weathered, have low inherent nutrient stocks and are deficient in nitrogen (N) and phosphorus (P) (Okalebo et al., 2007). This problem is exacerbated by the prevailing climate (Okalebo et al., 2007). N availability is particularly affected by farming system-specific conditions such as tillage, previous fertilization intensity and cropping patterns as well as the chemical, physical and biotic properties of soils (St. Luce et al., 2011). In conventional systems N fertilizer is applied as ammonium (NH_4^+) or nitrate (NO_3^-) based synthetic fertilizers, and/or manure prior to or during planting or as top dressing later, while in organic systems, N is supplied from manure or compost, crop residues, biological N_2 fixation and through crop rotations. The nitrogen availability in organic and integrated systems is therefore dependent on processes that transform N, such as decomposition, mineralization and nitrification (St. Luce et al., 2011). Organic and integrated farming systems are characterized by phases of N building followed by N utilization (Berry et al., 2002). When using synthetic fertilizers N is readily available, but in organic and mixed systems ensuring the availability of N can be challenging, due to the low N content of some manures, composts and crop residues and/or slow mineralization rates (Berry et al., 2002). Watson et al. (2002) argue that the availability of N in organic farming systems is more dependent on previous fertilization intensities (than is the case with using synthetic fertilizers), with the N that was unavailable and unused in previous seasons being captured in the following seasons. Nett et al. (2012) found that amendment history also influenced the N mineralization of freshly added organic inputs. Crews and Peoples (2005) studied the synchrony of N supply and crop demand from legume cover crop systems and conventional systems. They found that excess-N asynchrony is likely to occur in organic and integrated farming systems due to the continuous release of inorganic N from organic inputs and soil organic matter, and that N deficiencies may occur during periods of N immobilization (Crews and Peoples, 2005).

Nitrogen mineralization is affected by macro and microorganisms, the physico-chemical environment and the quality of organic inputs (Swift et al., 1979). Differences in the nature of synthetic fertilizer and organic inputs may affect mineralization trends in conventional and organic systems (Romanyà et al., 2012). In most of sub-Saharan Africa (SSA), manure plays a crucial role in soil fertility, with most farmers using manure, alone or in combination with synthetic fertilizers (Muriuki et al., 2013). Thus, most recommendations on conventional farming systems in this region focus on the integrated use of manure and fertilizer (Muriuki et al., 2013), which have been found to perform well in highly weathered SSA soils. For example, in Kenya, the application of 5 and 10 t ha^{-1} of FYM combined with synthetic fertilizer has been shown to increase maize yields (Mucheru-Muna et al., 2014) in different agro-ecological zones. Organic systems have been shown to have higher microbial activity and diversity (Fließbach et al., 2007), which may result in higher rates of mineralization. The quality of compost and other organic inputs varies seasonally and according to its composition, while manure quality can vary according to its age, how it is handled, the animals’ diet and bedding materials (Lekasi et al., 2003). N mineralization of organic resources is mainly affected by N content, the C:N ratio, lignin, the lignin:N ratio and the polyphenol content and these determine the extent to which N is released or immobilized (Vanlauwe et al., 2005). It is estimated that 4 – 57 % of the N (measured in terms of fertilizer equivalency) within fresh or composted cattle and poultry manure is recovered in the first year and 7 – 18 % in the second year, with the differences dependent on the manure type (Muñoz et al., 2008). N release from compost has been reported to be in the range of 5-15% in the first year of application and 2-8% in the following years (Amlinger et al., 2003). Thus, timing of the application of manure, compost and crop residues is essential in order to achieve synchrony between nutrient release and crop demand.

Most mineralization studies have been short-term studies, and hence do not capture the long-term effects of different farming systems. Moreover, most such studies have focused on conventional and integrated nutrient management systems, with little attention to organic farming systems in the SSA. N mineralization in organic farming systems may differ from that of conventional systems due to the farming systems' effects on the chemical and biological (such as microbial biomass and respiration etc.) properties of the soils (Berry et al., 2002; Fließbach et al., 2007). There are few, if any, studies on ways to improve N availability in organic farming systems.

In SSA crops production systems are under low external input (mostly subsistence and rainfed) and high external input systems that rely on high levels of input use and irrigation. In eastern Kenya, research into low external input agriculture (LEIA) has shown similar nutrient depletion problems as conventional farming systems (Tripp, 2006); while in western Kenya, research into LEIA has shown increased production with positive N balances (Tambang and Svensson, 2008). High input systems have been promoted for agricultural intensification, but there are potential drawbacks with these systems as soil acidification and a decline in SOM sometimes cause initially high yields to decline. These systems can also have negative environmental impacts (Bello 2008). Thus, this study tests the performance of farming systems at low and high input levels, representing existing subsistence and commercial production systems.

The hypothesis of this study was that mineral-N release, N release rates and synchrony between N release and crop N demand differed between conventional and organic systems due to their different sources of nutrients. The objectives of this study were therefore, to determine; i) mineral-N released in conventional and organic farming systems at low and high input levels; ii) the N release rates in conventional and organic farming systems; and iii) the patterns and periods of synchrony or asynchrony of soil mineral-N release and crop N-uptake for different crops.

2.3. Materials and Methods

2.3.1. Experimental sites

The research was conducted at Chuka and Thika in Kenya as part of the on-going long-term farming systems comparisons trial initiated in 2007 [SysCom; www.system-comparison.fibl.org; (Adamtey et al., 2016)]. The site at Chuka is located at 0° 20.864´S latitude, 37° 38.792´E longitude and lies at 1458 m above sea level (a.s.l.). It has an annual mean temperature of 20°C and mean annual rainfall of 1500 to 2400 mm (Jaetzold et al. 2006b). The site at Thika is located at 01° 00.231´S latitude, 37° 04.747E longitude. It lies at 1518 m above sea level (m a.s.l.) with an annual mean temperature of about 20°C and mean annual rainfall of 900 to 1100 mm (Jaetzold et al., 2006a). Both sites have a bimodal rainfall distribution that occurs in March-June (long rains, LR) and October-December (short rains, SR). According to the world reference base (IUSS Working Group WRB. 2006) the soils at Thika are Rhodic Nitisols and those at Chuka, Humic Nitisols (Adamtey et al., 2016; Musyoka et al., 2017).

2.3.2. Experimental treatments and management

Experimental trials were laid down in a Randomized Complete Block Design (RCBD) with plot sizes of 8 x 8 m (net plot size of 6 x 6 m) replicated 4 times at Chuka and 5 times at Thika.

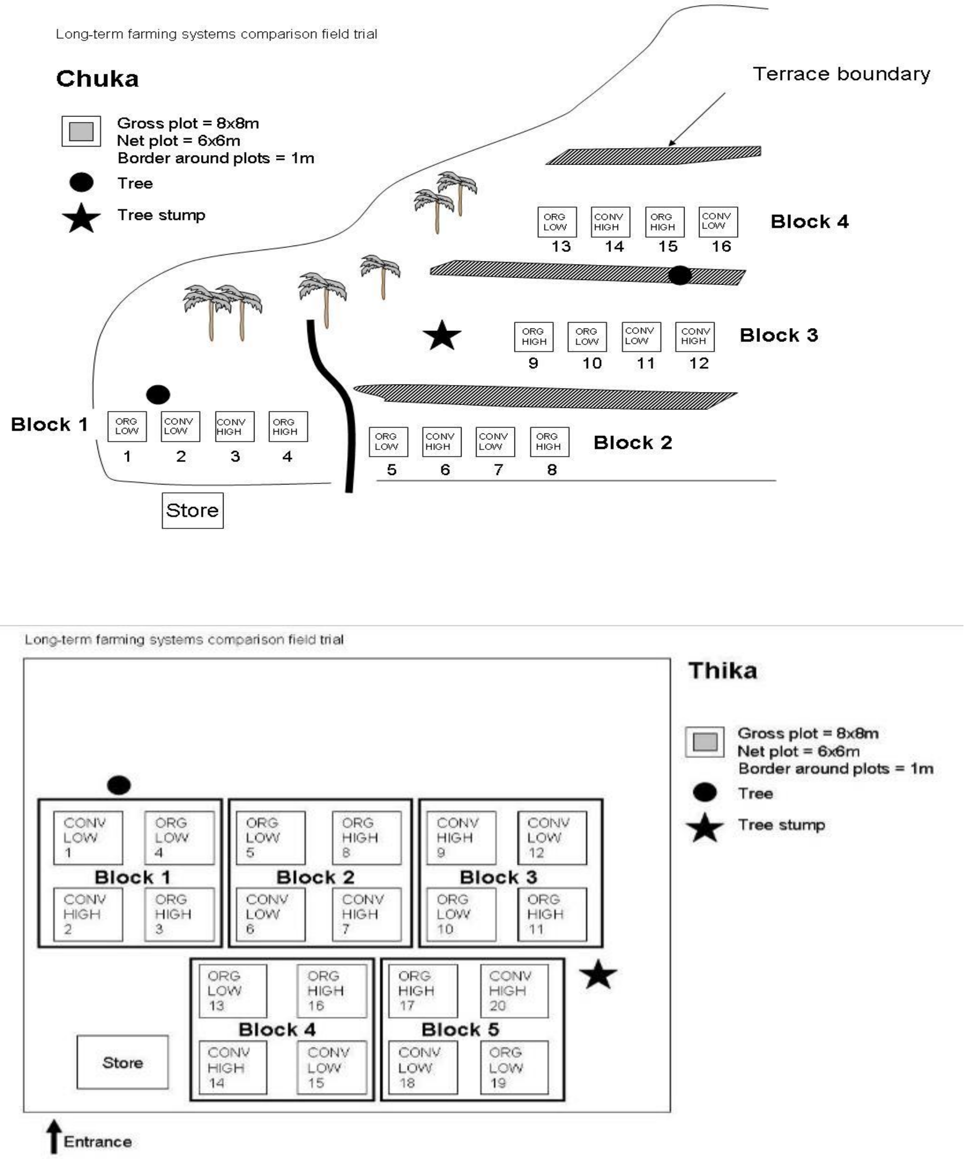


Fig. 1: Long-term farming systems comparison field layouts at Chuka and Thika trial sites

Four farming systems were compared at each site: Conventional high (Conv-High), organic high (Org-High) (where N and P, pesticides, botanicals and irrigation water were applied at recommended rates for potato, maize and cabbage crops), conventional low (Conv-Low) and organic low (Org-Low) (where N and P, pesticides, botanicals were applied at rates used by local farmers and under rainfed conditions). The trials were based on a two-season, three-year crop rotation (as shown in Table 1; see also Musyoka et al., 2017). In 2012 potato (*Solanum tuberosum* L.) was planted on 16^{th} October at Chuka and 25^{th} October at Thika (SR). In 2013 Maize (*Zea mays* L.) was planted on 27^{th} March at Chuka and 4^{th} April at Thika (LR) and vegetables (cabbage-*Brassica oleracea* var. capitata and kale-*Brassica oleracea* var. acephala intercropped with Swiss chard *Beta vulgaris* subsp cicla) were planted on 6^{th} and 8^{th} November 2013 at Chuka and Thika site (SR, Table 1).

Table 1: Crop rotation of the long-term farming systems comparison trial at Chuka and Thika in the Central Highlands of Kenya

	Year 2007, 2010, 2013		Year 2008, 2011, 2014		Year 2009, 2012, 2015	
Farming systems	LR	SR	LR	SR	LR	SR
Conv-High	Maize	Cabbage	Baby corn	French beans	Baby corn	Potatoes
Org-High	Maize/Mucuna[a]	Cabbage	Baby corn/Mucuna	French beans	Baby corn/Mucuna	Potatoes
Conv-Low	Maize	Collard/Swiss chard	Maize/Beans	Grain legumes	Maize/beans	Potatoes
Org-Low	Maize	Collard/Swiss chard	Maize/Beans	Grain legumes	Maize/beans	Potatoes

Conv-High conventional high input system, *Org-High* organic high inputs system, *Conv-Low*, conventional low input system, *Org-low* organic low input system, *LR* long rainy season, *SR*, Short rainy season,
[a]*Mucuna pruriens* planted as relay crop four weeks after the maize or baby corn were established. Mucuna biomass was applied in the short rainy season.

In the organic systems, N was applied in form of compost, *Mucuna pruriens* (Mucuna) biomass, crop residues at planting, with a *Tithonia diversifolia* (Tithonia) mulch added after germination and plant tea for topdressing. P was applied as Minjingu phosphate rock at the time of planting. Well-decomposed farm yard manure (FYM) and fresh FYM were applied in Conv-High and Conv-Low, respectively. In addition, di-ammonium phosphate (DAP) or triple super phosphate (TSP) was applied at planting with calcium ammonium nitrate (CAN) as a top dressing. For the low input systems, the trial aimed to follow common local practices, identified in a survey carried out in 2007 (Adamtey et al., 2016; Musyoka et al., 2017) using N and P rates of 50 kg N ha^{-1} $year^{-1}$ and 26 kg P ha^{-1} $year^{-1}$, respectively. In the high input systems N and P were applied at 225 kg N ha^{-1} $year^{-1}$ and 124 kg P ha^{-1} $year^{-1}$, following the recommendations of the Kenyan Ministry of Agriculture and the Japanese International Co-operation Agency (Adamtey et al., 2016; Musyoka et al., 2017).

To ascertain the actual amounts of nutrients applied in each system, FYM, compost, Tithonia, Mucuna and maize stover were analyzed for N and P, which revealed that the nutrients in the FYM and compost varied between the LR and SR. This, coupled with the N applied as Mucuna and crop residue (which were not initially factored in the N and P calculations), explains why the Org-High system received more N than Conv-High. Table 2 shows the N and P levels applied in the different systems during the period of data collection. Pest were managed using an integrated pest management approach (IPM) in the conventional systems and bio-pesticides in organic systems, with a low intensity of pest control in the low input systems (see Supplementary S2). The low input systems were rain-fed while high input systems received supplementary irrigation water through drip irrigation during periods of moisture stress. No irrigation was done during the potato cropping season as the amount and distribution of rainfall was sufficient (Fig. 1). Maize and cabbage received 102 and 209 mm ha^{-1} at Chuka and 287 mm ha^{-1} and 49 mm ha^{-1} at Thika, respectively (the last figure being lower than desired due to constraints in obtaining irrigation water due to a breakdown in the borehole system). The frequency of irrigation was determined by computing the dry spells (days with rainfall of <1 mm) as described by Adamtey et al. (2016). Thus, maize and cabbage received irrigation water 4 and six times respectively at Chuka while at Thika Maize and cabbage received irrigation water 7 and 8 times respectively. Total rainfall and its distribution during the three cropping seasons is shown in Fig. 1. Other details of the management practices in the farming systems can be found in Adamtey et al. (2016) and Musyoka et al. (2017).

Table 2: Actual total nitrogen (N) and phosphorus (P) contents of the inputs applied during the measurement period in the long-term system comparison trial at Chuka and Thika in the Central Highlands of Kenya

					Input application									
	Farming				FYM	Compost[a]	DAP	PR	TSP	CAN[b]	*Tithonia* mulch[c]	*Tithonia* tea[b]	**Total N applied**	**Total P applied**
Site	**systems**	**Year**	**Season**	**Crop**	Mg ha^{-1}	Mg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	Mg ha^{-1}	Mg ha^{-1}	kg ha^{-1}	kg ha^{-1}
Chuka	Conv-High	2012	SR	Potato	10.5	-	-	-	300	200	-	-	160	94
		2013	LR	Maize	3.9	-	200	-	-	100	-	-	113	60
		2013	SR	Cabbage	10.5	-	-	-	200	300	-	-	114	58
	Org-High	2012	SR	Potato	-	22	-	581	-	-	8.2	-	162 (173)[d]	118.5 (36.5)[d]
		2013	LR	Maize	-	22.7	-	364	-	-	5.4	3.9	246	133
		2013	SR	Cabbage	-	22	-	400	-	-	6	6	211 (15)[e]	115 (19)[e]
	Conv-Low	2012	SR	Potato	2	-	100	-	-	-	-	-	33	27
		2013	LR	Maize	5	-	50	-	-	-	-	-	63	32
		2013	SR	Kale/Swiss Chard	1	-	-	-	50	60	-	-	23	13
	Org-Low	2012	SR	Potato	4.5	-	-	200	-	-	2.72	-	48	45
		2013	LR	Maize	2.2	-	-	100	-	-	1.36	-	35	24
		2013	SR	Kale/Swiss Chard	4.5	-	-	90	-	-	1.2	1.2	21	13
Thika	Conv-High	2012	SR	Potato	14.1	-	-	-	300	200	-	-	124	83
		2013	LR	Maize	7.2	-	200	-	-	100	-	-	84	47
		2013	SR	Cabbage	11	-	-	-	200	300	-	-	184	67
	Org-High	2012	SR	Potato	-	24.4	-	581	-	-	8.2	-	131 (220)[d]	87 (41)[d]
		2013	LR	Maize	-	17.6	-	364	-	-	5.4	3.9	135	81
		2013	SR	Cabbage	-	24.4	-	400	-	-	6	6	290 (25)[e]	100(2)[e]
	Conv-Low	2012	SR	Potato	2	-	100	-	-	-	-	-	44	25
		2013	LR	Maize	5	-	50	-	-	-	-	-	31	20
		2013	SR	Kale/Swiss Chard	1	-	-	-	50	60	-	-	24	14
	Org-Low	2012	SR	Potato	6.9	-	-	200	-	-	2.72	-	33	37
		2013	LR	Maize	5	-	-	100	-	-	1.36	-	38	24
		2013	SR	Kale/Swiss Chard	6.9	-	-	90	-	-	1.2	1.2	18	13

Conv-High conventional high input system, *Org-High* organic high inputs system, *Conv-Low*, conventional low input system, *Org-low* organic low input system, *SR* Short rain season, *LR* Long rain season, *DAP* Di-ammonium phosphate, *CAN* calcium ammonium nitrate, *TSP* triple superphosphate, PR = phosphate rock

NB: FYM, compost, *Tithonia* inputs were on a fresh weight basis

[a]Compost was prepared with similar amount of fresh farm yard manure (FYM) as in Conv-high;

[b]*Tithonia* plant tea and CAN were applied as top-dressing in two split applications in high input systems, while in low input system topdressing was done once for specific crops.

[c]*Tithonia* mulch as starter N applied after crop germination.

[d]Extra nutrients supplied from other sources such as mulch (2 Mg ha^{-1} applied), maize stover residues (2 Mg ha^{-1}) and *Mucuna* at Chuka (10.3 Mg ha^{-1}) and at Thika (16.7 Mg ha^{-1}) during potato season;

[e]N and supplied as maize stover residues 2 Mg ha^{-1})

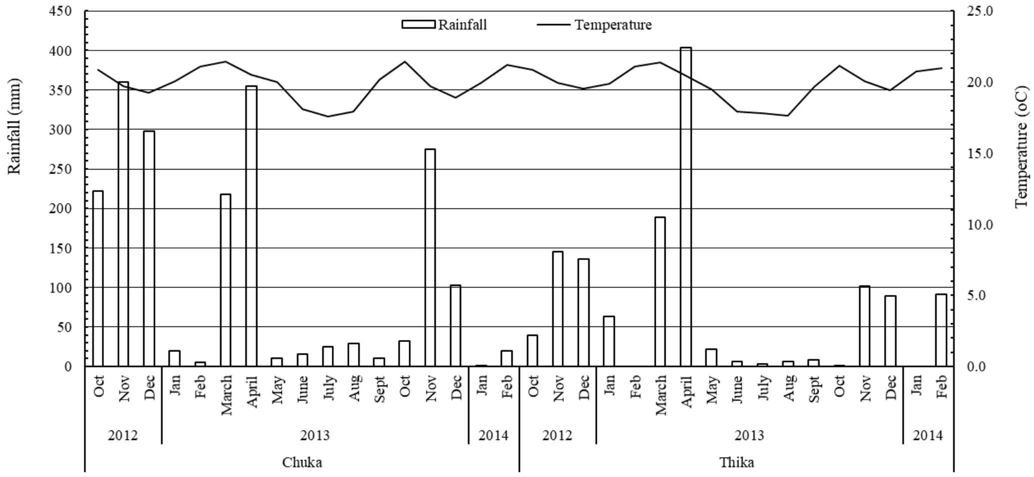


Fig. 1: Cumulative monthly rainfall and average temperatures (from planting to harvesting) during the three cropping seasons in the long-term systems comparison trial at Chuka and Thika in the Central highland of Kenya

2.3.3. Preparation of organic inputs

The compost used in Org-High was prepared using the layering heap method (Das 2014) with maize stover (30%), *Lantana camara* fresh and soft twigs (20%) and FYM (50%). Small amounts of wood ash and top soil were sprinkled on top of every layer to support microbial activity. The compost heap was turned once every three weeks until it matured (3 months). In Conv-High and Org-Low, fresh FYM was heaped and allowed to decompose for three months before use. In Conv-Low, fresh FYM was used directly from the cattle shed, following the common farmers' practice in the region. Vegetative organic inputs, such as *Mucuna pruriens* (Mucuna), crop residues and *Tithonia diversifolia* (Tithonia), were chopped into small pieces (of <5mm) before use.

2.3.4. Soil sampling and incubation procedures

Soil mineral-N in the topsoil was measured from soil sampled under natural soil-crop interaction at critical stages of the crop. Mineral-N released from applied inputs was studied through field incubation, using the buried bag approach as described by Eno (1960) and modified by Friedel et al. (2000). The soil used was collected from the plough layer (0-0.2 m) of each plot before the input application. The collected soil was sorted by hand to remove debris and big clods and homogenized, taking care to preserve aggregates of 5 mm. The soil was tested in its fresh form without sieving. The properties of the soils at the beginning of data collection (October 2012) are shown in Table 3.

An equivalent weight of 150 g of soil and 150 g of mixed resin beads (dry weight basis) were placed into polyethylene freezer bags (0.235 m x 0.38 m). The freezer bags used in the study were semi-permeable in order to allow an exchange of gases (Friedel et al., 2000).

Organic inputs were applied to the field in fresh form, with the rate of application based on the bulk density of the soil in each system (Supplementary S1). Corresponding inputs were manually mixed with the soil-resin beads mixture, placed into freezer bags and the moisture content adjusted to 60% water holding capacity, using distilled water. The bags were then sealed to avoid water entry and loss of content and then buried in the sampled plots, to ensure the replication of the bags was similar to the trial's layout. The mixed resin beads (Resinex™ MX-11) were obtained from Clean Water Group (CWG) Technology (GmBH Mannheim, Germany). Resinex™ MX-11 is a mixture of Resinex™ K-8 and Resinex™ A-4 and has a specific gravity of 730 kg m^{-3} and grain size of 0.45-1.2 mm. This study used ion exchange resin beads as these have been shown to prevent the re-immobilization of released N and also mimic the nutrient exchange of plant roots (Friedel et al., 2000).

Table 3: Soil chemical characteristics at the beginning of data collection in October 2012 in the long-term system comparison trial at Chuka and Thika in the Central Highlands of Kenya

Site	Farming systems	Bulk density	pH (1:2.5)	Total N	NO_3^--N	NH_4^+-N	OC	C/N ratio	P	K	Ca	Mg	Sand	Clay	Silt
	Units	g cm^3		g kg^{-1}	mg kg^{-1}	mg kg^{-1}	g kg^{-1}		mg kg^{-1}	mg kg^{-1}	mg kg^{-1}	mg kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}
Chuka	Conv- High	0.91	5.36 b	2.3	3.9	3.4	20.0 a	9	59	309	1462	94	186	708	106
	Org- High	0.92	5.83 b	2.4	2.6	3.0	23.9 a	10	31	704	1493	111	173	707	120
	Conv- Low	0.91	5.36 b	2.2	2.7	3.1	20.4 a	9	36	318	1198	80	175	731	94
	Org- Low	0.91	5.35 b	2.1	2.7	3.9	18.6 b	9	34	404	1384	81	181	714	105
Thika	Conv- High	1.09	5.38 b	1.9	17.7	1.9	15.0 bc	8	46	575	1322	92	188	740	72
	Org-High	0.99	6.83 a	2.0	28.6	3.4	17.8 b	9	27	1048	1493	116	172	708	120
	Conv- Low	1.04	5.24 b	1.7	7.0	1.0	14.7 c	9	14	481	669	73	182	709	109
	Org- Low	1.03	5.38 b	1.6	19.9	2.4	14.5 c	9	12	489	809	82	203	716	81
Sources of variations															
System		ns	***	ns	ns	ns	***	ns	ns	***	*	**	*	ns	ns
Site		***	ns	***	***	ns	ns	*	*	***	*	ns	ns	ns	ns
System x site		ns	*	ns	ns	ns	*	ns	ns	Ns	ns	ns	ns	ns	ns

Conv-High conventional high input system, *Org-High* organic high inputs system, *Conv-Low*, conventional low input system, *Org-low* organic low input system, *pH* pH in water, *OC* organic carbon, *C/N* C to N ratio; a, b, c are comparison of means, with only significant means being shown; K, Ca, and Mg are ammonium acetate extractable bases.

To assess the mineral-N released from the soil without input application (residual-N) and the mineral-N released from soils amended with inputs, two sets of polyethylene (PE) bags were buried in each experimental plot at a depth of 0.2 m. Twelve bags per replicate were buried at the beginning of the potato cropping season, 16 for maize and 14 for vegetables. This was to ensure that adequate samples were retrieved after 0, 3, 10, 20, 40, 90 days for potato; 0, 3, 10, 20, 41, 61, 122, 157 days for maize; and 0, 3, 10, 26, 41, 69, 109 days for vegetables, which corresponds with the critical development stages of each crop. Four extra bags were installed in each farming system at the beginning of the maize and vegetable cropping seasons to account for the N applied as top dressing during the cropping period. These four bags were retrieved from the maize plots at the V8 leaf stage and tasseling stages and from the cabbage plots at the precupping and head formation stages and the respective top dress inputs added. After that, the bags were buried and sampled during the consecutive sampling dates as indicated above. The positions of bags in each experimental plot were marked with distinct polyvinyl chloride (PVC) pegs to ensure that they remained intact during routine farm management activities. The retrieved bags were placed in air-tight polythene bags, labeled, and transported to the laboratory in ice chests for analysis. The soil mineral-N content was assessed before planting crops and at critical stages of crop development. Soil samples were collected at 0-0.2 m depth, placed in ice chests and transported to the laboratory for analysis.

2.3.5. Soil and FYM analysis

Soil bulk density was determined *in situ* using the core method described by Okalebo et al. (2002). Soil cores (length 0.0503 m; diameter 0.0503 m; and 0.0001 m^3 volume) were driven through undisturbed soil after clearing the surface of plant debris and loose soil. The cores were trimmed to size and closed at both ends, to ensure no loss of soil. They were oven dried at 105^oC to a constant weight. The bulk density was then calculated as the soil dry weight divided by the volume of the core. Soil and FYM pH-H_2O were determined potentiometrically in 2.5:1

and 5:1 water to soil suspensions, while electro-conductivity was determined in a saturated paste extract (Okalebo et al., 2002). Organic carbon was determined using Walkley-Black wet oxidation (Anderson and Ingram, 1993). Total N and P in FYM, compost and soil were measured after complete digestion of the samples with a mixture of hydrogen peroxide, sulphuric acid, selenium and salicylic acid, as described by Okalebo et al. (2002). Total N concentration was quantified using a SKALAR segmented flow analyzer at 660 nm wavelength and total P concentration was determined using a spectrophotometer at 400 nm. Potassium, calcium and magnesium were analysed with an atomic absorption spectrophotometer after extraction with ammonium acetate (according to the procedure described by Okalebo et al. 2002). Nitrate-N and ammonium-N were measured using a SKALAR (SKALAR Analytical B.V. Breda, the Netherlands) segmented flow auto analyzer at 540 and 660 nm respectively, after extraction with 0.5 M potassium sulphate. Olsen extractable P was determined after extraction of 2.5 g air-dry soil (sieved through a 2 mm mesh) with 50 mL of 0.5 M sodium bicarbonate and the absorbance of the solution measured at 880 nm wavelength (Okalebo et al., 2002). Lignin in FYM and other organic inputs were determined through the Acid-Detergent Fiber (ADF) method (Anderson and Ingram, 1993) while polyphenols were determined using the Folin-Denis method, as described by Anderson and Ingram (1993).

Soil samples collected from each system before applying the inputs, and at different crop growth stages, were analyzed to assess changes in mineral-N in the top soil during crop growth. Soil and soil-resin mixture samples were thoroughly mixed in the laboratory before analysis. Ten grams of freshly sampled soil and soil-resin samples were extracted using 50 mL of 0.5M K_2SO_4 (at a 1:5 soil solution ratio) shaken for 30 minutes in an end-to-end mechanical shaker. The content was then filtered through Whatman No. 42 filter paper and stored in the refrigerator. Nitrate and ammonium-N were determined at 540 and 660 nm respectively using a SKALAR segmented flow auto analyzer (SKALAR Analytical B.V. Breda, the Netherlands).

The moisture content of the samples were determined using the gravimetric method (Okalebo et al., 2002). At the beginning of each season three samples of unincubated resin were analyzed for nitrate and ammonium-N to determine the nitrogen content in the resin. This was used to correct for the nitrate and ammonium-N levels in the soil plus resin mixtures.

2.3.6. Mineral-N release

Mineral-N released from amended soil or soil alone was calculated on an area basis after considering bulk density in each farming system and the soil depth of the plough layer (0.2 m) and was calculated as the change in mineral-N between sampling dates (1, 2, 3, 4…) (Eq. 1 and 2 respectively).

Mineral-N released $_{\text{amended soil}}$ (kg ha^{-1}) = Mineral-N $_{t+k \text{ amended soil}}$ - Mineral-N $_{ti \text{ amended soil}}$ ....Eq. 1

Mineral- N released$_{\text{soil}}$ (kg ha^{-1}) = Mineral-N $_{t+k \text{ soil}}$ - Mineral-N $_{ti \text{ soil}}$ ....Eq. 2

where t_i is initial time i = 0, 1, 2, 3, 4… and t_{i+k} is t_i plus k intervals where k = 1, 2, 3, 4, 5… Mineral-N released from the inputs was calculated as the difference between mineral-N released from amended soil at time t_i to t_{i+k} and N released from soil alone at the time t_i to t_{i+k} (Eq. 3).

Mineral-N released $_{\text{inputs}}$ (kg ha^{-1}) = Mineral-N released $_{\text{amended soil}}$ – Mineral-N released $_{\text{soil}}$ …...…Eq. 3

The N release rate was calculated by dividing the mineral-N released from the inputs at each sampling date by the number of incubation days (Loecke et al., 2012). The total mineral-N released from the amended soil and the soil alone was calculated as the sum of the change in soil mineral-N from one sampling date to the next.

2.3.7. Synchrony of released N and plant N uptake

Daily nitrogen flux differences (mineral-N released - plant N uptake, kg ha^{-1} day^{-1}) were used to demonstrate the closeness of the link, or the synchrony, between mineral-N release from the inputs and crop N demand (Loecke et al., 2012). Asynchrony occurs when there is a positive N flux difference (an indication that mineral-N release is larger than the crops' N demand (Crews and Peoples, 2005)) or a negative N flux difference (when insufficient N is released to meet the crops' N demand or uptake (Crews and Peoples, 2005)). Daily mineral-N release budgets were constructed by dividing the amount of mineral-N released (kg ha^{-1}) at time t_i to t_{i+k} by the number of days of the incubation period (t_i to t_{i+k}).

Seasonal above-ground N uptake data collected at critical crop growth stages (as outlined in Musyoka et al., 2017) were used to calculate N uptake (Eq. 4). Daily N uptake budgets for each incubation period were as shown in Eq. 5.

N uptake (kg ha^{-1}) = [N content $_{crop\ stage}$ (%) x crop biomass $_{crop\ stage}$ (kg ha^{-1})]/100 ....…...……Eq. 4

Daily N uptake (kg ha^{-1} day^{-1}) = [N uptake t_{i+k} - N uptake $_{ti}$ (kg ha^{-1})]/ [(t_{i+k})-ti] ……………Eq. 5

where *ti* and t_{i+k} were days after planting when the N uptake measurement was done.

To assess N synchrony, the partial balances between plant N uptake and mineral-N released from the amended soils per day at each sampling date (Eq. 6) were constructed and modified from those reported by Loecke et al. (2012).

N flux (kg N ha^{-1} day^{-1}) = Mineral-N released $_{inputs}$ (kg N ha^{-1} day^{-1}) - Daily N uptake (kg N ha^{-1} day^{-1}) ….……………………………………………..Eq. 6

2.3.8. Data analysis

N release data were statistically analyzed using a linear mixed-effect model with *lmer* function from the *lme4* package in R statistical software (Bates et al., 2013). Sites were treated as fixed effects since they were selected based on the basis of prior knowledge of the weather, soil organic carbon and pH. Systems were also treated as a fixed effect while replicates were treated as random effect. Analysis was done after assessing for data normality using *Shapiro.test* and a homogeneity test using *Bartlett.test*. Mean separation was done using adjusted Tukey's method, implemented using "*multicompView package" for cld* function as developed by Graves et al. (2015) in R software version R3.1.1 (R Development Core Team. 2014) after calculation of the least mean square, using *lsmeans* package.

2.4. Results

2.4.1. The characteristics of the inorganic inputs applied

The characteristics of FYM, compost, plant and crop residues applied in the different farming systems at the beginning of every season are shown in Table 4. The quality of compost and FYM differed, both showing seasonal and site variations, with that made at Chuka having a higher N content than that from Thika. During the maize cropping season, a higher C:N ratio was observed at Thika than Chuka while lignin content was higher at Chuka.

Table 4: Quality of organic inputs used in different farming systems during the three different seasons in the long-term system comparison trials at Chuka and Thika in the Central highlands of Kenya

Site	Cropping period	System	Inputs	pH	EC ($S\ m^{-1}$)	org C (%)	NO_{3}-N ($mg\ kg^{-1}$)	NH^{+}-N ($mg\ kg^{-1}$)	N (%)	P (%)	K (%)	Lignin (%)	Polyphenols (%)	C:N ratio	Lignin:N ratio
Chuka	Potato	Conv-High	FYM	8.40±0.04	0.28±0.005	24.7±3	nd	nd	1.50±0.04	0.32±0.00	1.19±0.06	10.6±0.8	nd.	16±1.6	7±0.7
		Org-High	Compost	8.56±0.01	0.28±0.014	19.5±1.2	nd	nd	1.29±0.02	0.33±0.01	1.19±0.13	14.8±0.8	0.04±0.05	15±0.3	16±3.9
			Mulch	6.58±0.03	nd	54.5±1.9	nd	nd	1.92±0.03	0.26±0.01	1.85±0.04	19.5±0.3	0.90±0.1	28±1.8	10±0.6
			Maize	7.58±0.06	nd	46±1.14	nd	nd	1.46±0.09	0.21±0.01	0.64±0.12	5.9±0.6	1.48±0.1	25±0.6	3±0.8
			Mucuna	5.41±0.08	nd	47±1.92	nd	nd	2.9±0.13	0.07±0.02	0.47±0.12	8.9±0.5	0.36±0.1	16±0.9	7±0.5
			Tithonia	6.58±0.03	nd	nd	nd	nd	4.37±0.18	0.43±0.05	1.72±0.11	nd	1.10±0.1		nd
		Conv-Low	FYM	8.59±0.00	0.13±0.001	24.5±2	nd	nd	1.46±0.03	0.36±0.01	0.29±0.07	12.8±0.6	0±0.2	17±1.7	9±0.6
		Org-Low	FYM	8.97±0.00	0.24±0.005	19.8±0.1	nd	nd	1.07±0.01	0.43±0.00	0.96±0.02	9.5±0.4	0	19±0.3	9±0.4
	Maize	Conv-High	FYM	7.23±0.01	0.16±0.001	20.1±2.6	nd	nd	2.37±0.02	0.5±0.013	0.93±0.02	19.4±0.4	nd	8±1.0	8±0.1
		Org-High	Compost	8.78±0.14	0.15±0.005	10.3±1.3	nd	nd	1.45±0.03	0.37±0.00	1.11±0.00	14.1±0.3	nd	7±1.1	10±0.1
		Conv-Low	FYM	8.58±0.19	0.27±0.009	25±1.7	nd	nd	2.26±0.09	0.45±0.01	1.95±0.03	21.7±1.0	nd	11 ±1.2	10±0.1
		Org-Low	FYM	7.77±0.08	0.11+0.014	20.3±0.1	nd	nd	2.28±0.02	0.49±0.01	0.92±0.00	18.9±0.8	nd	9±0.1	9±0.3
	Vegetable	Conv-High	FYM	9.03±0.08	nd	18.6±4.9	80±2	63±3	1.13±0.05	0.27±0.05	1.32±0.14	13.7±0.4	0.2±0.01	16±3.8	12±0.1
		Org-High	Compost	8.32±0.18	nd	43.8±2.6	121±4	53±18	1.11±0.03	0.4±0.02	1.99±0.14	12.4±0.4	0.2±0.01	40±5.1	11±0.2
			Stover	nd	nd	nd	nd	nd	2.25+0.26	0.03+0.01	0.28±0.06	nd	0.9+0.1	nd	nd
			Tithonia	nd	nd	nd	nd	nd	4.37+0.04	0.43+0.02	1.72+0.2	nd	1.1+0.5	nd	nd
		Conv-Low	FYM	8.76±0.01	nd	36.2±1.2	141±1	55±2	1.53±0.03	0.33±0.01	1.71±0.18	18.6±1.1	0.4±0.2	24±1.4	12±0.4
		Org-Low	FYM	9.04±0.08	nd	26±5.0	136±11	58±1	1.14±0.11	0.38±0.03	1.59±0.13	12.7±0.7	0.2±0.2	23±1.3	11±0.5
Thika	Potato	Conv-High	FYM	7.85±0.28	0.27±0.005	19.7±4	nd	nd	0.66±0.07	0.19±0.00	0.97±0.09	9.5±1.9	nd	30±3.2	15±1.7
		Org-High	Compost	8.38±0.02	0.26±0.005	14.5±0.6	nd	nd	1.51±0.02	0.25±0.01	0.83±0.07	8.21±1.2	nd	10±1.4	5±0.3
			Maize	7.38±0.04	nd	47.3±1.1	nd	nd	3.01±0.02	0.12±0.01	0.51±0.26	nd	nd	16±1.7	nd
			Mucuna	5.57±0.06	nd	49.6±1.0	nd	nd	3.96±0.04	0.15±0.01	0.51±0.04	nd	nd	13±1.3	nd
			Tithonia	6.43±0.03	nd	nd	nd	nd	3.03±0.13	0.41±0.03	6±0.72	nd	nd	nd	nd
		Conv-Low	FYM	8.20±0.00	nd	33.9±1.3	nd	nd	2.54±0.06	0.25±0.00	1.02±0.04	9.9±0.2	0.4±0.1	13±0.2	4±0.1
		Org-Low	FYM	7.79±0.02	0.32±0.002	13.3±1.6	nd	nd	1.47±0.10	0.22±0.00	1.31±0.14	13.8±0.8	nd.	10±7.2	10±3.0
	Maize	Conv-High	FYM	8.21±0.03	0.38±0.022	47.6±4	440±28	95±27	0.95±0.18	0.27±0.04	1.56±0.00	13.1±1.3	3.2±0.3	55±5.9	15.±2.2
		Org-High	Compost	7.89±0.03	0.36±0.003	26.7±4.2	311±9	53±11	0.80±0.07	0.2±0.006	1.24±0.02	11.3±0.8	2.1±0.3	32±2.6	14±0.6
		Conv-Low	FYM	8.25±0.04	0.13±0.015	40.4±2.6	58±29	147±12	0.96±0.03	0.19±0.00	0.78±0.03	13.5±0.4	2.3±0.0.1	42±1.6	14±0.1
		Org-Low	FYM	7.34±0.10	0.26±0.008	21.5±2.9	352±20	192±65	0.89±0.09	0.24±0.00	1.08±0.08	11.6±1.0	2.3±0.2	27±5.0	13±0.3
	Vegetable	Conv-High	FYM	8.39±0.04	nd	20.1±3	247.1±84	6±1	0.88±0.06	0.17±0.00	0.83±0.16	13.0±0.1	0±0. 1	24±3.8	16±0.5
		Org-High	Compost	8.48±0.02	nd	12.9±1.1	225±49	24±7	0.66±0.04	0.14±0.00	0.72±0.03	9.0±0.7	nd.	20±2.1	14±0.2
			Stover	nd	nd	nd	nd	nd	1.87±0.07	0.03±0.00	0.20±0.01	nd	nd	nd	nd
			Tithonia	nd	nd	nd	nd	nd	4.36±0.10	0.22±0.03	3.5±0.80	nd	2.0±0.8	nd	nd
		Conv-Low	FYM	8.81±0.02	nd	20.2±3	164±24	311±57	1.26±0.04	0.36±0.00	1.41±0.01	14.1±0.6	0.3±0.1	17±2.9	11.±0.9
		Org-Low	FYM	7.79±0.13	nd	14.1±2.4	301±15	35±2	0.43±0.03	0.1±0.004	0.19±0.01	5.9±1.0	nd	33±5.6	16±3.5

Conv-High conventional high input system, *Org-High* organic high inputs system, *Conv-Low*, conventional low input system, *Org-low* organic low input system

2.4.2. The effects of farming systems on mineral-N released from soil and applied inputs

Potato: Expressed as a percentage of the total N applied, the mineral-N released showed no significant difference between systems, sites and their interactions.

Maize: There was no significant differences between the systems or within the sites on mineral-N released (expressed as a percentage of total N applied). However, a significant system x site interaction effect ($P<0.05$) on mineral-N released was observed (Table 5). More mineral-N was released in the two low input systems at Chuka than in the same systems at Thika.

Vegetables: There were no significant differences in mineral-N released from inputs, expressed as a percent of total N applied (Table 5).

Table 5: N released from soil alone, soil amended with inputs, inputs alone and percentage of applied N released in the long-term system comparison trials at Chuka and Thika in the Central Highlands of Kenya

		Potato cropping season				Maize cropping season				Vegetables cropping season			
		Mineral-N released from soil (kg ha^{-1})	Mineral-N released from soil+Inputs (kg ha^{-1})	Mineral-N released from Input (kg ha^{-1})	N released as % of N applied[a] (%)	Mineral-N released from soil (kg ha^{-1})	Mineral-N released from soil+Inputs (kg ha^{-1})	Mineral-N released from Input (kg ha^{-1})	N released as % of N applied[a] (%)	Mineral-N released from soil (kg ha^{-1})	Mineral-N released from soil+Inputs (kg ha^{-1})	Mineral-N released from Input (kg ha^{-1})	N released as % of N applied[a] (%)
Systems	Conv-High	176	231ab	55	40	118	120ab	2	5	112ab	180ab	68ab	44
	Org-High	219	312a	93	27	150	127a	-23	-16	133a	250a	118a	41
	Conv-Low	125	141b	16	39	95	96b	1	20	97b	122b	25b	49
	Org-Low	128	152b	24	45	103	95b	-8	-19	105b	129b	24b	43
Site	Chuka	152	178b	26	31	115	141a	26a	38	74b	108b	35	45
	Thika	173	240a	67	44	118	78b	-37b	-68	150a	233a	83	43
Chuka	Conv-High	131bc	186	55	34	102b	145	43	38abc	75	114	39	34
	Org-High	219ab	231	12	4	170a	166	-5	-2abcd	102	165	63	28
	Conv-Low	133bc	141	8	25	100b	129	29	46ab	58	68	11	47
	Org-Low	124c	154	30	61	97b	122	25	71a	60	85	25	71
Thika	Conv-High	221a	277	56	45	134ab	94	-40	-47cde	149	246	97	53
	Org-High	219ab	393	174	50	129ab	89	-40	-30bcde	164	335	171	54
	Conv-Low	118c	141	23	52	90b	63	-27	-85de	135	176	41	50
	Org-Low	132bc	150	18	28	108b	67	-41	-109e	150	173	22	15
Source of variations													
System		***	***	ns	ns	***	***	ns	ns	*	***	**	ns
Site		ns	*	ns	ns	ns	***	***	***	***	***	ns	ns
System x Site		*	ns	ns	ns	*	ns	ns	**	ns	ns	ns	ns

Conv-High conventional high input system, *Org-High* organic high inputs system, *Conv-Low*, conventional low input system, *Org-low* organic low input system,; *ns* not significant; **P* ≤0.05; ***P*≤0.01; ****P*≤0.001

[a]N released expressed as a percentage of the total N applied

2.4.3. Rates of N released from inputs during the cropping seasons

Potato: Rates of N release from inputs were significantly higher ($P<0.001$) at 0 to 14 days of incubation (corresponding to nutrient application and early potato growth stages) in all the farming systems (Fig. 2). Thereafter the rate declined. At Thika, significantly higher N release rates were observed during the initial 3 days of incubation (DOI, corresponding to the germination stage) in Conv-High and Org-High than in Conv-Low and Org-Low. This difference disappeared by 44 DOI (corresponding to tuber initiation), and there were no longer any discernible differences between the high and the low input systems (Fig. 2).

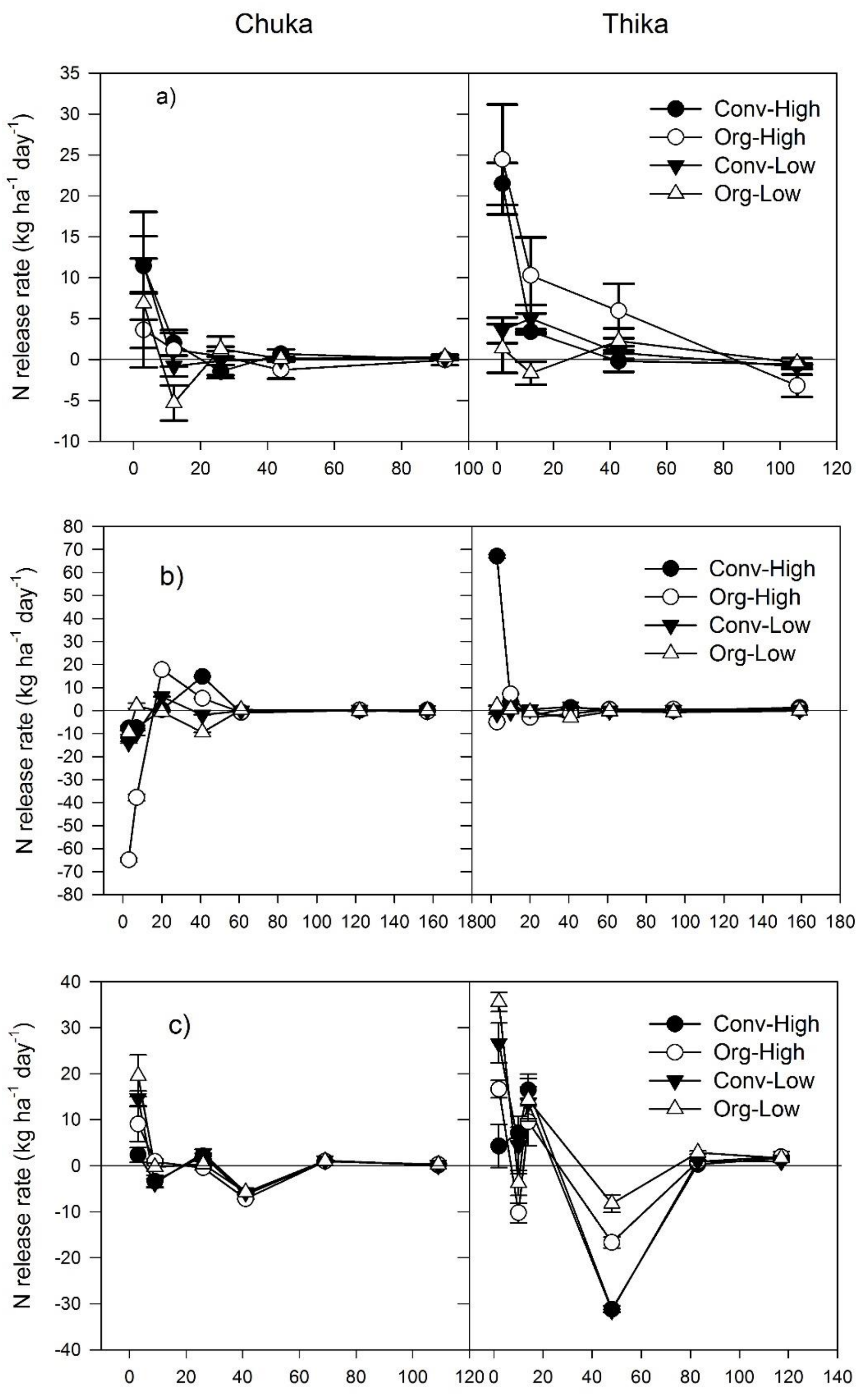


Fig. 2: Net mineral-N release rates of applied inputs in different farming systems during a) potato b) maize and c) vegetable cropping periods at Chuka and Thika (N released from inputs= N mineralized from amended soil - N mineralized from soil alone; negative values represent N

immobilization). Note: Bars for the standard error of means are only shown when they are larger than the symbols.

Maize: There was a strong net immobilization of N from the applied inputs at Chuka during the initial 10 days of incubation (corresponding to the maize seedlings stage) in the Org-High system. This was followed by a net N release rate at 20-41 DOI (corresponding to the vegetative growth stage i.e., V5-V12 leaf stage), although this difference declined thereafter to close to zero (Fig. 2). At Thika, there was a high N release rate in Conv-High at 0-7 days after planting (germination stage of maize).

Vegetables: At Chuka, significantly higher ($P<0.001$) net N release rates from the added inputs were observed at 2 DOI in the low input systems than in the high input systems (Fig. 2). N immobilization was observed at 48 days of incubation (corresponding to the pre-cupping stage of cabbage and development of harvestable vegetative plant parts and harvesting stages in kale and Swiss Chard) in all the farming systems at both sites (Fig. 2). Similar trends were observed at Thika except that the rate of N release was lower at 2 DOI.

2.4.4. The effects of farming and cropping systems on seasonal N fluxes

Potato: More mineral-N was released from amended soil, which exceeded N uptake at all potato growth stages at both sites (Fig. 3a). From 30 days after sowing (DAS), mineral-N release in Org-High was significantly higher than in all the other systems (except at maturity for Conv-High). At Chuka, soil mineral-N (SMN) was higher in all systems at 20-30 and 93 DAS (the vegetative and harvesting stage) of potato than at planting (Fig 3a) although Conv-Low had a significantly lower ($P<0.001$) SMN than the other systems (Fig 3a) at 0-33 DAS (planting and vegetative stages). Soil mineral-N declined after 49 DAS (tuber initiation stage) in all the systems and increased significantly at the time of harvest (Fig. 3a) in Conv-High and Org-High, which had a significantly higher ($P<0.05$) SMN than Conv-Low and Org-Low. Similar trends were observed at Thika (Fig. 3a).

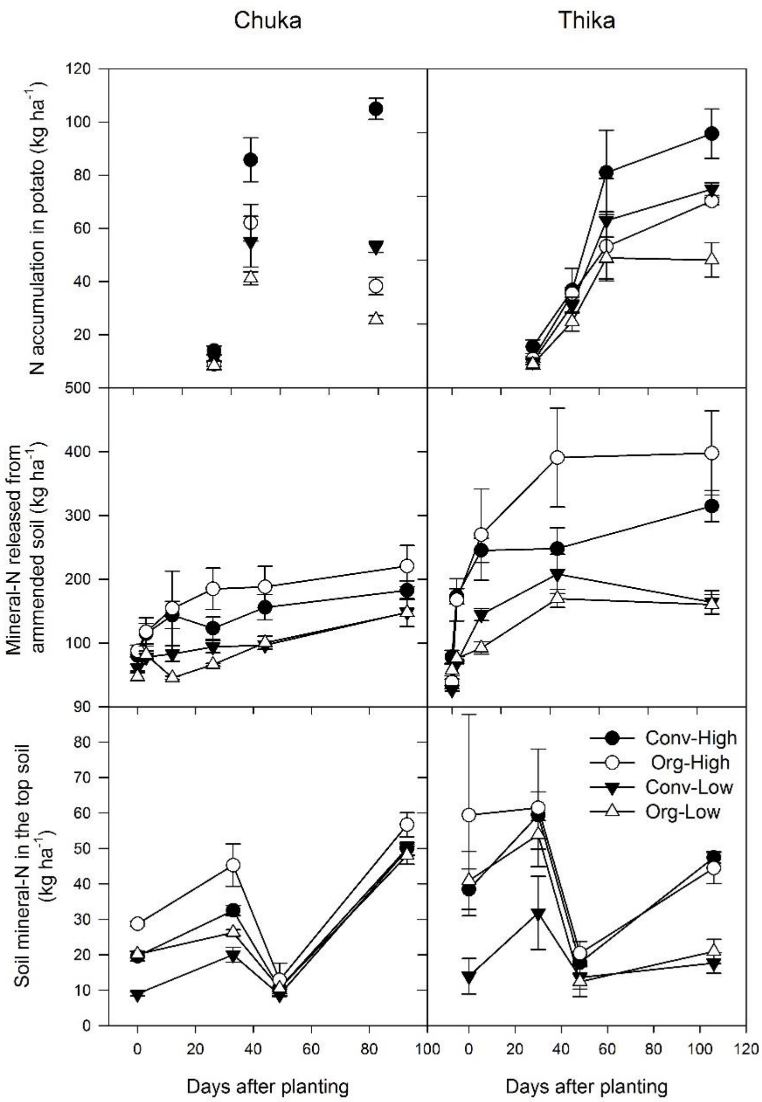


Fig. 3a: N uptake, cumulative N released from the amended soils (buried bags) and soil mineral-N (under natural soil-crop interaction) in different farming systems at different growth stages of potato at Chuka and Thika in the Central Highlands of Kenya. Note: Bars for the standard error of means are only shown when they are bigger than the symbols.

Maize: Large amounts of mineral-N were released from amended soil which exceeded the crop's N uptake between 0 and 40 DAS (corresponding planting and vegetative stage) in all the farming systems at both sites. At Chuka, the mineral-N released at 73 to 155 DAS (tasselling to harvesting stages) in the low input systems also exceeded maize's N uptake (Fig. 3b). By contrast, mineral-N released at Thika at 29-43 and 159 DAS (vegetative and harvesting stages) in all four systems was less than N uptake (Fig. 3b). A decline in mineral-N released from the amended soils was observed at 40 DAS at Thika and at 60 DAS at Chuka. At Chuka the SMN in the topsoil was high at the time of planting maize, but this declined to 20 kg ha^{-1} at 28-73 DAS (vegetative and reproductive stages). Soil mineral-N increased slightly at 159 DAS (corresponding to the harvest). At Thika, SMN remained below 40 kg ha^{-1} at 29-159 DAS (vegetative to harvesting stages) in all the systems except Org-High and Conv-Low, where SMN increased slightly at the silking stage of maize (94 DAS).

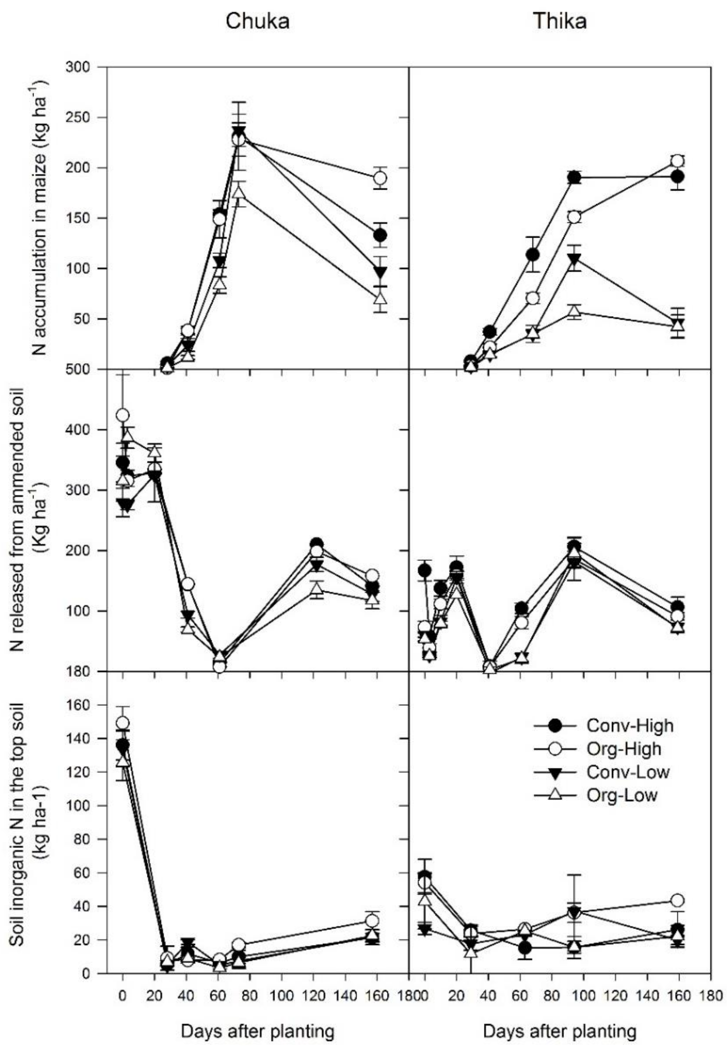


Fig. 3b: N uptake, cumulative N released from amended soil (buried bags) and soil mineral-N in different farming systems at different stages of maize at a) Chuka and b) Thika. Note: Bars for the standard error of means are only shown when they are bigger than the symbols.

Vegetables: Mineral-N released in the low input systems at both sites exceeded N uptake in kale and Swiss chard (Fig. 3c). At 0 to 69 DAS (corresponding to planting to the development of harvestable vegetative plant parts of kale and Swiss chard) mineral-N released exceeded cabbage N uptake in the high input systems (Fig. 3c). The SMN was significantly higher (P<0.001) at day 0 (before input application) for cabbage in the high input systems than in the low input systems at Chuka but declined to 4 kg ha^{-1} at 43 DAS (pre-cupping stage, Fig. 3c). An increase in SMN was also observed at 71 DAS (head formation stage of cabbage) with Org-High showing appreciably higher SMN than the other systems. The SMN at Thika was significantly lower (P<0.001) on day 0 (at before input application) than at Chuka. Soil mineral-N increased in all the systems at 25-44 DAS (vegetative and pre-cupping stages of cabbage and the development of harvestable vegetative plant parts for kale and Swiss chard) except in Org-High, where there was a decline at 44 DAS (pre-cupping stage of cabbage). Soil mineral-N was similar for all the systems at 83-114 DAS (corresponding to the head formation of cabbage and development of harvestable vegetative plant parts of kale and Swiss Chard and harvesting stages) at Thika.

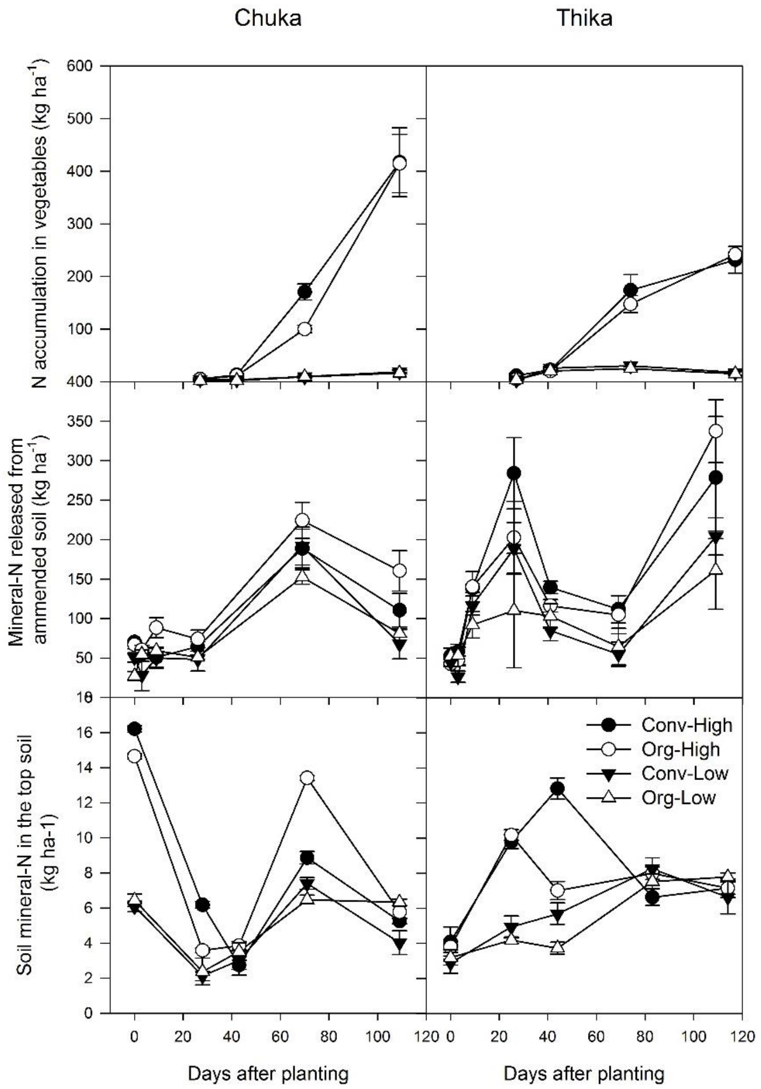


Fig. 3c: N uptake, cumulative N released from amended soil (buried bags) and soil mineral-N (0-20 cm) (under natural soil-crop interaction) in different farming systems at different stages of vegetables at a) Chuka and b) Thika sites. Note: Bars for the standard error of means are only shown when they are bigger than the symbols.

2.4.5. The effects of farming and cropping systems on patterns and degree of N synchrony

Potato: N fluxes during potato growth period ranged from -5.7 to 14 kg ha^{-1} day^{-1} at Chuka and -11 to 41 kg ha^{-1} day^{-1} at Thika. Positive N flux differences were observed at 3-12 DAS (corresponding to planting and germination stages) of potato in all the farming systems (Fig. 4). At Chuka, negative N flux differences (immobilisation) were observed at 44-63 DAS (tuber initiation and bulking stages) in Conv-High and Org-High; and at 44 and 93 DAS (tuber initiation and harvesting stages) in Conv-Low and Org-Low. At Thika the positive N flux differences in Conv-High and Org-High followed a similar pattern. They were observed at 3-12 DAS (planting and germination). Negative N flux differences at Thika were observed in Conv-High at 63 DAS (Tuber initiation) and in Org-High at 106 DAS. At 63 DAS (tuber bulking stage), the Org-High system at Thika exhibited a positive N flux difference, in contrast to the negative N flux differences in all the other farming systems ($P<0.002$).

Maize: N flux differences during the maize cropping period ranged between -60 to 23 kg ha^{-1} day^{-1} (Fig. 4). At Chuka, the two organic systems showed a higher ($P<0.002$) negative N flux difference at 7 DAS (the germination stage) than the two conventional systems. In addition, a negative N flux difference was observed at 28-61 DAS (the vegetative to tasselling stages). The negative N difference was significantly more pronounced ($P<0.001$) in the high input systems than the low input systems. By contrast, positive N flux differences were observed at 73-157 DAS (the silking and harvesting stages) in all the systems. At Thika, negative N flux differences were observed at 28-41 and 159 DAS (corresponding to the germination, vegetative and harvesting stages of maize crop) in all the farming systems. Positive N flux differences were observed at 70-94 DAS (corresponding to the tasselling and silking stages).

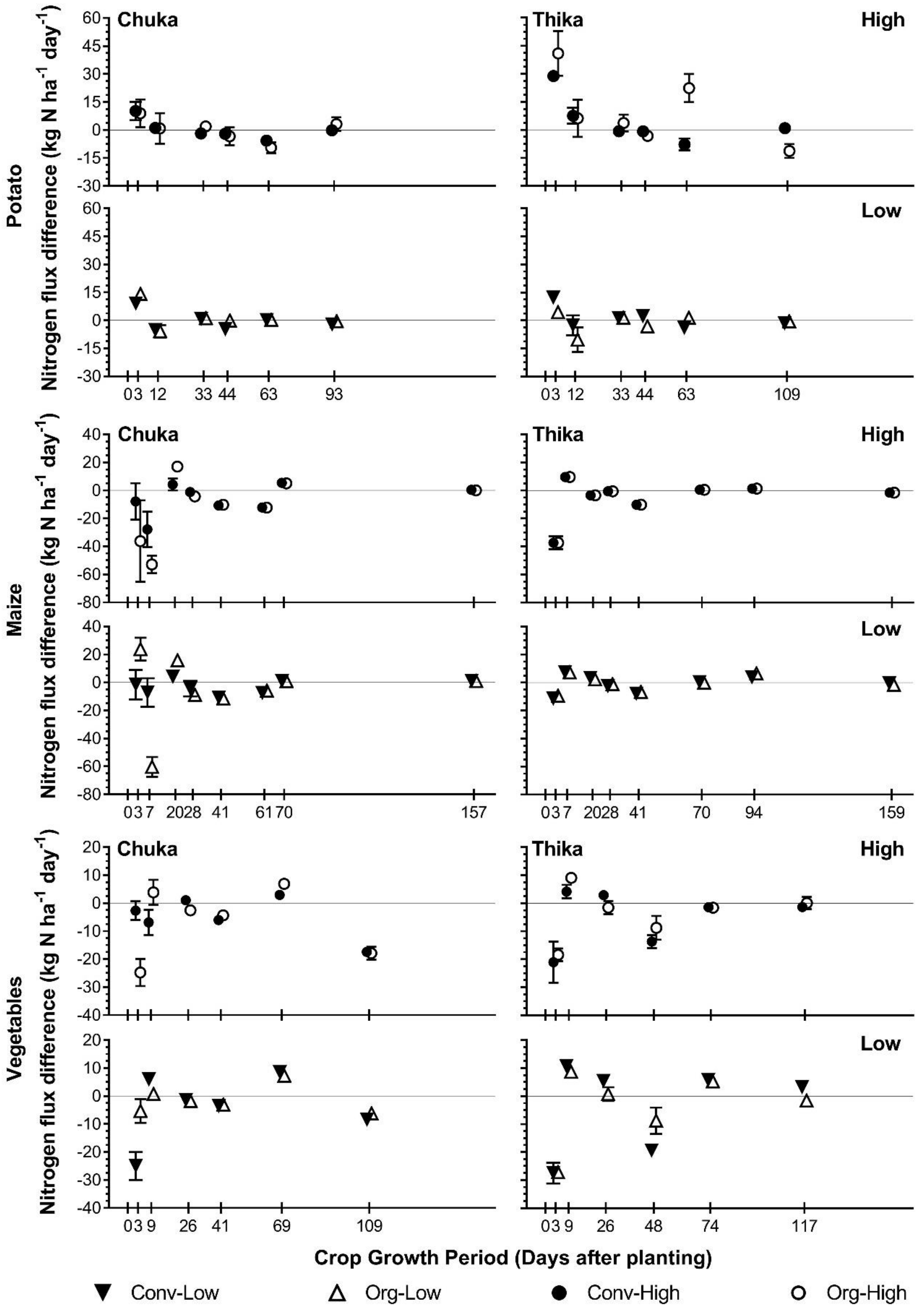


Fig. 4: Nitrogen flux differences (calculated per day) between N release and N uptake (amended soil) under potato, maize and vegetable based conventional and organic farming systems at different input intensities at Chuka and Thika in the Central Highlands of Kenya.

Note: Bars for the standard error of means are only shown when they are bigger than the symbols.

Vegetables: N flux differences during the growth periods for cabbage, kales and Swiss chard ranged from -25 to 8.5 kg ha^{-1} day^{-1}. At Chuka (Fig 4), a lower positive N flux (P<0.001) was observed in Conv-High than in the other systems at 69 DAS (head formation stage of cabbage) and at 109 DAS (harvest), The negative N flux differences were significantly higher (P<0.01) in the high input systems than the low input systems. Positive N flux differences were observed at 9 and 69 DAS (vegetative and heading stage) of the cabbage and kale/Swiss chard intercrop and negative N flux differences were observed at 41 DAS (the pre-cupping stage of cabbage the and development of harvestable vegetative plant parts for kale and Swiss chard).

At Thika, positive N flux differences were observed at 9 to 26 DAS (the vegetative stage) and at 117 DAS (harvest) stages in all the systems except in Org-High (at the vegetative stage) and Conv-High and Org-Low (at harvest), when a positive N flux difference was observed. At 74 DAS (head formation stage of cabbage), Conv-High and Org-High showed negative N flux differences while Conv-Low and Org-Low had significantly positive N flux differences (P<0.001).

2.5. Discussion

2.5.1. Effects of farming systems on synchrony of N supply to uptake

Potato: The higher rates of N release and positive N fluxes in amended soil during the early growth stages of potato in all the farming systems can be attributed to the provision of additional sources of carbon and materials with a low C:N ratio (e.g. FYM and compost) as well as the residual effects of previously applied inputs. Additions of fresh carbon sources are associated with increases in microbial biomass (Wang, 2015) that enhance rapid decomposition (El-Sharkawi, 2012). During decomposition, the low C:N ratio materials could be expected to supply sufficient N to meet the N needs of the decomposing organisms (El-Sharkawi, 2012).

This led to a net release and build-up of mineral-N in the soil (mineralization) and, hence, the high mineral-N observed at the early growth stages of potato. On the other hand, the use of organic inputs with high lignin content at Chuka could account for the low rates of N release at the initial stages of incubation (compared to the N released at Thika). The variation in the lignin content of the inputs may also account for the variations in the N release rates during potato growing period. Vanlauwe et al. (2005) investigated the relationship between the lignin:N ratio of materials and N release and concluded that there was a negative correlation between materials with a high lignin content (Class A) and N release. These reasons, coupled with the residual effects of previously applied inputs, were responsible for the major increase in N availability, in all the farming systems, before the crop was fully established.

High positive N flux differences observed in Org-High throughout the potato growth period at Thika indicate that large amounts of mineral-N were released in this system. This can be attributed to the application of Mucuna biomass (on average 7.3 t ha^{-1}) which was expected to supply 211 kg N ha^{-1} compared to 3.3 t ha^{-1} applied at Chuka (with a potential to supply 127 kg N ha^{-1}). Kaizzi et al. (2004) reported that Mucuna accumulates 170 and 350 kg N ha^{-1} in low and high potential agro-ecological zones, respectively. The resulting asynchrony observed at the planting and vegetative stages (3-33 DAS) of potato is in line with the findings of Lynch et al. (2008) who reported increases in mineral-N concentrations 30-35 days after planting potato. The negative N flux differences observed at the tuber initiation and bulking stages in Conv-High and Org-High at Chuka, and in Conv-High and Conv-Low at Thika were due to higher crop N demand which exceeded the mineral-N supply from the inputs. At this stage the crop was likely to derive extra N from lower soil layers, as shown by a lowering of NO_3^--N at a depth of 0.2-0.4 m (Musyoka et al., 2019). The positive fluxes observed in the high input systems at Chuka could have been due to a reduction in N uptake, due to the effect of late blight (*Phytophthora infestans)* disease which affected potato at this site. The result runs contrary to the observations of Nyiraneza and Snapp (2006), who reported synchrony of N release which matched potato N uptake throughout its growth period under cover crops, poultry manure and fertilizer application. The similarity in the pattern of N synchrony and the degree of N fluctuation in all the farming systems contradicts earlier reports by Kirchmann et al. (2008) that nutrient release in conventional systems always meets crop N demand, which is not the case in organic systems. The difference in our results can be attributed to the difference in the quality of organic inputs and their N release rates as well as the integrated application of synthetic fertilizer and FYM in our conventional systems.

Maize: Even though there was high residual mineral-N in the top-soil (due to poor N uptake by the preceding potato crop caused by late blight disease) at planting, there were negative rates of N release and negative N fluxes in the amended soil at the beginning of maize cropping season in the high input systems at Chuka. This indicates that immobilization occurred at the initial growth stages (from planting to the V8 leaf stage of maize). This can be attributed to the effects of the applied organic inputs with a high lignin content (>15%) at Chuka. The application of these organic inputs stimulated microbial growth and development, with the microbes making additional demands on the available N in the soil in order to decompose the applied organic inputs, resulting in N immobilization (Chen et al., 2014; Mooshammer et al., 2014). With time, the available carbon sources become exhausted, resulting in the death of the microbes and the release of N that they contain (Kuzyakov, 2010), which probably explains the high N release (mineralization) observed at 60-120 DAS (tasselling and silking stages).

The decline in mineral-N released from amended soil and soil alone between the V8 leaf and silking stages of maize (41-100 DAS) indicates the possibility of NO_3^--N being desorbed from the resin and assimilated by soil microbes (microbial immobilization) due to the long period (100-158 days) that the resin bags were deployed. Giblin et al. (1994) found that short deployment periods (44 days) of resins resulted in higher mineral-N release than long (whole season) deployment periods. There is also the possibility of N loss through denitrification on the resin films, possibly during periods of low oxygen availability. Therefore, it appears advisable not to incubate resins for extended periods in future studies. The duration at which the resin is kept as a sink is further dependent on the exchange capacity of the resin, nutrient availability and the conditions of the soil at the time of burial (Qian and Schoenau, 2002).

The significantly insufficient N asynchrony observed in Org-High at the germination stage at Chuka can be attributed to immobilization caused by the reasons discussed above. Insufficient-asynchrony, which mainly occurred at the vegetative stage of the maize crop (28 to 61 DAS), in all farming systems at both sites, can be attributed to low mineral-N release from the amended soil which was unable to meet the crop's high N demand. The high crop N demand during this period could have been partly met by the crop deriving N from lower soil layers. This also indicates that the supply of available N needs to be enhanced at these critical stages. One practical way would be to reduce the amount of N applied at the planting stage and increase the N supplied as a top dressing during the reproductive stages (V8 to silking stages of maize) to match the high N demand by the crop. This can be achieved by using CAN in conventional systems and the use of plant teas (prepared from leaves and soft twigs of Tithonia) in organic systems (Chikuvire et al., 2013; Adamtey et al., 2016). By contrast, there was an excess of N at the silking and harvesting stages (70-94 and 157 DAS) in all the farming systems, which can be explained by an increase in mineral-N release from both the residual and new inputs applied as top dressing in high input systems and crop failure in the in the low input systems at Thika, which affected N uptake (Musyoka et al., 2017). One implication of this is the likelihood of more N leaching into the environment. Our companion paper (Musyoka et al., 2019) confirms this assertion.

Vegetables: N release rates were high during the initial 10 days after incubation in the amended soils. This can be attributed to the application of fresh carbon sources with relatively low N, C:N ratio and lignin content of < 15% (class III, Gachengo et al., 2004) which resulted in short term mineralization. However, application of these materials could also have resulted in increasing the microbial population which would have taken up much of the available N in the soil to meet their N requirements (El-Sharkawi, 2012; Wang, 2015). This may explain the short period of immobilization observed at the vegetative and reproductive stages of vegetables in both the high and low input systems at both sites. The increase in N release rates at the pre-cupping and heading stages of cabbage and the development of harvestable vegetative plant parts for kale and Swiss chard (40-70 DAS) in all the systems can be explained by the top dressings of CAN or Tithonia tea that were applied. Insufficient-N asynchrony was observed during the vegetative and pre-cupping stages of cabbage and development of harvestable vegetative plant parts for kale and Swiss chard (26-41 DAS at Chuka and 48 DAS at Thika) in all the systems and at harvest (107 DAS) in the high input systems. This is an indication that the top dressings were inadequate to meet crop N demand and points to the need to increase the N application rate at this stage. By contrast, the excess asynchrony during the head formation stages of cabbage (69 DAS) in both high input systems at Chuka can be attributed to higher mineral-N release from the inputs as a result of the 2nd top-dressings with CAN and Tithonia tea. We also observed excess asynchrony at the development of harvestable leaves stage (69 DAS) of kale and Swiss chard in both low input systems at both sites. This was probably due to the effect of drought which led to low N uptake (Musyoka et al., 2017).

Research has shown that 4-57% of N applied as manure or compost can be released in the year following application (Muñoz et al., 2008). In our case, 4 to 71% of total N applied was released during the potato (three months) and vegetable (three months) cropping periods in the four different systems. The differences in mineral-N released can be attributed to variations in the quality of inputs used. The observed excess and insufficient asynchronies during the three cropping periods could have been higher if root N demand was also considered.

2.5.2. The effects of the environment on the synchrony of N supply and uptake

The effects of the environment on mineral-N release were mainly associated with the quality of FYM and composts used at each site. The farm yard manure available at Chuka site was from a zero-grazing unit, while the one for the Thika site was from free-grazing cows and goats, which may explain the difference in FYM and compost quality at the two sites. Seasonal variations in FYM quality were probably due to the seasonality of fodder available for the livestock. The C:N ratios of compost and FYM (7-55) were within the range of 5-81 obtained from manures and composts sampled from Central Highlands of Kenya by Lekasi et al., (2003). Nitrogen levels in the FYM and compost used in the study ranged from 0.43 – 2.54%, which was higher than the 0.33-1.91% reported by the same authors. The organic input qualities that mostly affected mineral-N release were N and the C:N and Lignin:N ratios. This is in line with the findings of other authors (Vanlauwe et al., 2005) who found that C, N, C:N ratio, Lignin, Lignin:N ratios influence decomposition and N release rates. The low C:N ratio of the compost is a result of the high proportion of N rich Lantana biomass and FYM used as composting material whilst that of FYM may be due to management effects such as the use of carbon rich materials as bedding material for livestock and the handling of FYM during collection. The differences between N fluxes observed at Chuka and Thika can also be partly attributed to differences in soil characteristics and mineralogy (Adamtey et al., *unpublished*), total active bacteria and archaea population (Karanja et al., unpublished), and the amount and distribution of rainfall (with Thika being drier).

2.6. Conclusions

The effects of the environment on mineral-N release were mainly associated with the quality of FYM and composts used at each site. The farm yard manure available at Chuka site was from a zero-grazing unit, while the one for the Thika site was from free-grazing cows and goats, which may explain the difference in FYM and compost quality at the two sites. Seasonal variations in FYM quality were probably due to the seasonality of fodder available for the livestock. The C:N ratios of compost and FYM (7-55) were within the range of 5-81 obtained from manures and composts sampled from Central Highlands of Kenya by Lekasi et al. (2003). Nitrogen levels in the FYM and compost used in the study ranged from 0.43 – 2.54%, which was higher than the 0.33-1.91% reported by the same authors. The organic input qualities that mostly affected mineral-N release were N and the C:N and Lignin:N ratios. This is in line with the findings of other authors (Vanlauwe et al., 2005) who found that C, N, C:N ratio, Lignin, Lignin:N ratios influence decomposition and N release rates. The low C:N ratio of the compost is a result of the high proportion of N rich Lantana biomass and FYM used as composting material whilst that of FYM may be due to management effects such as the use of carbon rich materials as bedding material for livestock and the handling of FYM during collection. The differences between N fluxes observed at Chuka and Thika can also be partly attributed to differences in soil characteristics and mineralogy (Adamtey et al. unpublished), total active bacteria and archaea population (Karanja et al., *unpublished*), and the amount and distribution of rainfall (with Thika being drier).

2.7. Acknowledgements

We gratefully acknowledge the financial support provided for this research by our financial partners: Biovision Foundation, the Swiss Coop Sustainability Fund, the Liechtenstein Development Service (LED) and the Swiss Agency for Development and Cooperation (SDC). We are also thankful to the kind contribution by *icipe* core funding provided by UK-Aid from the UK Government (DFiD), the Swedish International Development Cooperation Agency (Sida), the Swiss Agency for Development and Cooperation (SDC), the Federal Democratic Republic of Ethiopia, and the Kenyan Government. The support received from SysCom team members in Kenya: Jane Makena, Felistus K. Mutua and the late Peter Owuor during fieldwork was greatly appreciated. We also appreciate the assistance in laboratory analysis by Kenya

Agricultural Research Institute Muguga staff led by Nicholas Kungu and Peter Wakaba. We also thank Dr Daisy Salifu of *icipe* and Juan Laso of Hohenheim University for their statistical guidance and Nicholas Parrott of TextualHealing.eu whose empathetic English language editing greatly helped improve its readability. *The views expressed herein do not necessarily reflect the official opinion of the donors.*

2.8. Supplementary material

S1: Amounts and type of inputs applied per bag buried in plots in each farming system in the Long-term trial at Chuka and Thika from 2012-2014

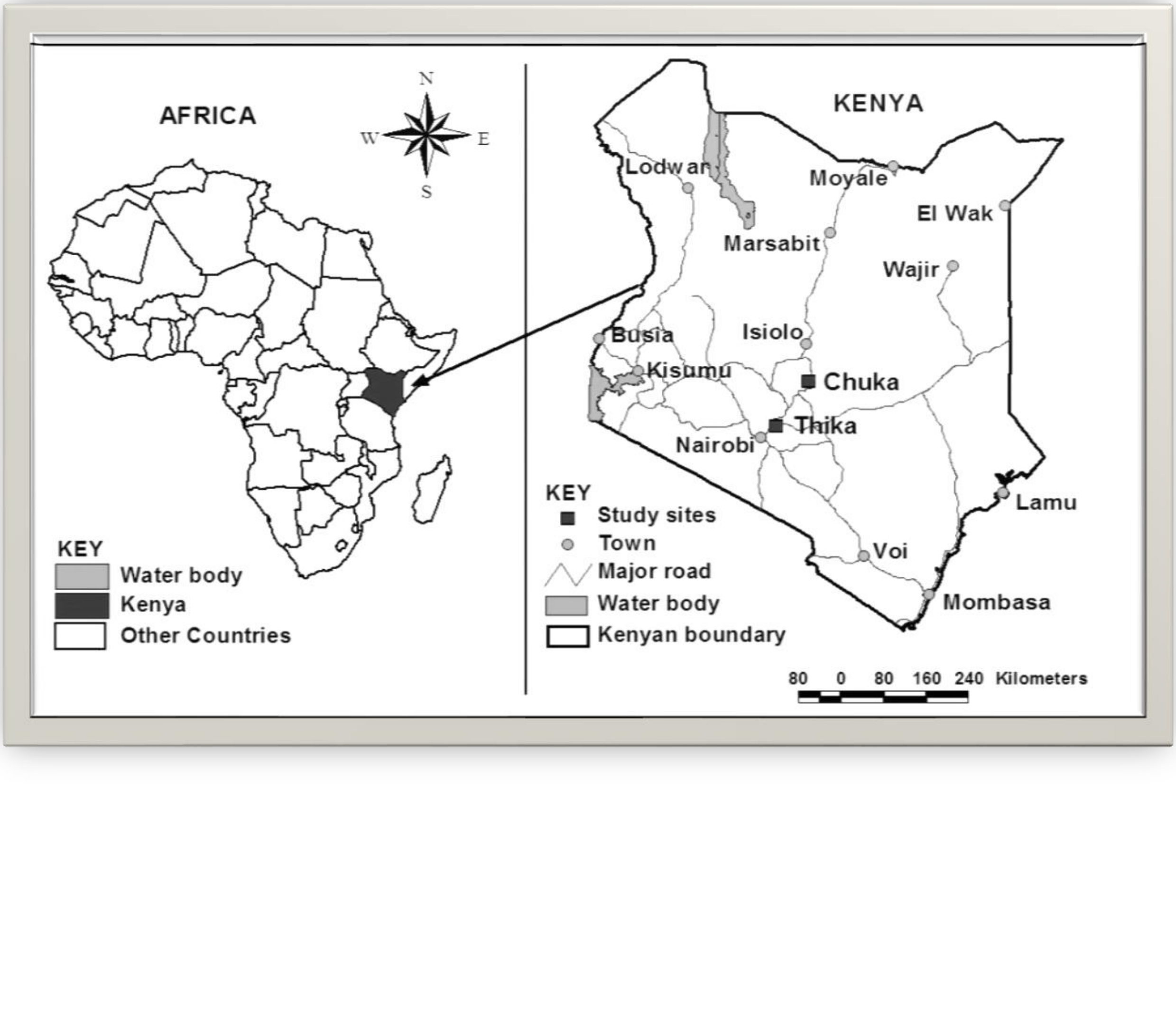
					Potato cropping season		Maize cropping season		Vegetable cropping season	
Site	**System**	**Bulk density**	**Amount of soil (0-20 cm)**	**Inputs**	**Amount applied**	**Amount per bag**	**Amount applied**	**Amount per bag**	**Amount applied**	**Amount per bag**
		g cm^3	**kg ha^{-1}**		**kg ha^{-1}**	**g per 150 g**	**kg ha^{-1})**	**g per 150 g**	**kg ha^{-1}**	**g per 150 g**
Chuka	Org-High	0.92	1840000	Compost	22031	1.8	22735	1.85	15000	1.22
			1840000	PR	581	0.665	364	0.03	400	0.03
			1840000	Tithonia mulch	8200	0.047	5400	0.44	6000	0.49
			1840000	Tithonia top dress	-	-	3900	0.32	6000	0.49
			1840000	Mucuna	-	0.843	-	-	-	-
			1840000	Maize stover	2000	0.163	-	-	2000	0.16
	Conv-high	0.91	1820000	Manure	10546	0.869	3906	0.32	6914	0.57
			1820000	DAP	-	-	200	0.02	-	-
			1820000	TSP	300	0.0247	-	-	200	0.016
			1820000	CAN	200	0.016	100	0.008	300	0.025
	Org-Low	0.91	1820000	Compost	4531	0.373	2227	0.18	390	0.03
			1820000	PR	200	0.016	100	0.01	90	0.007
			1820000	Tithonia mulch	2720	0.224	1360	0.11	1200	0.10
			1820000	Tithonia top dress	-	-	-	-	1200	0.10
	Conv-Low	0.91	1820000	Manure	2000	0.165	5000	0.41	1000	0.08
			1820000	DAP	100	0.008	50	0.00	50	0.004
			1820000	TSP	-	-	-	-	-	-
			1820000	CAN	-	-	-	-	60	0.005
Thika	Org-High	0.99	1980000	Compost	23475	1.85	17578	1.33	35281	2.673
			1980000	PR	581	0.04	364	0.03	400	0.030
			1980000	Tithonia mulch	8200	0.62	5400	0.41	6000	0.455
			1980000	Tithonia top dress	-	-	3900	0.30	6000	0.455
			1980000	Mucuna	-	1.265	-	-	-	-
			1980000	Maize stover	2000	0.15			2000	0.152
	Conv-high	1.09	2180000	Manure	10969	0.75	7187.5	0.49	17000	1.170
			2180000	DAP	-	-	200	0.014	-	-
			2180000	TSP	300	0.02	-	-	200	0.014
			2180000	CAN	200	0.14	100	0.007	300	0.021
	Org-Low	1.03	2060000	Compost	6875	0.2	5000	0.36	1688	0.123
			2060000	PR	200	0.5	100	0.01	90	0.007
			2060000	Tithonia mulch	2720	0.014	1360	0.10	1200	0.087
			2060000	Tithonia top dress	-	-	-	-	1201	0.087
	Conv-Low	1.04	2080000	Manure	2000	0.14	5000	0.36	1000	0.072
			2080000	DAP	100	0.007	50	0.004		
			2080000	TSP					50	0.004
			2080000	CAN	-	-	-	-	60	0.004

All the organic inputs were applied on fresh weight basis, as applied in the field

S2: List of biopesticides used in organic systems during potato, maize and vegetable seasons in the long-term trials at Chuka and Thika

Crop	Pests/diseases	Biopesticide trade name	Active ingredients
Potato	whiteflies	Pyegar®	Pyrethrin + garlic extract
	Bacteria and other wilts	GC 3®	Garlic extract
	Early and late blight	Fosphite®	Mono and di-potassium salts of phosphoric acid
Maize	Stem borer	Halt®	*Bacillus thuringiensis* var Kurstaki
	Termites		*Metarhizium anisopliae* (icipe isolate 30)
Vegetables	Aphids	Nimbecidine®	Azadirachtin
		Achook®	Azadirachtin
	Diamond back moth	Nimbecidine®	Azadirachtin Achook® Azadirachtin
	Cutworms	Pyegar®	Pyrethrin + Garlic extract
	Dumping	Root Guard®	*Trichorderma*, *Bacillus*, *Aspergillus*, *Chatomium*, *Escherichia*, *Azotobacter spp*
	Dumping off	GC 3®	Garlic extract

CHAPTER 3



AFRICA
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Water body
Kenya
Other Countries
KENYA
Lodwar
Moyale
El Wak
Marsabit
Wajir
Busia
Isiolo
Kisumu
Chuka
Thika
Nairobi
Lamu
Voi
Mombasa
KEY
Study sites
Town
Major road
Water body
Kenyan boundary
80 0 80 160 240 Kilometers

3.0. Effect of organic and conventional farming systems on nitrogen use efficiency of potato, maize and vegetables in the Central highlands of Kenya[‡‡]

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3.1. Abstract

Increased per capita food production in the tropics is closely tied to soil organic matter and water management, timely nitrogen (N) supply and crop N use efficiency (NUE) which are influenced by farming systems. However, there is lack of data on the effect of organic farming systems on NUE and how this compares to conventional farming systems under tropical conditions. Therefore, the objectives of this study were to determine the effect of conventional and organic farming systems at low and high management intensities on N-uptake and N use efficiency of potato (*Solanum tuberosum* L.), maize (*Zea mays* L.), cabbage (*Brassica oleracea* var. Capitata), kale (*Brassica oleracea* var. Acephala) and Swiss chard (*Beta vulgaris* sub sp. Cicla). The organic high input (Org-High) and conventional high input (Conv-High) farming systems are managed as recommended by research institutions while organic low input (Org-Low) and conventional low input (Conv-Low) farming systems are managed as practiced by

[‡‡]*Published with kind permission of Elsevier. The original article appeared in the journal in European Journal of Agronomy Vol.* 86, *pp 24–36 which can be found in the link https://www.sciencedirect.com/science/article/abs/pii/S1161030117300278?via%3Dihub*

small scale farmers in the Central highlands of Kenya. The study was conducted during three cropping seasons between October 2012 to March 2014 in an on-going long-term trial established since 2007 at Chuka and at Thika, Kenya. Synthetic N-based fertilizer and cattle manure were applied at ~225 kg N ha^{-1} yr^{-1} for Conv-High and at ~50 kg N ha^{-1} yr^{-1} for the Conv-Low. Composts and other organic inputs were applied at similar N rates for Org-High and Org-Low. Nitrogen uptake efficiency (NUpE) of potato was highest in Conv-Low and Org-Low at Thika and lowest in Org-High and Org-Low at Chuka site where late blight disease affected potato performance. In contrast, the NUpE of maize was similar in all systems at Chuka site but was significantly higher in Conv-High and Org-High compared to the low input systems at Thika site. The NUpE of cabbage was similar in Conv-High and Org-High while the NUpE of kale and Swiss chard were similar in the low input systems. Potato N utilization efficiencies (NUtE) and agronomic efficiencies of N use (AE_N) in Conv-Low and Conv-High were 11-21% and 1.4 - 3.4 times higher than those from Org-Low and Org-High respectively. The AE_N of maize was similar in all the systems at Chuka but was 3.2 times higher in the high input systems compared to the low input systems at the drier Thika site. The AE_N of vegetables under conventional systems were similar to those from organic systems. Nitrogen harvest index (NHI) of potato was similar between Conv-High and Org-High and between Conv-Low and Org-Low. N partitioned into maize grain was similar in all the system at Chuka but significantly lower ($P<0.001$) in Conv-low and Org-Low at Thika site. The NHI of cabbage in Org-High was 24% higher than that of Conv-High. The study concluded that for maize and vegetables, conventional and organic farming systems had similar effects on NUpE, AE_N, NUtE and NHI, while for potato conventional systems improved NUE compared to organic systems. The study recommends that management practices for potato production in organic systems should be improved for a more efficient NUE.

Key words: Organic farming systems, Conventional farming systems, Agronomic efficiency of N use, N-uptake efficiency, N-utilization efficiency, N-harvest index

3.2. Introduction

There is an immediate need to increase per capita food production to match high population growth while maintaining environmental stability (Ciampitti and Vyn, 2014). Since nitrogen (N) plays a critical role in food, feed and fibre production, and its increased application resulted in tripling per capita food production in the last 50 years (Prasad, 2013), an adequate N management is essential in food production. However, N remains one of the major limiting nutrients to food production especially in sub-Saharan Africa (SSA) (Bekunda et al., 2010). In most farming systems, N management poses a major challenge due to its high mobility and propensity for loss from the soil-plant system into the environment. Efficient N management techniques are required to improve N-delivery and -retention in soils in order to increase N-use efficiency (N-uptake and N-utilization), improve economic yields, reduce cost of production, and improve the economic sustainability of most farming or cropping systems (Van Eerd, 2005; Garnett et al., 2009).

Nitrogen use efficiency (NUE) in crops is determined by uptake, assimilation, translocation and, when plants are ageing, recycling and remobilization. As a concept, NUE is expressed as a ratio of output (biological yield or economic yield) and input (total soil N, fertilizer N applied, or available soil N plus fertilizer N applied) (Dobermann, 2005; Fageria and Baligar, 2005; Ladha et al., 2005). The biological yield may include total aboveground plant dry matter, whereas the economic yield includes part of the crop with economic value for example grain, or tuber yield.

Several techniques, such as use of slow release fertilizer (Ghosh et al., 2015) as well as adoption of appropriate soil fertility management practices including use of manure, rate and timing of fertilizer applications, have been used to improve NUE (Fageria and Baligar, 2005; Ghosh et al., 2015; Kumar et al., 2015). Similarly, crop management practices such as crop rotation, use of catch crops, crop residues and the use of N efficient genotypes can also improve NUE (Fageria and Baligar, 2005; Ladha et al., 2005; Alva et al., 2006; Hirel et al., 2011). Current agricultural production systems like conservation agriculture, organic farming and combined organic and conventional farming that make use of crop varieties with highly efficient use of N have been perceived to have major effects on NUE (Fageria and Baligar, 2005; Ladha et al., 2005; Hirel et al., 2011). N application levels and timing of application play a critical role in improving NUE (Hirel et al., 2007). Studies comparing low external input farming systems with conventional farming systems at different input levels in Kenya reveal that both systems may result in N mining or a positive N balance depending on the agro-ecological zone in which they are cultivated (De Jager et al., 2001; Tripp, 2006; Tambang and Svensson, 2008). Organic farming systems in Europe have been associated with low N use efficiency (Kirchmann and Ryan, 2004; Bergström et al., 2008a; Alaru et al., 2014) possibly due to slow mineralization of applied organic inputs and poor synchrony between supplied N and crop demand (Berry et al., 2002; Mikkelsen and Hartz, 2008; Alaru et al., 2014). Nitrogen supply in these systems is often limited by mineralization-immobilization processes and may be unpredictable resulting in excess or deficient asynchrony (Mallory and Griffin, 2007) which eventually affects NUE. In addition, low input and organic farming systems have different N sources, cycling and management options compared to conventional systems that heavily rely on synthetic fertilizers and these in turn affect N availability and use efficiency (Dawson et al., 2008). On the other hand, application of conventional fertilizers that are readily available may be prone to losses such as leaching and denitrification, reducing NUE of conventional farming systems (Chien et al., 2009; Hirel et al., 2011). Assessments of low input and organic agriculture (Badgley et al., 2007a; Badgley et al., 2007b) reveal that there is potential of supplying enough N through fixation by legumes, cover crops and other organic sources in organic farming systems.

Most small holder farming systems in SSA are associated with low nutrient inputs due to limited access to synthetic fertilizers as well as poor agronomic practices such as sporadic pest and weed control, and this may affect nutrient use efficiencies (Keating et al., 2010). Nitrogen use efficiency of maize in Africa small holder' farms has been reported to be very low, ranging from 5 to 18 kg for every kg of N applied, with the NUE being mainly dependent on resource endowment, management ability, soil conditions, drought, pest and diseases as well as maize varieties (Snapp et al., 2014). On the other hand, research indicates that organic farms have lower soil and plant nitrate levels even though yields are comparable to those of conventional systems (Arihara and Srinivasan, 2013). Thus, nutrient acquisition and uptake patterns may differ between conventional and organic farming systems. In temperate regions, studies comparing long-term organic and conventional farming systems suggest that agronomic efficiency of N use is lower in organic than conventional systems (Kirchmann et al., 2007). However, the comparison of such results is hampered because the studies were performed in regions of different climatic conditions, soil types and farming practices. In addition, long-term trials that compare different farming systems in the tropics are scarce, and where they exist they are faced with inconsistencies in management and data collection due to funding constraints (Kibunja et al., 2011; Bationo et al., 2012; Kihanda and Warren, 2012).

In summary, it is envisaged that organic or conventional farming systems may affect nitrogen cycle (mineralization, volatilization, denitrification and immobilization) in soils differently and consequently crop N uptake and utilization in the long term. Based on current evidence this study hypothesized that organic farming systems may promote plant nutrient uptake comparable to conventional systems but differ in the effect on crop nitrogen use efficiency. The objectives of this study were to determine the effect of four farming systems i.e. Org-High, Conv-High, Org-Low, Conv-Low on N-uptake, NUE (i.e. N-uptake efficiency, N-utilization efficiency, agronomic efficiency of N-use, N-Harvest index) of potato, maize and vegetables in two agro-ecological zones in the Central highlands of Kenya.

3.3. Materials and Methods

3.3.1. Field site

The study was conducted between October 2012 and March 2014 within the on-going Long-term Farming Systems Comparison (SysCom). The trials were established in April 2007 at Chuka and Thika in the Central highlands of Kenya. Both sites have bimodal rainfall patterns. Long rain season (LS) occur in April-August while short rain season (SS) occurs between October-February. Thika site lies at 1500 meters above sea level (m a.s.l.) with an annual mean temperature of about 20 °C and mean annual rainfall of 900 to 1100 mm yr^{-1}. The site is situated in upper midlands 3 (UM 3) agro-ecological zone (Sunflower-Maize zone) according to Jaetzold et al. (2006a) and within the premises of Horticulture Research Institute Headquarters, Kenya Agriculture and Livestock Research Organization, (KALRO, Kandara) in Murang'a County about 50 km north-east of Nairobi (Longitude 037° 04.747' and Latitude 01° 00.231'). Chuka site lies at 1458 m a.s.l. with an annual mean temperature of 20 °C and mean annual rainfall of 1500 mm yr^{-1}. According to Jaetzold et al. (2006b), Chuka site lies within upper midland 2 (UM2) agro-ecological zone (Main Coffee Zone) and is located at Tharaka Nithi County (Longitude 037° 38.792' & Latitude 00° 20.864'), about 150 km north-east of Nairobi. The soil at Thika is classified as Rhodic Nitosol (Wagate et al., 2010a) while that of Chuka site is classified as Humic Nitisol (Wagate et al., 2010b) based on FAO World reference system of soil classification (IUSS Working Group WRB., 2006). The two zones were selected due to differences in rainfall and soil fertility status with Chuka (1500 mm yr^{-1}) having higher rainfall and comparatively higher soil organic carbon and soil extractable phosphorus compared to

Thika (900 to 1100 mm yr^{-1}). Soil characteristics during the establishment of the trials in 2007 were similar across the systems at each site as shown in Table 1.

Table 1: Initial soil characteristics at the beginning of the trials in March 2007 in the long-term systems comparisons trial at Chuka and Thika in the Central Highlands of Kenya

Site	Farming systems/	pH	CEC	OC	Total N	Olsen P	K	Ca	Mg	Sand	Clay	Silt
		H_2O 1:2.5	cmolc kg^{-1}	g kg^{-1}	g kg^{-1}	mg kg^{-1}	mg kg^{-1}	mg kg^{-1}	mg kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}
Chuka	Org-High	5.72	18.8	24.7	2.0	33.3	507	380	58	85	745	170
	Conv-High	5.81	17.8	21.7	2.1	24.8	507	356	55	88	730	183
	Org-Low	5.73	16.8	22.0	2.1	26.8	468	332	53	88	750	163
	Conv-Low	5.82	16.5	24.5	2.1	30.5	468	332	53	118	735	148
Thika	Org-High	5.46	11.0	23.0	1.6	10.5	468	156	46	50	836	114
	Conv-High	5.33	10.5	22.1	1.5	12.5	507	120	41	56	808	136
	Org-Low	5.45	10.8	22.8	1.7	13.5	507	140	43	42	814	144
	Conv-Low	5.45	11.8	22.4	1.6	12.3	507	148	53	68	762	170

Conv-High, conventional high inputs system; Org-High, organic high inputs system; Conv-Low, conventional low inputs system, Org-low, organic low inputs system; pH, soil pH in water (1:2.5); SOC, soil organic carbon; K, Ca, and Mg are ammonium acetate extractable bases.

The soil characteristics of the two research sites at the start of data collection in 2012 are presented in Table 2.

Table 2: Soil chemical characteristics at the beginning of data collection in October 2012 in the long-term system comparison trial at Chuka and Thika in the Central Highlands of Kenya.

Site	Parameter	pH (H_2O)	Total N	NO_3^--N	NH_4^+-N	OC	C/N ratio	P (Olsen)	K	Ca	Mg	Sand	Clay	Silt
	Units		g kg^{-1}	mg kg^{-1}	mg kg^{-1}	g kg^{-1}		mg kg^{-1}	mg kg^{-1}	mg kg^{-1}	mg kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}
Systems														
	Conv- High	5.37 b	2.1	10.8	2.7	17.5 b	9	53	442 b	1392 a	93 ab	187 ab	724	89
	Org- High	6.33 a	2.2	15.6	3.2	20.9 a	10	29	876 a	1493 a	114 a	173 b	707	120
	Conv- Low	5.30 b	2.0	4.9	2.1	17.6 b	9	25	400 b	934 b	77 b	179 b	720	101
	Org- Low	5.37 b	1.8	11.3	3.2	16.7 b	9	18	447 b	1097 ab	82 b	192 a	715	93
Sites														
	Chuka	5.48	2.3 a	9.5 b	3.24	20.8 a	10 a	40 a	434 b	1384 a	92	179	715	106
	Thika	5:71	1.9 b	18.4 a	3.5	15.5 b	9 b	25 b	648 a	1073 b	91	186	718	96
Site x farming systems														
Chuka	Conv- High	5.36 b	2.3	3.9	3.4	20.0 a	9	59	309	1462	94	186	708	106
	Org- High	5.83 b	2.4	2.6	3	23.9 a	10	31	704	1493	111	173	707	120
	Conv- Low	5.36 b	2.2	2.7	3.1	20.4 a	9	36	318	1198	80	175	731	94
	Org- Low	5.35 b	2.1	2.7	3.9	18.6 b	9	34	404	1384	81	181	714	105
Thika	Conv- High	5.38 b	1.9	17.7	1.9	15.0 bc	8	46	575	1322	92	188	740	72
	Org-High	6.83 a	2.0	28.6	3.4	17.8 b	9	27	1048	1493	116	172	708	120
	Conv- Low	5.24 b	1.7	7.0	1.0	14.7 c	9	14	481	669	73	182	709	109
	Org- Low	5.38 b	1.6	19.9	2.4	14.5 c	9	12	489	809	82	203	716	81
Sources of variations														
System		***	ns	ns	ns	***	ns	ns	***	*	**	*	ns	ns
Site		ns	***	***	ns	ns	*	*	***	*	ns	ns	ns	ns
System x site		*	ns	ns	ns	*	ns	ns	ns	ns	ns	ns	ns	ns

Conv-High, conventional high input system; Conv-Low, conventional low input system; Org-High, Organic high input system; Org-Low, Organic low input system; pH, soil pH in water (1:2.5); SOC, soil organic carbon; C/N, C to N ratio; ns, not significant; only significant means are indicated. Different letters (a, b, c, d & e) indicate that sample means are significantly different between systems or site (*$P \leq 0.05$; **$P \leq 0.01$ and ***$P \leq 0.001$); K, Ca, and Mg are ammonium acetate extractable bases.

3.3.2. Experimental design and farming systems

The long-term trial is based on two season three-year crop rotation as shown in Table 3. Four farming systems i.e. Conv-High, Org-High (managed as recommended by research institutions and practiced by commercial farms) and Org-Low and Conv-Low (managed as commonly practiced by small scale farmers) were compared in a Long-term trial initiated in 2007.

Table 3: Crop rotation of the long-term systems comparison trials at Chuka and Thika in the Central Highlands of Kenya.

Farming systems	Year 2007, 2010, 2013		Year 2008, 2011, 2014		Year 2009, 2012, 2015	
	LS	SS	LS	SS	LS	SS
Conv-High	Maize	Cabbage	Baby corn	French beans	Baby corn	Potatoes
Org-High	Maize/*Mucuna*[a]	Cabbage	Baby corn/*Mucuna*[a]	French beans	Baby corn/*Mucuna*[a]	Potatoes
Conv-Low	Maize	Kale/Swiss chard	Maize/Beans	Grain legumes	Maize-beans	Potatoes
Org-Low	Maize	Kale/Swiss chard	Maize/Beans	Grain legumes	Maize-beans	Potatoes

Conv-High, conventional high input system; Org-High, organic high input system; Conv-Low, conventional low input system, Org-low, organic low input system; LS, Long rains season; SS, Short rains season; Potato variety Asante, maize. H513 variety, cabbage - Gloria F1variety, Kale – Collard variety, Swiss chard – Giant Fordhook variety.
[a]*Mucuna* planted as relay crop four weeks after maize or baby corn establishment. The biomass of *Mucuna* was always incorporated at the start of the short rains season crops.

The experiment was a randomized complete block design with plot sizes of 8 m by 8 m (64 m^2) (net harvest plot sizes of 6 m by 6 m, 36 m^2) and four replicates at Chuka and five replicates at Thika site. A six season, 3-year cropping rotation was followed but data presented here were collected in 2012 SS and 2013 LS and SS seasons (Table 3). The crops grown during these periods are highlighted in Table 3 above. Potato was planted at a spacing of 75 x 30 cm in all the systems, maize at a spacing of 75 x 30 cm (one plant per hole) in high input systems and 75 x 60 cm (two plants per hole) in low input systems while cabbage and kale/Swiss chard intercrop were planted at a spacing of 60 x 60 cm in all the systems. Supplementary irrigation (via drip irrigation system to a depth of 30 cm) was given in the high input systems during periods of drought while the low input systems were grown solely under rain-fed conditions. Supplementary irrigation was given after soil moisture assessment using Time Domain Reflectometer (TDR, TRIME-PICO IPH, IMKO GmbH) and when soil moisture was below

40% of the field capacity. Maize and cabbage crops at Chuka received 1016 and 2090 m^3 ha^{-1} of supplementary irrigation water respectively. At Thika site, maize received 2867 m^3 ha^{-1} while cabbage received 489 m^3 ha^{-1} of irrigation. No irrigation was done during potato crop at both sites because rainfall amount and distribution were adequate with no occurrence of more than 15 consecutive drought days (days with <1 mm of rainfall) (Mzezewa et al., 2009; Ngetich et al., 2014; Kisaka et al., 2015) at both sites. Other system specific management practices are as shown in Table 4 and further outlined in Adamtey et al. (2016).

Table 4: System specific management aspects in the long-term farming system comparisons trials at Chuka and Thika in the Central Highlands of Kenya.

Farming systems	Planting density	Fertilizer		Pest and disease control		Irrigation	weed control	Market
		Type	Rate	Type	Intensity			
Conv-High	One plant per hole	INM	High[b]	IPM	High[d]	Supplementary irrigation[f]	Hand	High value
Org-High	One plant per hole	Organic	High[b]	Bio pesticides	High[d]	Supplementary irrigation[f]	Hand	High value
Conv-Low	Two plants per hole[a]	INM	Low[c]	IPM	Low[e]	Rain-fed	Hand	Subsistence and local
Org-Low	Two plants per hole[a]	Organic	Low[c]	Ash and Bio pesticides	Low[e]	Rain-fed	Hand	Subsistence and local

Conv-High, conventional high input system; Org-High, organic high input system; Conv-Low, conventional low input system, Org-low, organic low input system; INM -Integrated nutrient management; IPM – integrated pest management. INM includes use of calcium ammonium nitrates, di-ammonium phosphate or triple superphosphate and cattle manure; Organic inputs include compost, phosphate Rock, *Tithonia* and plant teas.

[a] two plants per hole for maize and beans but one plant per hole for vegetables
[b] as recommended by research institutions.
[c] as practiced by small scale farmers.
[d] Based on scouting for pests and diseases.
[e] based on observation of pests and diseases.
[f] Irrigation given only during periods of drought

The N and P application rates of organic and inorganic fertilizers into the systems were based on recommendations from literature on similar studies done within the region (Supplementary sheet 2). However, to be able to monitor actual amounts of N being released into the systems, all inputs were analyzed season by season during the period of study (Table 5).

Table 5: Actual total nitrogen (N) and phosphorus (P) contents of the inputs applied during the experimental period in the long-term system comparison trial in Chuka and Thika in the Central Highlands of Kenya. Note: Target was to have similar amounts of external N and P applied in conventional and organic systems, but due to varying nutrient concentrations in organic inputs, actual inputs may vary somewhat.

Site	Farming Systems	Year	Season	Crop	FYM	Compost[a]	DAP	PR	TSP	CAN[b]	*Tithonia* Mulch[c]	*Tithonia* plant tea	Total N applied	Total P applied
					Mg ha^{-1}	Mg ha^{-1}	Kg ha^{-1}	Kg-ha^{-1}	Kg-ha^{-1}	Kg ha^{-1}	Mg ha^{-1}	Mg ha^{-1}	Kg-ha^{-1}	Kg-ha^{-1}
Chuka	Conv-High	6	2	Potato	10.5	-	-	-	300	200	-	-	160	94
		7	1	Maize	3.9	-	200	-	-	100	-	-	113	60
		7	2	Cabbage	10.5	-	-	-	200	300	-	-	114	58
	Org-High[4]***	6	2	Potato	-	22	-	581	-	-	8.2	-	162 (173)[d]	118.5 (36.5)[d]
		7	1	Maize	-	22.7	-	364	-	-	5.4	3.9	246	133
		7	2	Cabbage	-	22	-	400	-	-	6	6	211	115[γ]
	Conv-Low	6	2	Potato	2	-	100	-	-	-	-	-	33	27
		7	1	Maize	5	-	50	-	-	-	-	-	63	32
		7	2	Kale/Swiss Chard	1	-	-	-	50	60	-	-	23	13
	Org-Low	6	2	Potato	4.5	-	-	200	-	-	2.72	-	48	45
		7	1	Maize	2.2	-	-	100	-	-	1.36	-	35	24
		7	2	Kale/Swiss Chard	4.5	-	-	90	-	-	1.2	1.2	21	13
Thika	Conv-High	6	1	Potato	14.1	-	-	-	300	200	-	-	124	83
		7	1	Maize	7.2	-	200	-	-	100	-	-	84	47
		7	2	Cabbage	11	-	-	-	200	300	-	-	184	67
	Org-High[4]***	6	2	Potato	-	24.4	-	581	-	-	8.2	-	131 (220)[d]	87 (41)[d]
		7	1	Maize	-	17.6	-	364	-	-	5.4	3.9	135	81
		7	2	Cabbage	-	24.4	-	400	-	-	6	6	290	100
	Conv-Low	6	2	Potato	2	-	100	-	-	-	-	-	44	25
		7	1	Maize	5	-	50	-	-	-	-	-	31	20
		7	2	Kale/Swiss Chard	1	-	-	-	50	60	-	-	24	14
	Org-Low	6	2	Potato	6.9	-	-	200	-	-	2.72	-	33	37
		7	1	Maize	5	-	-	100	-	-	1.36	-	38	24
		7	2	Kale/Swiss Chard	6.9	-	-	90	-	-	1.2	1.2	18	13

Conv-Low, conventional low input system; Conv-High, conventional high input system; Org-Low, organic low input system and Org-High, organic high input system; FYM farm yard manure; DAP = Di-ammonium phosphate; PR=phosphate rock; TSP= triple superphosphate; CAN= calcium ammonium nitrate.

FYM, compost, *Tithonia* inputs are on a fresh weight basis.

[a] Compost preparation starts with the indicated amount of Fresh FYM

[b] Applied as top-dress to all crops except in potato where it is applied at planting. Under high input topdressing was done in two split applications, while in low input topdressing was not done or it was done once for specific crops.

[c] *Tithonia* mulch is applied after crop germination as starter N.

[d] Extra nutrients supplied from mulch (applied at 2 Mg ha^{-1}), maize stover residues applied at 2 Mg ha^{-1} and *Mucuna* average rate of 10.3 Mg ha^{-1} at Chuka and 16.7 Mg ha^{-1} at Thika during potato season. No *Mucuna* was intercropped with maize during maize season hence no *Mucuna* biomass was incorporated.

3.3.3. Rainfall and temperature data collection

Daily precipitation and air temperature data were obtained from weather stations installed at 3 m above the ground at each site. Cumulative rainfall for each season was calculated from planting date to harvesting date and presented in Fig. 1. Average daily air temperatures were calculated by averaging all the daily readings for each day from planting to harvesting date (Fig. 1).

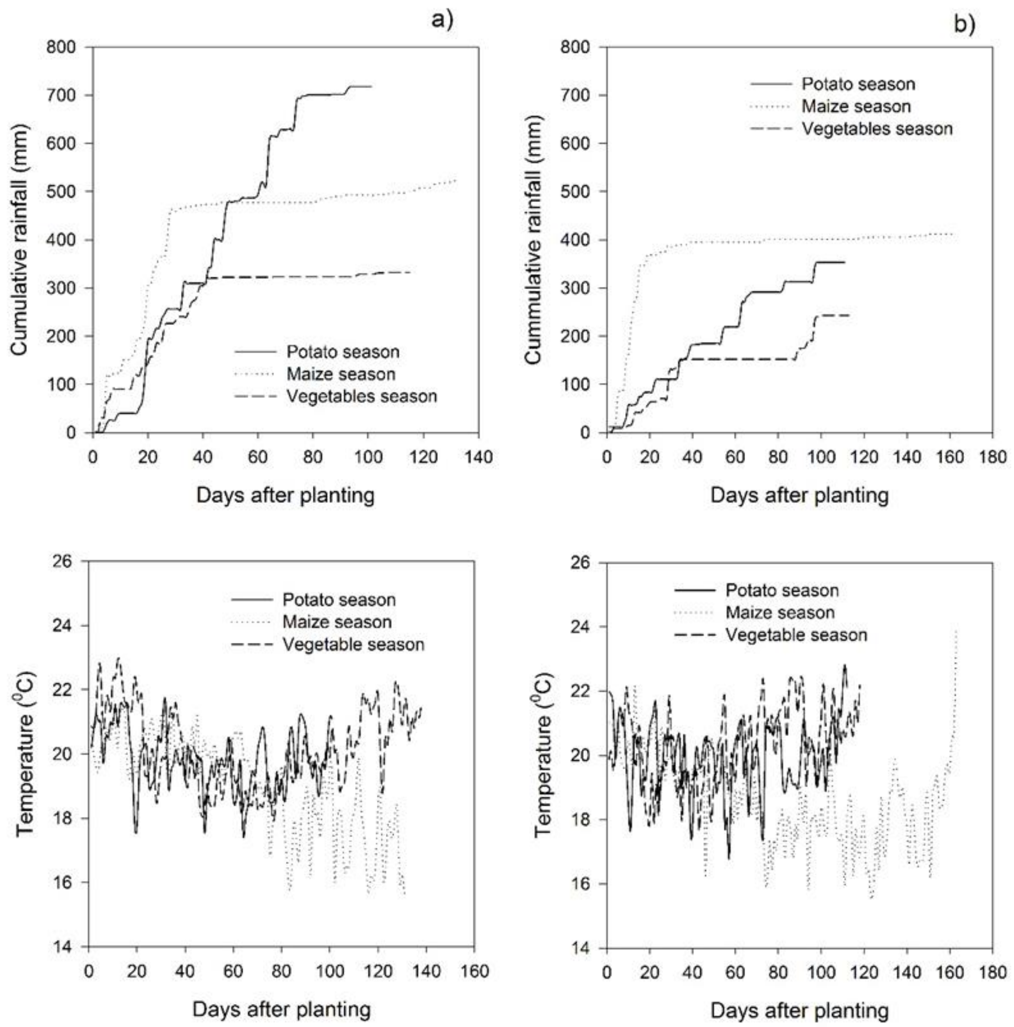


Fig. 1: Cumulative rainfall and mean temperature during the cropping period in the long-term farming systems comparisons trials at (a) Chuka and (b) Thika in Central Highlands of Kenya.

3.3.4. Plant sampling

To evaluate seasonal N uptake and dry matter accumulation, two plants per plot (totalling 8 plants in 4 blocks) were periodically selected at random outside the net plot harvest area of 6 x 6 m. Destructive plant sampling was done when 50% of the crops reached critical stages in their growth cycle: for potato - vegetative, tuber initiation, and tuber bulking stages (Jefferies and Lawson, 1991); for maize - 6 and 8 leaves stage of the vegetative phase, tasseling and silking phase and at harvest (Lancashire et al., 1991); and for vegetables, at 4^{th} - 6^{th} leaf stage, pre-cupping, head formation and at harvest (Everaarts, 1994) and days after sowing (DAS, transplanting for vegetables) recorded. Above ground plant biomass (except for potato where roots and tubers were included) were separated into leaves, stems, tubers for potato; leaves, stems, grain, cobs, husks for maize; cabbage head, stems for cabbage, and leaves and stems for kale and Swiss chard. At final harvest, all plants were harvested from the 6 x 6 m net plot after counting the number of plants within this area. Potatoes were separated into tubers and haulms, maize into grain, cobs, husks and stover, while cabbage was separated into cabbage head and non-edible cabbage residues. Plant samples were oven-dried at 60 ˚C to a constant weight to determine the dry matter yield (DMY) except grain samples which were determined at 13% moisture content with a grain moisture meter (PM600 seed and grain moisture tester, Kett electrical laboratories, Japan).

3.3.5. Plant tissue, compost, manure and soil analysis

Soil characteristics were analyzed on soils sampled at 0-20 cm plough depth in 2012 before planting potatoes (Table 2). Soil Texture was determined using the hydrometer method (Okalebo et al., 2002), soil organic carbon was analyzed after total oxidation with acidified dichromate solution as described by Anderson and Ingram (1993). Mineral N (NO_3-N and NH_4-N) in soil was extracted from 10 g of fresh soil using 50 mL of 0.5 M potassium sulphate and the concentrations of nitrate and ammonia determined by a segmented flow auto analyzer

(SKALAR Analytical B.V., BREDA, The Netherlands) at 540 and 660 nm wavelength respectively. Olsen extractable P was analyzed after extraction of 2.5 g air-dry soil sieved through (2-mm mesh size) with 50 mL of 0.5 M sodium bicarbonate; and the absorbance of the solution was measured at 880 nm wavelength according to the method described by Okalebo et al. (2002). Maize stover and potato haulm samples were oven dried at 60 ^{0}C to a constant weight and ground (<0.25 mm, 60 µm mesh). Potato tubers, cabbage, kale and Swiss chard samples were air-dried under shade to reduce the moisture content before being oven dried and ground. Maize grain was air-dried to 13% moisture before being ground. Compost and manures samples were air-dried under shade to a constant weight after which they were ground (<0.25 mm, 60 µm mesh). Thereafter, 0.3 g of the oven-dried material was analyzed for total N after digestion with 2.5-ml digestion mixture prepared using 3.2 g salicylic acid in 100 mLs of concentrated sulphuric acid- selenium mixture (sulphuric acid-selenium mixture was prepared using 3.5-g selenium powder in one litre of concentrated sulphuric acid) as described by Okalebo et al. (2002). Concentration of total N was obtained using a segmented flow auto analyzer (SKALAR Analytical B.V., BREDA, The Netherlands) after oxidation to NH_4^- (660 nm wavelength).

In addition, soil N supply during the cropping season was determined using a modified buried bag approach with mixed resin beads as described by Friedel et al. (2000). Soil samples for mixing with resin beads were collected from the plough layer (0-20cm) of each plot before input application for each season**.** An equivalent weight of 150 g of soil and 150 g of resin (Resinex^{TM} MX-11 Clean Water Group (CWG) Technology, GmBH Mannheim, Germany) was weighed into polyethylene bags (PE, freezer bags). The moisture content was then adjusted to 60% field capacity using distilled water. Bags were then sealed to avoid water entry and loss of content. Sufficient PE bags were buried in the respective experimental plots at a depth of 20 cm to allow one bag to be retrieved per plot (4 bags in 4 replicates) after 3, 10, 20, 40, 90 for potato; 3, 10, 20, 41, 61, 122, 157 for maize and 3, 10, 26, 41, 69, 109 days of incubation for vegetables. One bag was also extracted for nitrate and ammonium-N immediately after preparation (time zero). Retrieved bags were placed in air-tight polythene bags, labelled and transported to the laboratory in ice chests for analysis. Mineral-N (NO_3^--N and NH_4^+-N) in the soil-resin beads mixture was analyzed after extraction with 0.5 M potassium sulphate as above. Total mineral-N mineralized from soil alone was calculated as the sum of change in soil mineral-N from one sampling date to the next (N mineralized = Min-N_{n+1} –Min-N_n, where n is the incubation interval). Total mineral-N was converted to a per hectare basis using bulk density determined at the end of potato season and before planting maize crop. The resulting N supply from the soil in each system is shown in Table 6.

Table 6: Total N supplied to the crops during different cropping season in the long-term farming systems comparisons trials at Chuka and Thika in the Central Highlands of Kenya.

		Potato	Maize	Vegetables
Site	Farming Systems	Total N supplied to the crops (kg ha^{-1})		
Chuka	Conv-High	369 (209)	213 (100)	186 (73)
	Org-High	549 (214)	410 (164)	309 (98)
	Conv-Low	167 (133)	163 (100)	80 (57)
	Org-Low	168 (120)	129 (94)	79 (57)
Thika	Conv-High	375 (251)	249 (153)	376 (171)
	Org-High	591 (225)	267 (132)	459 (169)
	Conv-Low	182 (138)	135 (104)	181 (156)
	Org-Low	147 (113)	154 (116)	179 (161)

Conv-Low, conventional low input system; Conv-High, conventional high input system; Org-Low, organic low input system and Org-High, organic high input system; Values in brackets indicate total N mineralized from the soil while values outside the brackets indicate N inputs from all the N inputs added (N applied plus N mineralized from the soil) into the farming systems during the season.

3.3.6. Nitrogen use efficiency components

In this study the different components of NUE considered included: (i) the ratio of the total plant N to N supply (defined as N mineralized from soil plus N applied as inputs) - referred to as N uptake efficiency (NUpE); the ratio of economic yield (part of the crop with economic value for example grain, or tuber yield) to total plant N - referred to as N utilization efficiency (NUtE); (iii) the ratio of economic yield to N supply referred to as agronomic efficiency of N

(AE_N); and (iv) the partitioning of total plant N into economic yield referred to as N harvest index (NHI) (Fageria and Baligar, 2001; Fageria and Baligar, 2003, 2005; Ladha et al., 2005). The different components of nitrogen use efficiency by the different crops were assessed at harvest as shown in Table 7.

Table 7: Nitrogen use efficiency (NUE) determinations

Components of NUE	Calculation	Units	Reference
N uptake	TDM x N_c	kg N ha^{-1}	(Reddy, 2004; Dawson et al., 2008)
Agronomic efficiency of N (AE_N)	Y_w / Ns	kg YDM kg^{-1}N	(Fageria and Baligar, 2005; Ladha et al., 2005)
N uptake efficiency (NUpE)	N_t / N_s	kg N kg^{-1}N	(Fageria and Baligar, 2005; Ladha et al., 2005; Dawson et al., 2008)
N utilization efficiency (NUtE)	Y_w / N_t	kg DM kg^{-1}N	(Fageria and Baligar, 2005; Ladha et al., 2005; Dawson et al., 2008)
N harvest Index (NHI)	(N_Y /N_t) x 100	%	(Reddy, 2004; Fageria and Baligar, 2005)

TDM = Total dry matter yield (economic yield + biomass; kg ha^{-1}); YDM = economic yield dry matter content; N_c = N concentration in plant (%); Y_w = economic yield (in dry matter, kg ha^{-1}); N_s = N supply (N input as fertilizer, compost, manure + N mineralized from the soil during the season, kg N ha^{-1}); N_t = Total nitrogen in the plant (biomass + grain, potato tubers and cabbage head; kg N ha^{-1}) at harvest, and N_Y = Total N in economic yield (kg N ha^{-1}).

3.3.7. Statistical data analysis

Analysis of variance were performed on N uptake, yield and NUE components data using a linear mixed-effect model effect with '*lmer'* function from the package *lme4* in R statistical software (Bates et al., 2013) with site and system as fixed effects and replication as random effect. Data normality was assessed using *Shapiro test* while homogeneity test was done using *Bartlett test*. We compared the four farming systems (Conv-high, Org-High, Conv-Low and Org-Low) when similar crops were grown in the four systems but separately for Conv-High vs Org-High and Conv-Low vs Org-Low systems during the vegetable season when the crops were different in the systems. Site was handled as a fixed effect since according to the design of the trials; sites were selected based on prior knowledge of weather and soil analysis for pH, soil organic carbon as well as soil extractable phosphorus. In addition, a random effect that is not liaised with the fixed effect to be tested may be taken as a fixed effect when the random effect has less than 5 or 10 levels (Piepho et al., 2003). Computation of least squares means was done using '*lsmeans'* package, followed by mean separation using adjusted Tukey's method implemented using "*multicompView package*" for *cld* function as developed by Graves et al., (2015) in R software version R3.1.1 (R Development Core Team., 2014).

3.4. Results

3.4.1. Effects of farming systems and sites on crop and dry matter yields at harvest

There was significant system (P<0.001) and site (P<0.001) effects on potato tuber yields (Table 8). Tuber yields from Conv-High and Conv-Low were 2.2 and 1.7 times higher than the yields from Org-High and Org-Low respectively. In addition, tuber yield in Conv-High system was 2.2 times higher than tuber yields in Conv-Low and Org-Low (Table 8). At Thika, potato tuber yields were 2 times higher than the yields at Chuka. Potato haulm yields from Conv-High and Conv-Low were also 2 times higher than the yields from Org-High and Org-Low respectively (P<0.001). The yields of potato haulms between the two sites followed a similar trend as in potato tuber (Supplementary sheet 3).

Table 8: Effect of farming systems on economic yields and crop residues of potato, maize and vegetables under high and low input levels in the long-term farming systems comparisons trials at Chuka and Thika in the Central Highlands of Kenya.

		Potato Tuber Yield (FWT) $Mg\ ha^{-1}$	Potato Haulms (DM) $Mg\ ha^{-1}$	Maize grain yield[a] (DM)* $Mg\ ha^{-1}$	Maize residues[b] (DM) $Mg\ ha^{-1}$	Cabbage head yield[c] (FWT) $Mg\ ha^{-1}$	Cabbage residues[c d] (DM) $Mg\ ha^{-1}$	Kale leaf yields[e] (FWT) $Mg\ ha^{-1}$	Kale residues[e f] (DM) $Mg\ ha^{-1}$	Swiss chard leaf yield[e] (FWT) $Mg\ ha^{-1}$	Swiss chard residues[e g] (DM) $Mg\ ha^{-1}$
Farming Systems											
	Conv-High	20.9 a	1.3 a	4.1 a	7.0 b	50.2	1.92	na	na	na	na
	Org-High	9.6 b	0.8 ab	5.2 a	9.0 a	38.6	1.42	na	na	na	na
	Conv -Low	15.6 ab	0.65 b	0.8 b	3.1 c	na	na	6.3 α	0.3	3.5	0.07
	Org-Low	9.1 b	0.38 b	0.7 b	2.6 c	na	na	4.4 β	0.21	3.1	0.08
Sites											
	Chuka	8.6 b	0.5 b	2.8	5.8 a	46.4	1.37	6.7	0.29	4.6 α	0.11
	Thika	18.9 a	1.1 a	2.7	5.0 b	42.3	1.96	4.0	0.22	2.0 β	0.03
Chuka	Conv-High	15.9	0.94	3.4 b	6.2 ab	53.5	1.62	na	na	na	na
	Org-High	5.0	0.43	4.6 ab	7.6 a	39.4	1.13	na	na	na	na
	Conv -Low	9.5	0.36	1.6 c	4.0 bc	na	na	8.1	0.36	5.4	0.1
	Org-Low	4.0	0.21	1.4 c	3.0 cd	na	na	5.3	0.21	3.7	0.12
Thika	Conv-High	25.9	1.72	4.9 ab	6.3 a	46.8	2.23	na	na	na	na
	Org-High	14.1	1.17	5.7 a	8.3 a	37.8	1.70	na	na	na	na
	Conv -Low	21.7	0.94	0.1 c	1.5 d	na	na	4.5	0.24	1.6	0.03
	Org-Low	14.1	0.55	0.06 c	1.7 d	na	na	3.6	0.20	2.5	0.04
Sources of variations											
System		***	***	***	***	ns	ns	*	ns	ns	ns
Site		***	***	ns	*	ns	ns	ns	ns	**	*
Site x System		ns	ns	***	***	ns	ns	ns	ns	ns	ns

FWT = fresh weight basis; DM = oven dried weight basis; *DM at 13% moisture content. Conv-High = conventional high input systems; Conv-Low = conventional low input system; Org-High = Organic high input system; Org-Low= Organic low input system; na, not applicable; ns, not significant.
Only significant means were indicted. Different letters (a, b, c, d & e) next to the mean indicate that sample means are significantly different between system or site (*P ≤0.05; **P≤0.01 and ***P≤0.001).
[a] DM at 13% moisture content
[b] Maize residues refers to non-edible maize parts i.e. stems, cobs and husks
[c] Cabbage was only grown in Conv-High and Org-High
[d] Cabbage residues refers to cabbage stems and non-edible 4 lower leaves of the plant.
[e] Kale was grown as an intercrop with Swiss chard in Conv-Low and Org-Low.
[f] Kale residues refers to the stem and non-edible and non-marketable leaves of the plant.
[g] Swiss chard residues refers to the plant stem and non-edible and non-marketable plant leaves.

Significant system by site interaction effects (P<0.001) on maize grain and residues yields were observed (Table 8). Conv-High and Org-High produced similar grain and residues yields at both sites. The grain yields from Conv-High and Org-High were 2.9 and 4.6 times higher than the yields from Conv-Low and Org-Low respectively. However, maize grain yields from Org-Low and Conv-Low at Chuka site was 23 and 16 times higher than the grain yields of the same systems at Thika. A similar but less pronounced effect was observed for the maize residues (Supplementary sheet 3).

With vegetables, there were no significant differences in cabbage head and residues in the high input systems (Table 8). In the low input system kale leaf yields from conventional were 43% higher (P<0.05) than those from organic systems. While there were no system and site effects on kale residues, Swiss chard leaf and residues yields at Chuka were 2.3 (P< 0.01) and 3.3 times higher (P<0.05) than the respective yields at Thika. Similar trends were observed in cabbage, kale and Swiss chard residues (Supplementary sheet 3).

3.4.2. Nitrogen uptake during development of potato, maize and vegetable crops

Nitrogen uptake in potato at the different growth stages was affected by farming system (Fig. 2a-b). At vegetative and tuber initiation stages, N uptake in Conv-High was 20%, 35% and 74% higher (P< 0.05) than the uptake in Org-High, Conv-Low and Org-Low, respectively. Similar trends as during the vegetative and tuber initiation stages were observed in the N uptake at harvest. Site effects were only observed at vegetative stage when potato N uptake at Thika site was 2 times higher than the uptake at Chuka site.

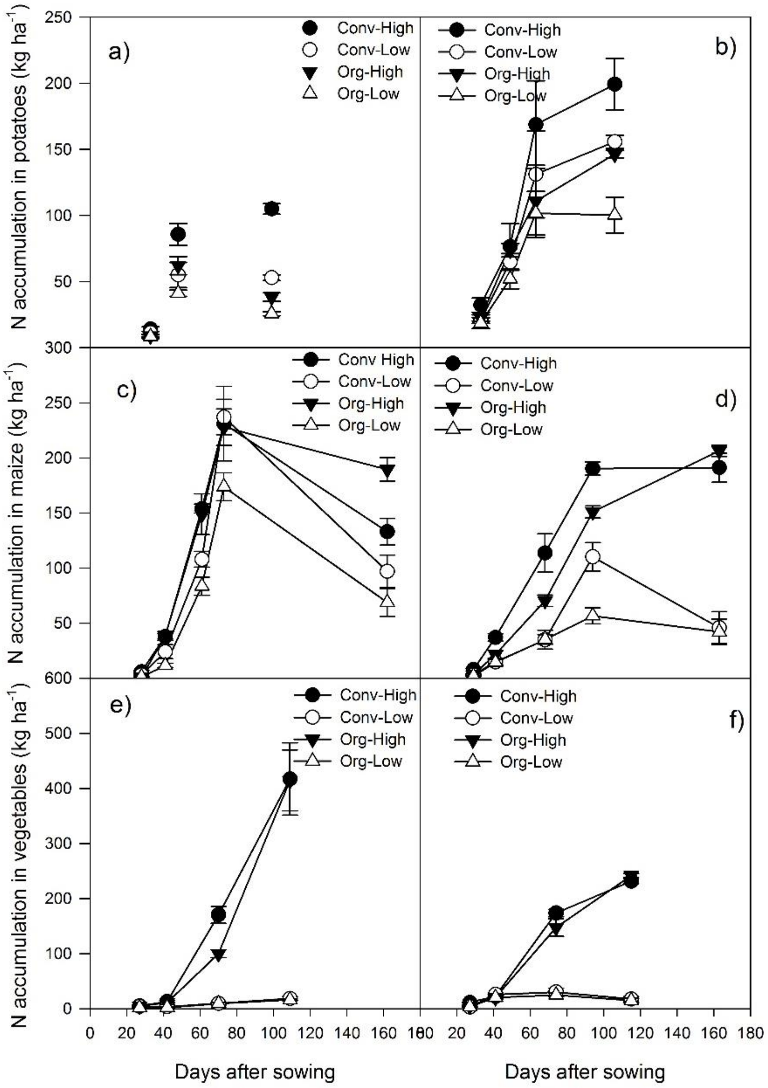


Fig. 2: N uptake patterns in potato (a and b), maize (c and d), cabbage, kale and Swiss chard (e and f) in the long-term systems comparison trials at Chuka (a, c, e) and Thika (b, d, and f). Note: There was late blight disease infection at potato tuber bulking stage at Chuka.

In maize, N uptake was affected by farming system at most development stages. At V3-4 leaf stage, N uptake in Conv-High was 2.5, 3 and 4.6 (P<0.001) times higher than the uptake in Conv-Low, Org-High and Org-Low (Fig. 2). At V6 leaf stage at Chuka, the N uptake of maize in Org-High was similar to that of maize Conv-High. At Thika N uptake of maize in Org-High was 25% lower (P<0.001) than the uptake of maize in Conv-High. At tasseling and silking stages at Chuka, N uptake of maize in Org-High still matched N uptake of maize in Conv-High, but at Thika N uptake of maize in Org-High at silking and tasseling stages was 26 and 62%

lower (P<0.001) than the uptake in Conv-High. However, N uptake of maize was similar between Conv-Low and Org-Low at both sites at all the maize crop stages. Highest N uptake occurred at the tasseling and silking stages of the maize plant (70 and 90 DAS). There was higher (P<0.001) N uptake at Chuka compared to Thika (Fig. 2). At harvest, a system by site interaction effect (P<0.01) on N uptake of maize was observed. N uptake in maize was similar in Org-High and Conv-High and between Org-Low and Conv-Low at Thika site. In addition, N uptake in maize in Org-High was 36% higher than in Conv-High but was similar in Conv-Low and Org-Low systems at Chuka site.

Farming systems did not show any significant effect on N uptake in cabbage at both sites, except at heading stage (70 DAS) in Thika where N uptake in cabbage under Conv-High was 70% higher (P< 0.01) than the uptake in cabbage under Org-high at Chuka site. N uptake in cabbage at the different growth stages was affected by site (P<0.001) with higher N uptake observed at Chuka site. Uptake of N by cabbage in both Conv-High and Org-High was low until pre-cupping (13-19 true leave stage, 40 DAS), thereafter N uptake increased linearly until maturity to 420 kg N ha^{-1} at Chuka and to 240 kg N ha^{-1} at Thika (Fig. 2e-f). In kale and Swiss chard N uptake in the low input systems was below 20 kg ha^{-1} throughout the growing period of the crops (Fig. 2e - f).

3.4.3. Nitrogen use efficiency of potato, maize and vegetable crops

3.4.3.1. Nitrogen uptake efficiency

There was a significant system by site interaction (P<0.001) effect on N uptake efficiency (NUpE) of potato (Table 9). The NUpE of potato in Conv-High was 2 times higher than NUpE of potato in Org-High at Thika site. However, NUpE of potato was similar in Conv-Low and Org-Low at both Chuka and Thika. At Chuka site, NUpE of potato was similar in Conv-High and Conv-Low and in Org-High and Org-Low farming systems. There was a significant system by site interaction effect (P<0.01) on NUpE of maize. While, NUpE of maize was similar in all the systems at Chuka site, at Thika site NUpE of maize was significantly higher ($P<0.01$) in the high input systems compared to the low input systems (Table 9).

With vegetables, N uptake efficiency of cabbage was affected by site ($P<0.05$) in the high input system (Table 9), i.e. NUpE of cabbage at Chuka was 2.5 times higher than at Thika. There were no site or system effects on NUpE of kale and Swiss chard in the low input systems.

Table 9: Effect of farming systems on nitrogen use efficiency of potato, maize, cabbage, kale and Swiss chard under high and low input levels in the long-term farming systems comparisons trials at Chuka and Thika in the Central Highlands of Kenya.

		Potato				Maize				Cabbage[a]				Kale[b]				Swiss chard[b]			
		NUpE	NUtE	AEN	NHI	NUpE	NUtE	AEN	NHI	NUpE	NUtE	AEN	NHI	NUpE	NUtE	AEN	NHI	NUpE	NUtE	AEN	NHI
		$kg\ kg^{-1}$ N	$kg\ kg^{-1}$ N	$kg\ kg^{-1}$ N	%	$kg\ kg^{-1}$ N	$kg\ kg^{-1}$ N	$kg\ kg^{-1}$ N	%	$kg\ kg^{-1}$ N	$kg\ kg^{-1}$ N	$kg\ kg^{-1}$ N	%	$kg\ kg^{-1}$ N	$kg\ kg^{-1}$ N	$kg\ kg^{-1}$ N	%	$kg\ kg^{-1}$ N	$kg\ kg^{-1}$ N	$kg\ kg^{-1}$ N	%
Systems	Conv-High	0.50 a	23.8 b	16.1 a	77 ab	0.7 a	25.9 a	50.6 a	52 a	0.84	12.3 b	20.8	55 b	na	na	na	na	na	na	na	na
	Org-High	0.16 b	19.7 c	4.8 b	69 b	0.62 ab	26.0 a	42.3 ab	50 a	0.60	15.2 a	14.2	68 a	na	na	na	na	na	na	na	na
	Conv-Low	0.59 a	29.2 a	20.7 a	83 a	0.47 ab	8.2 b	27.9 b	19.5 b	na	na	na	na	0.52	28	15.4	83	0.52	32	17.4	83
	Org-Low	0.42 ab	26.2 ab	14.3 ab	78 ab	0.41 b	9.9 b	25.5 b	20.0 b	na	na	na	na	0.40	31.6	10.3	72	0.40	39.8	13.6	72
Sites																					
	Chuka	0.26 b	24.1	8.5 b	72 b	0.54	20.9 a	36.1	41.8 a	1.03 a	16.7	25.1 a	72 a	0.47	45.5 β	19.6 α	56 β	0.47	57.6 α	24.9 α	56 β
	Thika	0.58 a	25.3	19.5 a	81 a	0.55	14.1 b	37.0	28.7 b	0.41 b	10.8	9.9 b	50 b	0.45	14.2 α	6.0 β	99 α	0.45	14.2 β	6.1 β	93 α
Site x Farming systems																					
Chuka	Conv-High	0.48 bc	24.4	15.4 c	71	0.63 ab	25.8 ab	46 ab	49.7 ab	1.23	15.3	30.3	66	na	na	na	na	na	na	na	na
	Org-High	0.07 e	17.9	2.0 e	64	0.46 abc	24.4 ab	29.7 bc	47.6 abc	0.83	18	19.8	78	na	na	na	na	na	na	na	na
	Conv-Low	0.33 cd	28.8	11.5 cd	79	0.60 abc	15.0 c	37.1 abc	32.8 c	na	na	na	na	0.57	40.6	23.5	67	0.24	52.1	10	35
	Org-Low	0.16 de	25.4	5.1 de	75	0.53 abc	18.4 bc	35.4 abc	37.3 bc	na	na	na	na	0.36	50.2	15.7	45	0.19	25.1	5.8	27
Thika	Conv-High	0.53 bc	23.2	16.9 bc	83	0.77 a	27.6 a	54.0 a	53.9 a	0.45	9.2	11.2	43	na	na	na	na	na	na	na	na
	Org-High	0.26 de	21.4	7.7 de	75	0.77 a	26.0 ab	55.1 a	51.7 ab	0.36	12.3	8.6	57	na	na	na	na	na	na	na	na
	Conv-Low	0.86 a	29.6	30.0 a	87	0.34 bc	1.4 d	18.7 c	5.8 d	na	na	na	na	0.48	15.4	7.2	99	0.11	19.4	2.0	93
	Org-Low	0.69 ab	27.0	23.5 ab	81	0.28 c	1.3 d	15.5 c	3.4 d	na	na	na	na	0.43	13	4.8	99	0.17	18.8	3.1	92
Sources of variations																					
System		***	***	***	**	**	***	***	***	ns	*	ns	*	ns	ns	ns	ns	ns	ns	ns	ns
Site		***	ns	***	***	ns	***	ns	***	*	ns	**	**	ns	**	***	***	ns	*	**	***
System x Site		***	ns	***	ns	**	***	***	***	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

Conv-High = conventional high input system; Conv-Low = conventional low input system; Org-High = Organic high input system; Org-Low= Organic low input system; AE_N = Agronomic efficiency of N use; NUpE = N uptake efficiency; NUtE = N utilization efficiency; NHI = N harvest Index; na, not applicable; ns= not significant.
only significant means were indicated. Different letters (a, b, c, d & e) next to the mean indicate that sample means are significantly different between the systems or sites (*P ≤0.05; ** P≤0.01 and *** P≤0.001).
[a] Cabbage was only grown in Conv-High and Org-High;
[b] Kale was grown as an intercrop with Swiss chard in Conv-Low and Org-Low

3.4.3.2. Nitrogen utilization efficiency

A significant system effect (*P*<0.001) on N utilization efficiency (NUtE) of potato (Table 9) was observed. The NUtE of potato was 23% higher in Conv-low compared to Conv-High, while NUtE of potato in Org-Low was 33% higher than that of potato in Org-High (*P*<0.001). In addition, NUtE of potato was significantly lower in Org-High (*P*<0.001) than in the other systems.

In maize, a significant system by site interaction effect (*P*<0.001) on NUtE was observed. The NUtE of maize was similar between Org-High and Conv-High and between Conv-Low and Org-Low at both sites. However, NUtE of maize in Org-High and Conv-High was 20 times higher than NUtE of maize in Conv-Low and Org-Low systems at Thika site (Table 9). There was no site effect on NUtE of cabbage in the high input system, but NUtE of cabbage in Conv-High was 24% higher (*P*<0.05) than that in Org-High. In the low input system, significant site effects on NUtE of kale (*P*<0.01) and Swiss chard (*P*<0.05) were observed being 3.2 and 4 times higher at Chuka site compared to Thika site.

3.4.3.3. Agronomic efficiency of nitrogen use

A farming system by site interaction effect (*P*<0.001) on agronomic N-use efficiency (AE_N) of potato was observed (Table 9). The AE_N of potato was similar in Conv-Low and Org-Low while AE_N of potato was 2.2 times higher in Conv-High compared to Org-High at Thika site. At Chuka site, AE_N of potato was similar in Conv-High and Conv-Low but AE_N of potato was 2.5 times higher in Org-Low compared to Org-High. A farming system by site interaction effect (*P*<0.001) on AE_N of maize was observed. With the exception of Chuka where the AE_N of maize was similar in all the systems, the AE_N of maize was 3.2 times higher in the high input systems compared to the low input systems at Thika site (Table 9). There was a higher AE_N of cabbage (*P*<0.01), kale (*P*<0.001) and Swiss chard (*P*<0.01) at Chuka compared to Thika.

3.4.3.4. Nitrogen harvest index

NHI of Potato in the low input systems was 11% higher ($P<0.01$) than the NHI in high input systems (Table 9). In addition, NHI of potato was 13% higher at Thika compared to Chuka site. In maize, there was a system by site interaction effect ($P<0.001$) on NHI (Table 9). The NHI of maize was similar in all the systems at Chuka but the NHI of maize in Conv-High and Org-High were 11.5 times higher than that of Conv-Low and Org-Low at Thika site. In vegetables, significant system ($P<0.05$) and site ($P<0.01$) effects on NHI of cabbage were observed. NHI of cabbage in Conv-High was 24% higher than Org-High system (Table 9). In addition, the NHI of kale and Swiss chard were 77 and 66% times higher at Thika than at Chuka site.

3.5. Discussion

3.5.1. The effect of farming systems on yield, N uptake and N-use efficiency

In potato, high N uptake (up to 200 kg N ha^{-1}) was observed particularly during tuber initiation and bulking stages (60 to 100 DAS) (Fig. 2a-b). This result conforms to other reports (Alva, 2004; Mikkelsen, 2006; Horneck and Rosen, 2008; Zotarelli et al., 2014; Zotarelli et al., 2015; Rens et al., 2016) that potato at tuber initiation and bulking stages takes up to 50-66% of plant total N (equivalent to 200-450 kg N ha^{-1}). The higher N partitioned into tubers in Conv-Low compared to Org-High (Fig. 2) can be largely attributed to the low NUpE in the organic systems (Table 9). This could be due to the effects excess N applied in Org-High due to addition of *Mucuna* biomass possibly resulting to higher potato haulms development at the expense of tuber formation (Ahmed et al., 2009; Rumhungwe et al., 2016). N'Dayegamiye et al. (2013) in a two year study also observed the combined effect of manure and synthetic N-fertilizer to increase N uptake in potato as compared to those from organic-amended fields.

As expected, NUpE of potato was higher in low input systems than in high input systems at Thika. Such a behaviour is commonly observed in potato crop physiology (Zebarth et al., 2004). However, assessing the system by site interaction for NUpE of potato revealed that at Chuka both low input systems (Org-Low, Con-Low) had low NUpE likely to be associated with severe late blight disease that affected potato at tuber bulking stage at this site. The effect of late blight on NUpE of potato in high input systems was lower possibly due to higher frequency of preventive spraying compared to the low input systems where spraying was done after observing the symptoms of the disease as this is the farmers practice (Table 4). The higher NUtE of potato in Conv-High when compared to that of Org-High can probably be attributed to lower potato tuber yield (Table 8) and higher N supply in the Org-High system (Table 6) affecting partitioning within the plant (Table 9) and subsequent use. The higher AE_N of potato observed in conventional over those in organic systems (Table 9) can be attributed mainly to the higher N supply in organic systems than in conventional systems (Table 6). In addition, AE_N is an integrated index on NUpE and NUtE (Ladha et al., 2005) and hence an increase of either factors can result in an increase in AE_N. This may explain the higher AE_N observed in conventional over those of organic systems that had lower NUpE and NUtE.

According to Fageria (2014), NHI is mainly influenced by crop genotype and efficient utilization of N. The higher NHI of potato in Conv-Low over Org-High can be attributed to higher N uptake efficiency in Conv-Low system (Tables 9). The observed NHI of potato (64-87%) compares well to values (73-86%) reported by Zebarth et al. (2004). This indicates that the potato crop was efficient in recycling vegetative N into potato tubers (Sinclair and Rufty, 2012), independent of farming system.

In maize, N uptake at 70 DAS (34-154 kg N ha^{-1}) and 90 DAS (50-237 kg N ha^{-1}), corresponding to silking and tasselling stage (Fig. 2c-d), was within the range of 65-157 kg N ha^{-1} reported by Francis et al. (1993) at the same growth stages. The high N uptake at the reproductive stage was expected because the crop requires high amounts of N for ear and grain formation (Masclaux et al., 2001; Wang et al., 2014). Higher N uptake in Conv-High compared to Org-High at 70 and 90 DAS (tasseling and Silking stages) could be associated to lower N availability in organic systems given the high lignin and C/N composts applied at this site (Supplementary sheet 1). In addition, the more pronounced differences in yield and NUE between high and low input systems at Thika compared to Chuka site could have been due to low rainfall received (Fig. 1) at Thika site resulting in moisture stress in low input systems at these critical stages while the high input systems received supplementary irrigation. On the other hand, the higher dry matter accumulation in maize at maturity in Org-High (Supplementary sheet 3) compared to Conv-High could be accounted for by the higher N uptake in Org-High at late development stages (Fig. 2). N uptake in Org-High may have continued past the silking stage (Fig. 2) as the maize crop remained green for a longer period than in the conventional systems. N uptake, NUpE, NUtE, AE_N and NHI of maize were similar between Conv-High and Org-High and between Conv-Low and Org-Low at Chuka site possibly due to the higher rainfall received at this site (Fig. 1) facilitating decomposition, mineralization and N uptake which resulted to higher efficiencies in all the systems. However, at the drier Thika site NUpE, NUtE, AE_N and NHI were significantly higher in Conv-High and Org-High compared to Conv-Low and Org-Low and this could be attributed to higher N applied as well as supplementary irrigation given to the high input systems. The NHI of maize obtained from both sites for Conv-High and Org-High (48-54%) and from Chuka site for Conv-Low and Org-Low (33-37%) were within the range of 26-71% reported for different maize genotypes (Hefyn and Aly, 2008; Gondwe, 2014). NHI of maize in low input systems (3-9%) at Thika site was below the reported range due to drought experienced during the season which was more severe at this site resulting to minimal grain formation (Fig. 1).

Fresh matter yield of cabbage and total N uptake at harvest was within the range observed by Katroschan et al. (2014). N uptake of cabbage at 70-109 DAS was higher (80-410 kg N ha^{-1}) than the range of 30-60 kg N ha^{-1} reported at heading and maturity by Salo (1999) and Vasu and Reddy (2013), suggesting that both systems supplied sufficient N to cabbage resulting in high dry matter accumulation.

3.5.2. Effect of sites on yield, N uptake and N-use efficiency

The observed site effects on crop yield, nutrient uptake and nitrogen use efficiency were mainly due to prevailing disease and weather effects as corroborated also by other authors (Palmer et al., 2013). For example, at Chuka, growth, N uptake and use efficiency of potato was severely reduced by late blight (*Phytophthora infestans*) due to excessive rainfall (718 mm received against the average rainfall or irrigation water requirement of 460 mm for most potato cultivars (Directorate of plant production, 2013)). Late blight is known to reduce potato yield by 30-75% in East Africa (Olanya et al., 2001; Were et al., 2013). This may explain the poor crop performance at Chuka site as compared to Thika where rainfall was considerably lower.

The site effects on maize and vegetable performance were particularly evident in the low input systems as these were relying on natural rainfall conditions while high inputs systems were irrigated as is common in commercial farms. Thus, differences in the low input systems in yield, nutrient uptake and N use efficiency observed in maize and vegetables can be attributed to varying environmental factors especially low amounts and uneven rainfall distribution (Fig. 1 and Supplementary sheet) in addition to nutrient application levels (Table 5). Rainfall was lower at Thika during maize growing season compared to Chuka site, and this reduced crop N uptake in Conv-Low and Org-Low particularly at 40-90 and 90-100 days DAS (Fig. 1) as these low input systems relied on rainfall only. Similar reasons account for the poor development and low yield of kale and Swiss chard yield in Conv-Low and Org-Low at Thika. Dry matter accumulation of cabbage at 70-109 DAS was below the range of 7000-13000 kg ha^{-1} reported by Salo (1999) and Vasu and Reddy (2013) at heading and maturity stages of cabbage and this could have been due to drought effects as availability of irrigation water was also low at Thika as indicated by the volume of irrigation water given to the crop (Section 2.2 above). An interactive effect between N and water supply on crop yield has been also documented elsewhere (Acharya and Sharma, 2010; Adamtey et al., 2010; Yin et al., 2014). Water deficit has been shown to strongly reduce maize grain yield, N utilization and uptake efficiencies (Hammad et al., 2012). Maize and cabbage in Org-High and Conv-High performed well at both sites due to the supplementary irrigation supplied to both systems. On the other hand, maize and vegetables under Conv-Low and Org-Low performed well at Chuka due to higher rainfall received at this site.

3.6. Conclusion

The study revealed that depending on the type of crop, the effect of conventional and organic system on crop N uptake and N-use efficiency may differ or be similar. Our study shows that potato had higher N uptake, N uptake efficiency (NUpE), N utilization efficiency (NUtE) and agronomic N-use efficiency (AE_N) under conventional systems. On the other hand, maize N uptake at the reproductive stages from the area with adequate water as in Chuka was similar for conventional and organic systems, but at the drier site of Thika, there was higher N uptake from conventional systems compared to organic systems. With the exception of AE_N in maize and NUtE and NHI of cabbage in the high input systems, conventional and organic systems had similar effects on maize and vegetable N-use efficiencies. Maize showed higher NUtE under organic system compared to those from conventional systems. The systems, however, had similar effects on the N partitioned into maize and vegetable yields and residues. Agronomic efficiency of N use may be influenced by N supply, NUpE, and environment. The effect of NUtE on AE_N was different depending on the crop type. Low input systems performed poorly under drier conditions at Thika, with organic systems to date not performing better than conventional systems. In the subsequent years, the study recommends that management practices for potato production in organic systems should be improved for efficient NUE.

3.7. Acknowledgements

This work was financially supported by Swiss Agency for Development and Cooperation (SDC), Liechtenstein Development Service (LED), CCoop Sustainability Fund and Biovision Foundation to whom we are indebted. We appreciate the support offered by SysCom Kenya team; Dr. Komi Fiaboe, Mr. Edward Karanja, the late Peter Owuor, Jane Makena and Felistas Mutua during data collection. We are indebted to the entire Kenya Agricultural and Livestock Research Organization (KALRO) Muguga laboratory team led by Dr. John Lekasi and Mr. Nicholas Kung'u for the support in laboratory analysis. Statistical support offered by Dr. Daisy Salifu (ICIPE), Dorcas Kareithi (Bramble consultants Kenya) and Dr. Juan Laso (University of Hoheinhem) is much appreciated. Authors appreciate all the support given by the staff of the international division of the Research Institute of Organic Agriculture (FiBL), Switzerland.

3.8. Appendices

Appendix 1: Quality of organic inputs used in the long-term systems comparison trials (2007-2012) in the Central highlands of Kenya (Chuka and Thika)

Site/Farming system	Organic Input	N	P	K	Ca	Mg	B	Cu	Fe	Mn	Zn
Chuka		%	$mgkg^{-1}$	$mgkg^{-1}$	$mgkg^{-1}$	$mgkg^{-1}$	$mgkg^{-1}$	$mgkg^{-1}$	$mgkg^{-1}$	$mgkg^{-1}$	$mgkg^{-1}$
Conv- High	Rotten Manure	1.25±0.10	0.27±0.02	1.94±0.21	1.20±0.09	0.37±0.02	65.72±1.17	45.83±12.98	44840±680	3890.30±655	235.75±36.5
Org -High	Compost	1.20±0.13	0.30±0.02	1.91±0.14	2.20±0.32	0.49±0.04	58.95±0.34	16.03±0.80	43950±1895	3747.50±299	198.25±3.75
	Mucuna	2.01±0.14	2.60±1.07	1.37±0.15	1.28±0.07	0.28±0.01	18.15±1.78	8.86±0.41	1505±170	362.86±24	29.28±1.35
	Tithonia	2.64±0.67	3.64±1.30	3.67±0.10	1.90±0.08	0.37±0.01	59.55±2.03	11.07±0.34	764±0.48	332.70±9	73.45±2.89
	*Maize stover	0.77±0.08	0.94±0.36	1.32±0.05	0.33±0.02	0.21±0.01	12.04±0.89	4.57±0.42	2689±306	346.64±37	37.79±2.41
	*French beans stover	2.28±0.06	0.16±0.02	1.44±0.10	1.07±0.08	0.24±0.02	23.78±4.04	40.75±6.80	3933±179	497.75±0.86	40.75±6.80
	**Latana camara*	1.69±0.08	2.05±1.08	1.83±0.13	0.96±0.06	0.30±0.02	28.28±1.89	9.97±0.69	1051±89	609.53±30.41	43.93±5.79
	*Ash	0.36±0.12	1.15±0.16	8.75±0.30	13.20±1.59	1.94±0.08	NA	NA	NA	NA	NA
Conv -Low	Fresh Manure	1.51±0.14	0.29±0.23	1.95±0.27	1.20±0.09	0.37±0.02	65.72±1.17	45.83±12.98	44840±680	3890.33±655	235.75±36.55
Org -Low	Rotten manure	0.73±0.13	0.25±0.03	1.44±0.18	1.82±0.18	0.42±0.03	52.80±1.36	25.80±3.90	32233±1895	2477±259	194.67±7.91
Thika											
Conv -High	Rotten Manure	1.47±0.16	0.30±0.04	2.21±0.20	1.38±0.10	0.41±0.03	46.60±5.80	13.40±2.31	28972±4517	1639.71±204	92.84±8.65
Org- High	Compost	1.13±0.09	0.22±0.03	1.63±0.15	1.58±0.10	0.32±0.03	50.97±7.74	10.57±3.14	36560±6206	1476.67±180	83.70±9.52
	Mucuna	2.59±0.12	0.15±0.01	1.57±0.09	0.89±0.03	0.24±0.01	21.59±1.39	7.40±0.32	2542±485	234.87±23.94	30.05±2.54
	Tithonia	3.03±0.09	0.41±0.02	6.00±0.26	2.94±0.12	0.50±0.02	90.51±4.19	18.03±1.29	3667±570	485.19±50.33	136.30±10.76
	*Maize stover	1.24±0.11	0.11±0.02	1.51±0.25	0.29±0.04	0.23±0.03	14.73±1.58	4.65±0.72	4423±799	249.98±37.23	36.87±4.09
	*French beans stover										
	**Latana camara*	1.95±0.09	0.18±0.01	2.84±0.22	1.38±0.13	0.39±0.03	37.26±3.17	13.85±1.10	1315±182	502.85±59.13	43.67±3.79
	*Ash	0.62±0.12	0.45±0.15	3.25±0.68	8.51±2.99	0.96±0.28	NA	NA	NA	NA	NA
Conv- Low	Fresh Manure	1.47±0.10	0.30±0.02	2.88±0.20	1.36±0.05	0.52±0.05	49.89±7.11	23.26±3.26	19788±4579	1793±324	112.25±10.46
Org -Low	Rotten manure	1.21±0.11	0.20±0.03	1.87±0.14	1.07±0.11	0.32±0.03	48.60±6.17	12.71±2.16	31636±5345	1661±231	110.28±15.17

*Maize stover, *French Beans, * *Latana camara*, *Ash were all used as composting materials in addition to manure and rock phosphate, #Adopted from Adamtey et. al., 2016

Appendix 2: Recommended application rates of inputs in the long-term system comparison trial in Chuka and Thika, Kenya

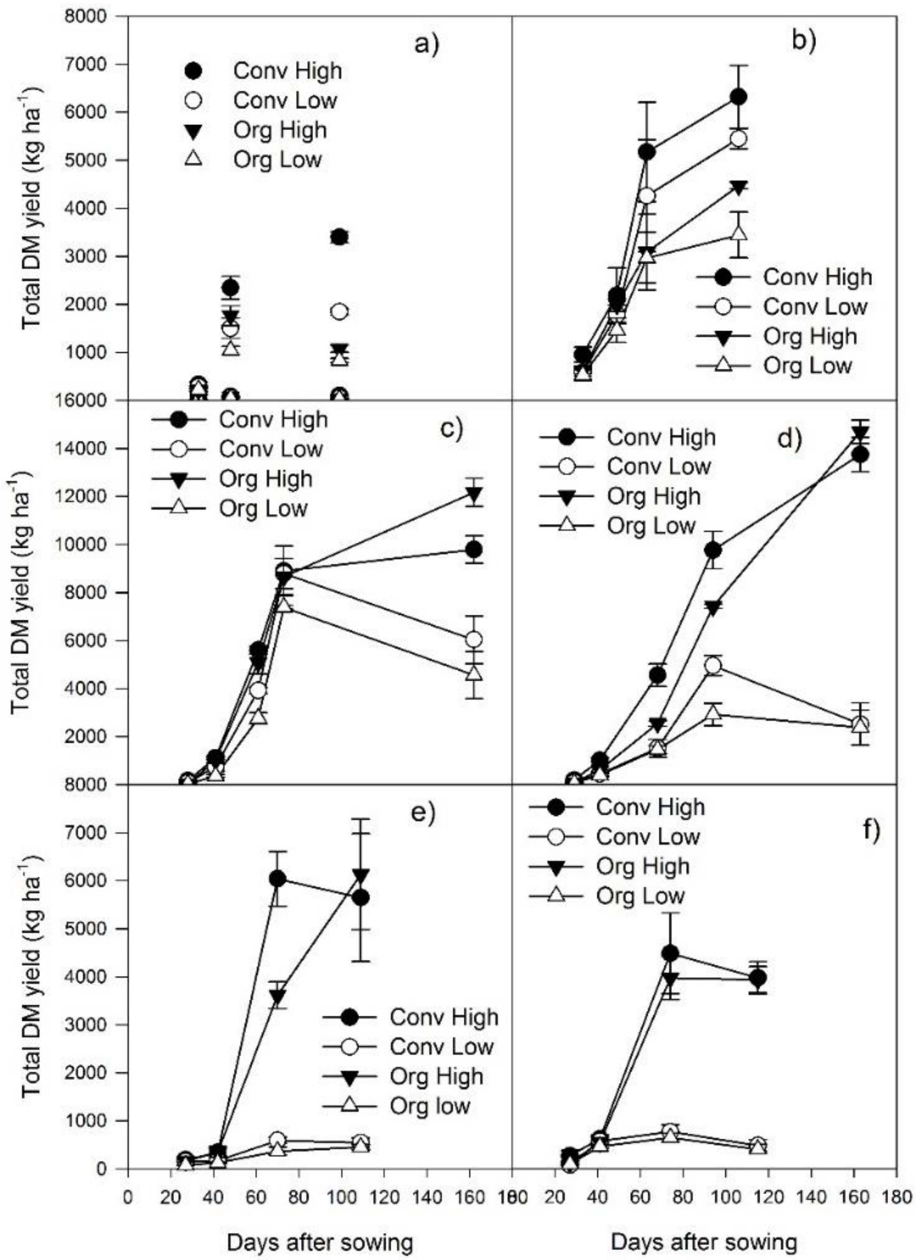
Farming systems	Year	Season	Crop	FYM (Mg ha^{-1})	Compost* (Mg ha^{-1})	DAP (kg ha^{-1})	PR (kg ha^{-1})	TSP (kg ha$^{-1)}$	CAN[ǂ] (kg ha^{-1})	*Tithonia*** (Mg ha^{-1})	*Tithonia*[x] (plant tea) Mg ha^{-1}	Total N applied (kg ha^{-1})	Total P applied (kg ha^{-1})
	1	1	Maize	5		50						31	18
		2	Kale/Swiss Chard	1				50	60			20	13
Conv-Low[1]	2	1	Maize/beans	5		50						31	18
		2	Beans	0		0						0	0
	3	1	Maize/beans	5		50						31	18
		2	Potato	2		100						27	25
	1	1	Maize	7.5		200			100			96	54
		2	Cabbage	15				200	300			145	64
Conv-High[2]	2	1	Baby corn	11.3		200			100			113	60
		2	French beans	11.3		200			100			113	60
	3	1	Baby corn	11.3		200			100			113	60
		2	Potato	11.3				300	200			100	83
	1	1	Maize		5		100			1.36		31	18
		2	Kale/Swiss Chard		1		90			1.2	1.2	20	13
Org-Low[3]	2	1	Maize/beans		5		100			1.36		31	18
		2	Beans		0		0			0		0	0
	3	1	Maize/beans		5		100			1.36		31	18
		2	Potato		2		200			2.72		27	26
	1	1	Maize		7.5		364			5.4	3.9	96	54
		2	Cabbage		15		400			6	6	147	70
Org-High[4]***	2	1	Baby corn		11.3		364			5.4	3.9	113	59
		2	French beans		11.3		364			5.4	3.9	113	59
	3	1	Baby corn		11.3		364			5.4	3.9	113	59
		2	Potato		11.3		581			8.2		105	83

[1]Conv-Low, conventional low input system; [2]Conv-High, conventional high input system; [3]Org-Low, organic low input system and [4]Org-High, organic high input system

ǂ Applied as top-dress to all crops except in potato where it is applied at planting. Under high input topdressing was done in two split applications, while in low input topdressing was not done or it was done once for specific crops. *Compost preparation starts with the indicated amount of Fresh FYM. ***Tithonia* mulch is applied after crop germination as starter N. ***Organic high system also receives maize stover residues at 2 Mg ha^{-1} during the short rain season. The plots were also intercropped with *Mucuna* during the first season and the *Mucuna* biomass was applied during the short rain season. French bean biomass was also incorporated during the next baby corn season. DAP = Di-ammonium phosphate; CAN= calcium ammonium nitrate; TSP= triple superphosphate; PR=phosphate rock

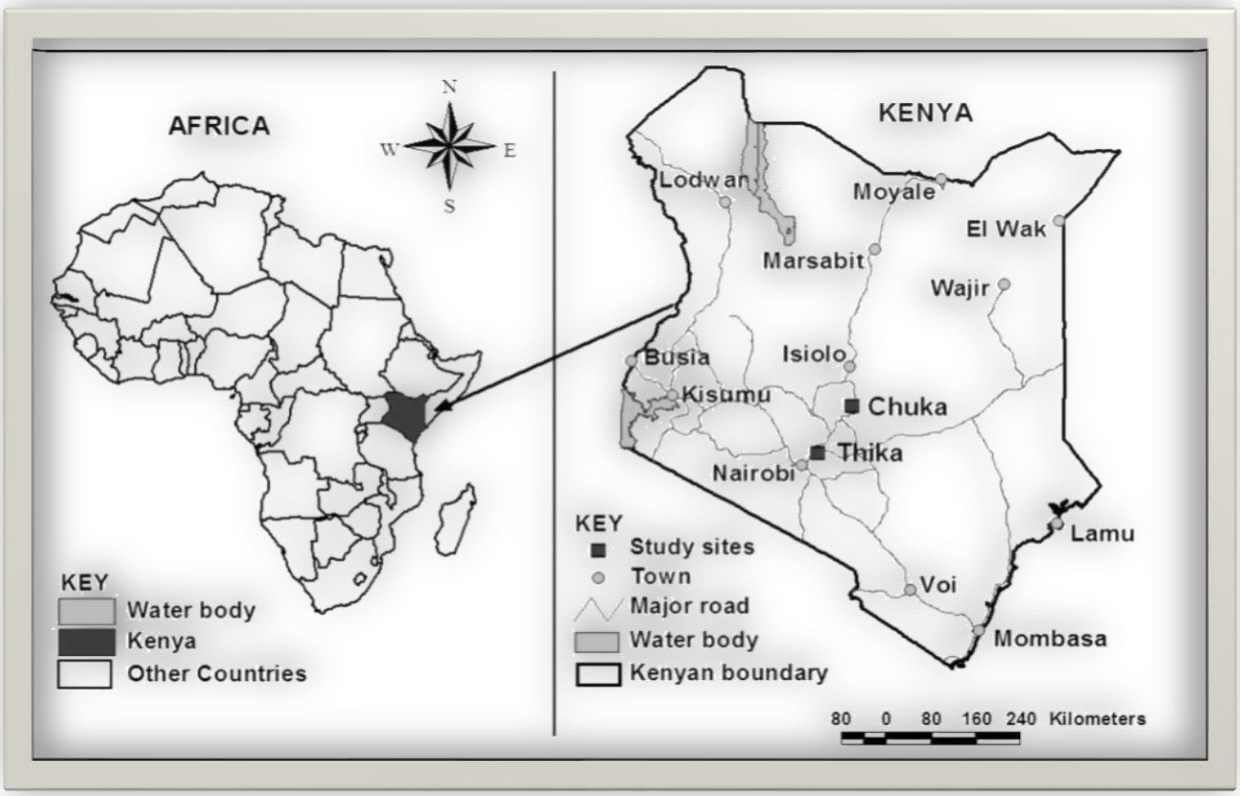
Assumptions:

FYM/compost (DW): 1.12% total N and 0.3% P (Lekasi et al., 2003); DM of FYM is assumed to be 40%; *Tithonia diversifolia* (DW): 3.3% N; 0.31% P; 3.1% K (Nziguheba et al., 2004); DM of *Tithonia* = 20%; Phosphate rock from West Africa (Finck): 11 - 13% P



Appendix 3: Dry matter accumulation of potato (a-b) maize (c-d) and vegetables at Chuka and Thika sites

CHAPTER 4


AFRICA
N
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KEY
Water body
Kenya
Other Countries
KENYA
Lodwar
Moyale
El Wak
Marsabit
Wajir
Busia
Isiolo
Kisumu
Chuka
Thika
Nairobi
Lamu
Voi
Mombasa
KEY
Study sites
Town
Major road
Water body
Kenyan boundary
80 0 80 160 240 Kilometers

4.0. Nitrogen leaching losses and balances in conventional and organic farming systems in Kenya‡

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4.1. Abstract

Organic farming has been proposed as a solution to foster agricultural sustainability and mitigate the negative environmental impacts of conventional farming. This study assessed N losses and soil surface N balances in conventional and organic farming systems in a sub-humid and semi-humid (Chuka and Thika) sites in Kenya. Nitrate-N (NO_3^--N) leached was trapped at 1 m depth using the Self Integrating Accumulator core method and the changes in mineral-N were assessed at different soil depths and different crop growth stages. Both conventional and organic farming systems lost

‡ *Published with kind permission of Springer. The original article appeared in the journal Nutrient Cycling in Agroecosystems Vol. 114 No. 3 pp 237-266 which can be found in the link https://link.springer.com/article/10.1007%2Fs10705-019-10002-7*

substantial amounts of NO_3^--N at the early growth stages of all the crops. Cumulative NO_3^--N leached was similar in all the farming systems in each cropping season. More NO_3^--N was leached during potato cropping (22-38 kg N ha^{-1}) than during maize (0.9-5.7 kg N ha^{-1}) and vegetable cropping (1.9-2.9 kg N ha^{-1}). Under maize cultivation, three times more NO_3^--N was leached at Chuka site than at Thika site. During the potato cropping, between 79-83% of the N applied in the low input systems was leached, compared to 10-20% in the high input systems. Only Org-High exhibited a positive soil surface N balance (797-1263 kgha^{-1}) over a whole rotation period at both sites. We recommend reducing N applications for potato in all farming systems and at the early growth stages for all the crops in order to reduce N loss into the environment. We also recommend increasing N application rates in the low input systems and to developing a model to guide application of organic inputs.

Key words: Farming systems, high input, low input, nitrate-N leaching, N-balance

4.2. Introduction

Nitrogen (N) is one of the major nutrients in crop production and is required in large amounts, as it plays a vital role in biological processes (Pypers et al., 2005). Many soils of Africa are low in N due to low inherent nutrient reserves, N mining, low buffering capacity, as well as rapid decomposition of soil organic matter triggered by high temperatures and changes in land use (Tully et al., 2015). To meet crop N demands, N is commonly supplied through mineral fertilizers and/or organic inputs. Crops' N recovery from fertilizers and organic inputs is often low (Raun and Johnson, 1999) and up to 50-70% of the N added to the soil can be lost through leaching, volatilization and denitrification (Raun and Johnson, 1999).

N losses through leaching range from 5-50% of applied N, so leaching clearly represents one the major pathways of N losses in agro-ecosystems (Ross et al., 2008), especially in the wet and humid tropics in soils with low soil organic matter content (Robertson and Vitousek, 2009). N leaching is influenced by a number of factors including: i) soil type and rainfall patterns (Knudsen et al., 2006), (ii) the form, rate and stage of N application, (iii) the stages of crop development, (iv) cropping systems, and (v) tillage practices (Meisinger and Delgado, 2002). Periods of excess N, coupled with high rainfall, have been found to increase leaching losses in most farming systems (Pimentel et al., 2005). On the other hand, drought reduces crop N demand resulting in N accumulation in the soil, although this N can be lost through leaching when conditions are favourable for this to occur (Pimentel et al., 2005).

Some studies in both tropical and temperate conditions, have shown N leaching to be lower when N is applied in organic form as opposed to inorganic forms (Kimetu et al., 2004; Carneiro et al., 2012). This is possibly due to the slower release of mineral-N through the mineralization of organic resources (Goulding, 2000) as well as the use of catch crops (crops grown to capture nutrients from deeper soil layers and prevent nutrient losses) in organic systems (Askegaard et al., 2011; Guzys and Miseviciene, 2015). On the other hand, some findings in Europe have shown that organic and conventional systems leach similar amounts of N (Stopes et al., 2002; Knudsen et al., 2006; Aronsson et al., 2007). This could be due to the organic inputs remaining in the system for longer after application, and may mineralize when the crop's N demand is low or when there is no crop (Bergström et al., 2008; Evanylo et al., 2008; Musyoka et al., 2019). Assessment of when N leaching losses are likely to occur during the cropping season is critical to ensure that N application coincides with N demand (Abebe and Feyisa, 2017).

N balances (the difference between inflows and outflows of N) are key indicators of N depletion or accumulation in the soil and thus play an important role in environmental conservation and sustainability. N balances can be expressed as full N budgets which include N applied as fertilizer and organic inputs, environmental inflows such as deposition, N_2 fixation and sedimentation while the outflows include N losses through leaching, volatilization, denitrification, run off, soil erosion, plant senescence (as volatile ammonia and amines emissions) and removal in yields and other biomass (Cobo et al., 2010; Sainju, 2017). On the other hand, partial N balances does not include all inputs and outputs and they may include only easy to measure inputs and outputs such as fertilizer and FYM inputs and crop removal outputs and exclude difficult to measure N inputs and outputs such as sedimentation, denitrification and volatilization (Roy et al., 2003; Kimetu et al., 2006; Wang et al,. 2008; Cobo et al., 2010; van Leeuwen et al., 2019). In addition, soil surface N balances are partial N balance that include N inputs and outputs at the field surface (van Leeuwen et al., 2019). Full N balances have been shown to be positive in organic farming systems in Europe (Watson et al., 2002). In Kenya, full N balances in conventional small scale farms have been shown to vary depending on resources such as cash, labour and inputs available to farmers, with farmers who have a strong resources base (often including off farm employment) having positive N balances (as they have increased capacity to apply more N) (Tittonell et al., 2007), and negative balances associated with farmers who have a medium to weak resource base (Onwonga and Freyer, 2006). However, most of these studies assessed N balances of low to moderate input smallholder farms and hardly included any assessment of N balances at the recommended N application levels (which is the novelty in our study). Thus, quantitative estimations of plant nutrient depletion from soils under organic and conventional systems are needed to understand patterns of soil degradation or improvement as well as to devise corrective measures. This study seeks to improve the understanding of the impact of these different farming systems on the environment and to provide empirical evidence as a basis for advisory services and policy development. The study hypothesized that leaching losses and soil surface N balances would differ in conventional and organic farming systems due to differences in management practices, chemical characteristics of inputs, the transformation of inputs into forms that are usable by plants, and the availability of N in the soil. The objectives were twofold: firstly, to assess the effects of conventional and organic farming systems on the total nitrate-N leached beyond the crop root zone and secondly to establish surface N balances for different farming systems over the entire crop rotation.

4.3. Materials and Method

4.3.1. Field sites

Data collection was done in the on-going long-term farming systems comparison (SysCom; www.system-comparison.fibl.org) trials in Kenya (Adamtey et al., 2016). The trials were established in 2007 at two locations: Chuka (Tharaka Nithi County) and Thika (Murang'a County) in the Central Highlands of Kenya. The sites have a bimodal rainfall pattern with long rains (LR) occurring between March and June and short rains (SR) occurring between October and December. The site at Chuka is located at 1458 m a.s.l. (Longitude 037° 38.792' and Latitude 00° 20.864') with an annual mean temperature of 20°C and mean annual rainfall of 1500 to 2400 mm. This site is situated in the upper midland 2 agroecological zone, also referred to as the coffee zone (Jaetzold et al., 2006a). The site at Thika is located at 1500 m a.s.l. (Longitude 037° 04.747' and Latitude 01° 00.231') with an annual mean temperature of about 20°C and mean annual rainfall of 900 to 1100 mm. This site is situated in the upper midlands agroecological zone 3 (UM3), also referred to as the sunflower maize zone (Jaetzold et al., 2006b). The soils at Chuka site are classified as Humic Nitisols and those at Thika as Rhodic Nitisols (Adamtey et al., 2016) in the FAO World reference base for soil resources (IUSS Working Group WRB. 2006). The soils thus differ in their physical and chemical characteristics, as shown in Table 1 and Supplementary S1.

Table 1: The chemical characteristics of the soils at the beginning of data collection in October 2012 in the long-term system comparison trial at Chuka and Thika in the Central Highlands of Kenya

Site	Parameter	Bulk density	pH (1:2.5)	Total N	NO_3^--N	NH_4^+-N	OC	C/N ratio	P (Olsen)	K	Ca	Mg	Sand	Clay	Silt
		g cm^3		g kg^{-1}	mg kg^{-1}	mg kg^{-1}	g kg^{-1}		mg kg^{-1}	mg kg^{-1}	mg kg^{-1}	mg kg^{-1}	%	%	%
Systems															
	Conv- High	1.01	5.37 b	2.1	10.8	2.7	17.5 b	9	53	442 b	1392 a	93 ab	18.7 ab	724	8.9
	Org- High	1.00	6.33 a	2.2	15.6	3.2	20.9 a	10	29	876 a	1493 a	114 a	17.3 b	707	12.0
	Conv- Low	0.99	5.30 b	2.0	4.9	2.1	17.6 b	9	25	400 b	934 b	77 b	17.9 b	720	10.1
	Org- Low	0.99	5.37 b	1.8	11.3	3.2	16.7 b	9	18	447 b	1097 ab	82 b	19.2 a	715	9.3
Sites															
	Chuka	0.91 b	5.48	2.3 a	9.5 b	3.2	20.8 a	10 a	40 a	434 b	1384 a	92	17.9	715	10.6
	Thika	1.04 a	5.71	1.9 b	18.4 a	3.5	15.5 b	9 b	25 b	648 a	1073 b	91	18.6	718	9.6
System x Site															
Chuka	Conv- High	0.91	5.36 b	2.3	3.9	3.4	20.0 a	9	59	309	1462	94	18.6	70.8	10.6
	Org- High	0.92	5.83 b	2.4	2.6	3.0	23.9 a	10	31	704	1493	111	17.3	70.7	12.0
	Conv- Low	0.91	5.36 b	2.2	2.7	3.1	20.4 a	9	36	318	1198	80	17.5	73.1	9.4
	Org- Low	0.91	5.35 b	2.1	2.7	3.9	18.6 b	9	34	404	1384	81	18.1	71.4	10.5
Thika	Conv- High	1.09	5.38 b	1.9	17.7	1.9	15.0 bc	8	46	575	1322	92	18.8	74.0	7.2
	Org-High	0.99	6.83 a	2.0	28.6	3.4	17.8 b	9	27	1048	1493	116	17.2	70.8	12.0
	Conv- Low	1.04	5.24 b	1.7	7.0	1.0	14.7 c	9	14	481	669	73	18.2	70.9	10.9
	Org- Low	1.03	5.38 b	1.6	19.9	2.4	14.5 c	9	12	489	809	82	20.3	71.6	8.1
Sources of variations															
System		ns	***	ns	ns	ns	***	ns	ns	***	*	**	*	ns	ns
Site		***	Ns	***	***	ns	ns	*	*	***	*	ns	ns	ns	ns
System x site		ns	*	ns	ns	ns	*	ns	ns	ns	ns	ns	ns	ns	ns

Conv-High conventional high input system, *Org-High* organic high inputs system, *Conv-Low* conventional low input system, *Org-low*, organic low input system, *pH* pH in water, *OC* organic carbon; *C/N* C to N ratio

a, b, c are used to compare means, with only significant mean differences shown; K, Ca, and Mg are ammonium acetate extractable bases.

4.3.2. Experimental design and management practices

Data was collected in conventional and organic farming systems in the long-term system comparison trials based on a two-season, three-year crop rotation (Table 2) (Adamtey et al., 2016). In this study, the FAO (Dixon et al., 2001) definition for farming systems, as a set of population of individual farm systems that have broadly similar resource bases, enterprise patterns, household livelihoods and constraints and for which similar development strategies and interventions would be appropriate, was adopted. Thus, at each site, conventional (Conv) and organic (Org) systems were compared at low input levels (Conv-Low and Org-Low), where the N and P application rates and management practices (Table 4) mimicked small-scale farmers' practices in the region. Conventional (Conv) and organic (Org) systems at high input levels (Conv-High and Org-High) represented recommended N and P application rates and other management practices (Table 4) embraced by market-oriented and large-scale production systems farmers (Musyoka et al., 2017). The high input systems received supplementary irrigation during the dry period and pest and disease were controlled based on scouting (Adamtey et al., 2016). The four farming systems were arranged in a randomized complete block design (RCBD) with plot sizes of 8 by 8 m (with a net harvest area of 6 × 6 m). Farming systems were replicated 4 and 5 times at Chuka and Thika sites, respectively. Potato (*Solanum tuberosum* L. var Asante) was planted in all the systems in the short rain season (on the 16th and 25th October 2012 at Chuka and Thika respectively). Maize (*Zea mays* L. var H513) was planted in all the farming systems in the long rain season (on the 27th March and 4th April 2013 at Chuka and Thika sites respectively). Cabbage (*Brassica oleracea* var. capitate) was planted in the high input systems and kale (*Brassica oleracea* var. acephala) intercropped with Swiss chard (*Beta vulgaris* subsp cicla). The vegetable crops in the low and high input systems were planted in the short rain season (on the 6th and 8th November 2013) at Chuka and Thika respectively.

Table 2: Crop rotation in of the long-term farming systems comparison trial at Chuka and Thika in the Central Highlands of Kenya

	Year 2007, 2010, 2013		Year 2008, 2011, 2014		Year 2009, 2012, 2015	
Farming systems	LR*	SR**	LR	SR	LR	SR
Conv-High[1]	Maize	Cabbage	Baby corn	French beans	Baby corn	Potatoes
Org-High[2]	Maize/Mucuna[a]	Cabbage	Baby corn/Mucuna	French beans	Baby corn/Mucuna	Potatoes
Conv-Low[3]	Maize	Collard/Swiss chard	Maize/Beans	Grain legumes	Maize/beans	Potatoes
Org-Low[4]	Maize	Collard/Swiss chard	Maize/Beans	Grain legumes	Maize/beans	Potatoes

[1]*Conv-High* conventional high input system, [2]*Org-High* organic high inputs system, [3]*Conv-Low* conventional low input system, [4]*Org-low*, organic low input system, **LR*, long rainy season; ***SR*, Short rainy season; [a]*Mucuna pruriens* planted as relay crop four weeks after the maize or baby corn were established. Mucuna biomass was applied in the short rainy season. The shaded region shows the period of data collection in 2012 and 2013.

The trial set up aimed at providing similar amounts of external N and P from the applied inputs in the high (Conv-High and Org-High, 225 kg N ha^{-1} $year^{-1}$ and 125 kg P ha^{-1} $year^{-1}$) and low input systems (Conv-Low and Org-Low, 45 kg N ha^{-1} $year^{-1}$ and 26 kg P ha^{-1} $year^{-1}$) (Adamtey et al., 2016). However, due to the nutrient contained in *Mucuna pruriens* (Mucuna) biomass, together with seasonal variations of the nutrient content of Farm Yard Manure (FYM) and compost, the actual N and P applied in the conventional and organic farming systems at the two sites exceeded the intended rates (Table 3). The conventional systems' plots received FYM, di-ammonium phosphate (DAP) or triple supper phosphate (TSP) at planting. In Conv-High, two split top dress applications of calcium ammonium nitrate (CAN) were made during maize and cabbage cropping, but only once during kale/Swiss chard cropping in the Conv-Low (Table 3). The organic plots received compost in Org-High and composted FYM in Org-Low, as well as Minjingu phosphate rock powder at planting. *Tithonia diversifolia* (Tithonia) harvested from the trial sites' live fences was applied as starter-up and top-dressing N in Org-High and Org-Low at the rates indicated in Table 3. Tithonia was applied as mulch two weeks after germination and as a plant tea (prepared by soaking soft leaves and twigs of Tithonia in water at the ratio of 1:2 for 7-10 days (Adamtey et al., 2016) in two split top dress applications during maize and cabbage cropping (Table 4) in Org-High and only once during kale/Swiss chard cropping in Org-Low. In the Org-High, Mucuna was relay intercropped with baby corn (40 days after planting) in the long rain season crop in 2011 and the biomass was harvested, weighed and incorporated into the soil together with baby corn stover applied at the rate of 2 t ha^{-1} a week before planting of the short rain season crops (potato and French beans).

Table 3: Actual N and P applied from different inputs in each farming system during the study period in the Long-term system comparison trial at Chuka and Thika, in Central Highlands of Kenya.

Site	Farming systems	Year	Season	Crop	*Mucuna*		Baby corn/maize stover		FYM/Compost		DAP		PR	TSP	CAN	*Tithonia*		Total N applied	Total P applied
					N	P	N	P	N	P	N	P	P	P	N	N	P		
					kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}
Chuka	Conv-High	2012	SR	Potato	-	-	-	-	106.5	34.2	-	-	-	60.0	54.0	-	-	160	94
		2013	LR	Maize	-	-	-	-	50.2	19.6	36.0	40.4	-	-	27.0	-	-	113	60
		2013	SR	Cabbage	-	-	-	-	32.5	18.4	-	-	-	40.0	81.0	-	-	114	58
	Conv-Low	2012	SR	Potato	-	-	-	-	15.4	7.2	18.0	20.2	-	-	0	-	-	33	27
		2013	LR	Maize	-	-	-	-	53.9	22.4	9.0	10.1	-	-	0	-	-	63	32
		2013	SR	Kale/Swiss Chard	-	-	-	-	6.5	3.3	-	-	-	10.0	16.2	-	-	23	13
	Org-High	2012	SR	Potato	132.8	26.5	39.8	2.8	110.5	51.9	-	-	69.7	-	0	51.8	3.8	335	155
		2013	LR	Maize	-	-	-	-	170.5	84.7	-	-	43.7	-	0	75.8	4.3	246	133
		2013	SR	Cabbage	-	-	40.2	0.4	72.8	60.7	-	-	48.0	-	0	97.8	5.6	211	115
	Org-Low	2012	SR	Potato	-	-	-	-	25.6	19.4	-	-	24.0	-	0	22.2	1.3	48	45
		2013	LR	Maize	-	-	-	-	24.3	10.9	-	-	12.0	-	0	11.1	0.6	35	24
		2013	SR	Kale/Swiss Chard	-	-	-	-	1.9	1.5	-	-	10.8	-	0	19.6	1.1	21	13
Thika	Conv-High	2012	SR	Potato	-	-	-	-	70.1	22.6	-	-	-	60.0	54.0	-	-	124	83
		2013	LR	Maize	-	-	-	-	21.0	6.7	36.0	40.4	-	-	27.0	-	-	84	47
		2013	SR	Cabbage	-	-	-	-	103.0	27.3	-	-	-	40.0	81.0	-	-	184	67
	Conv-Low	2012	SR	Potato	-	-	-	-	25.5	4.8	18.0	20.2	-	-	0	-	-	44	25
		2013	LR	Maize	-	-	-	-	21.9	9.7	9.0	10.1	-	-	0	-	-	31	20
		2013	SR	Kale/Swiss Chard	-	-	-	-	8.3	3.6	-	-	-	10.0	16.2	-	-	24	14
	Org-High	2012	SR	Potato	180.3	35.0	40.2	3.9	90.2	28.2	-	-	59.7	-	-	40.3	2.3	351	129
		2013	LR	Maize	-	-	-	-	89.2	34.5	-	-	43.7	-	-	45.7	2.6	135	81
		2013	SR	Cabbage	-	-	38.4	0.8	192.8	48.0	-	-	48.0	-	-	59.0	3.3	290	100
	Org-Low	2012	SR	Potato	-	-	-	-	19.7	12.5	-	-	24.0	-	-	13.4	0.7	33	37
		2013	LR	Maize	-	-	-	-	31.4	11.9	-	-	12.0	-	-	6.7	0.4	38	24
		2013	SR	Kale/Swiss Chard	-	-	-	-	5.9	1.8	-	-	10.8	-	-	11.8	0.7	18	13

Conv-High conventional high input system, *Org-High* organic high inputs system, *Conv-Low* conventional low input system, *Org-low*, organic low input system, *DAP* Di-ammonium phosphate, *CAN* calcium ammonium nitrate, *TSP* triple superphosphate; *PR* phosphate rock

The set up aimed at arriving at similar amounts of external N and P from the applied inputs in conventional and organic systems. But due to contributions of nutrients from mulch, baby corn or maize stover and *Mucuna,* together with seasonal variations of the nutrient content of FYM and compost the actual final N and P content of both conventional and organic farming systems differed.

Additional management aspects specific to the farming systems are shown in Table 4. Further details of the trial description and management practices can be found in Adamtey et al. (2016).

Table 4: System specific management aspects

Farming systems	Planting density	Green manure crop	Fertilizer		Pest and disease control		Irrigation	Weed control	Mulch	Market
			Type	Rate	Type	Intensity				
Conv-High	One plant per hole	None	INM	High[a]	IPM	High**	Supplementary irrigation*	Hand	None	High value
Org-High	One plant per hole	*Mucuna*	Organic	High[a]	Bio pesticides	High**	Supplementary irrigation*	Hand	Yes	High value
Conv-Low	Two plants per hole***	None	INM	Low[b]	IPM	Low#	Rain-fed	Hand	None	Subsistence and local
Org-Low	Two plants per hole***	None	Organic	Low[b]	Ash and Bio pesticides	Low#	Rain-fed	Hand	None	Subsistence and local

[a]As recommended by research institutions, [b]As practiced by small scale farmers, INM - Integrated nutrient management which include use of Calcium ammonium nitrates, Di-ammonium phosphate or Triple superphosphate and FYM; Organic inputs include compost, phosphate rock, Tithonia and plant teas; *IPM* Integrated pest management; *Irrigation given only during periods of drought; **Based on scouting for pests and diseases;***two plants per hole for maize and beans but one plant per hole for vegetables #pest control based on when the pests and diseases are observed.

4.3.3. Rainfall amount and distribution

Rainfall was measured at each site using a tipping-bucket (installed three meters above the ground) attached to a data logger on an automated weather station (30 minutes interval). Supplementary irrigation (using drip irrigation at a depth of 0.3 m) was given to crops under the Org-High and Conv-High systems during periods of drought and when soil moisture was below 40% of field capacity. Soil moisture was measured using Time Domain Reflectometer (TDR, TRIME-PICO IPH, IMKO GmbH). Maize in the high input systems at Chuka received 102 mm of supplementary irrigation water and cabbage 209 mm ha^{-1}. At Thika, maize received 287 mm ha^{-1} while cabbage received 49 mm ha^{-1} (due to constraints in obtaining irrigation water due to the borehole system breaking down) of irrigation. No irrigation was done during potato cropping at either site because the rainfall amount and distribution were adequate, with no occurrence of drought (more than 15 consecutive days with <1 mm of rainfall) (Adamtey et al., 2016). At Chuka, most of the rainfall was received during the initial 0-30 days after sowing (DAS) for maize and vegetables while at Thika, most of the rainfall was received within 0-20 DAS for maize and 0-30 DAS for vegetables.

4.3.4. Soil, inputs and plant sampling and analysis

Soil samples for site characterization were collected from twelve auger hole points taken diagonally from the net plot (6 by 6m) at 0-20 cm depth before planting potato in 2012. Soil bulk density was determined *in situ* using the core method described by Okalebo et al. (2002). Soil pH (in H_2O) was determined potentiometrically in 2.5:1 water to soil suspensions while electro-conductivity was determined in a saturated paste extract (Okalebo et al., 2002). Organic carbon was determined using Walkley-Black wet oxidation (Anderson and Ingram, 1993). Soil total N content was measured with a SKALAR (SKALAR Analytical B.V. Breda, the Netherlands) segmented flow analyzer at 660 nm wavelength after complete digestion of the samples with a digestion mixture of hydrogen peroxide, sulphuric acid, selenium and salicylic acid, as described by Okalebo et al. (2002). Nitrate-N and ammonium-N were measured using a SKALAR segmented flow auto analyzer at 540 and 660 nm respectively, after extraction with 0.5 M potassium sulphate. Olsen extractable P was determined after extraction of 2.5 g air-dry soil (sieved through a 2 mm mesh) with 50 mL of 0.5 M sodium bicarbonate and the absorbance of the solution measured at 880 nm wavelength (Okalebo et al., 2002). Potassium, calcium and magnesium in soil were analysed with an atomic absorption spectrophotometer after extraction with ammonium acetate (Okalebo et al., 2002). Soil texture was determined using hydrometer method as described by Okalebo et al. (2002).

Compost, FYM, Tithonia and Mucuna samples were air-dried under shade to a constant weight after which they were ground and sieved (<0.25 mm, 60 µm mesh). The air-dried organic inputs (0.3 g) were analysed for total N after digestion with a 2.5 mL digestion mixture as described in Okalebo et al. (2002). Plant N uptake and dry matter accumulation for the different crops at harvest were determined using yield and biomass and their N concentration from the net plot (6 x 6 m, Musyoka et al., 2017). 0.3 g of the oven-dried plant material (yield and biomass) was analyzed for total N after digestion with 2.5-mL digestion mixture as described above. Concentration of total N was obtained using a segmented flow auto analyzer (SKALAR Analytical B.V., BREDA, The Netherlands) after oxidation to NH_4^- (660 nm wavelength). N uptake was obtained by multiplying N concentration (in percent) and the total dry matter yield (economic yield + biomass; kg ha^{-1}).

4.3.5. Nitrate-N movement in the soil profile and leaching beneath the crop root zone

Nitrate-N movement down the soil profile was monitored and sampled at 0-0.2, 0.2-0.4, 0.4-0.6, 0.6-0.8 and 0.8-1.0 m depth before input application, and at the vegetative, tuber initiation, tuber bulking and harvesting stages for potato; at the 6 and 8 leaves stage of maize's vegetative phase and tasseling, silking and harvest, and for vegetables at the 4^{th} - 6^{th} leaf stage, pre-cupping, head formation and harvest. For each sampling depth, soil was collected from three different points selected at random within the net plot (6 x 6 m) and was mixed thoroughly to form a composite sample. Samples for analysis were drawn using the quartering method (i.e. dividing the thoroughly mixed composite samples into four equal parts, with two opposite quarters being discarded and the two other remaining quarters mixed thoroughly, with the process being repeated until the desired sample size was obtained (Campos and Campos 2017). Samples were placed in air-tight polythene bags, labeled and transported to the laboratory in ice chests. Mineral-N (NO_3^--N and NH_4^+-N) was extracted from 10 g of fresh soil using 50 mL of 0.5M K_2SO_4. The soil solution was then filtered through Whatman No. 42 filter paper and the solution stored in a refrigerator until analysis. Nitrate-N and ammonium-N were measured as described above. Nitrate-N and ammonium-N data were used to compute the nitrate-N to ammonium-N ratio, which is an indicator of N transformation during cropping period (Supplementary S3).

Different methods have been used to measure leaching in the field. These include drainage lysimeters, sampling soil solutions using ceramic suction cups or pan samplers, the soil coring method (Ramos and Kücke, 2001) and use of exchange resins. such as self-integrating accumulators (SIA) (Bischoff, 2009). These methods have advantages and limitations in their use. The current study used self-integrating cores (SIA, Pat. No. 19726813, Federal Republic of Germany) that use both cation and anion resin mixed with quartz (Bischoff, 2009). The advantage of this method, compared to those mentioned above, is that the resin cores closely represent the soil water fluxes under field conditions and allow the measurement of cumulative N leaching in undisturbed soils (Bischoff, 2009). The method combines the use of anion and cation resins, which have been shown to satisfactorily recover NO_3^- and NH_4^+ in leachates; it is also cost effective and maintenance free. However, the process of installing resin cores is laborious, and the method can only be used for longer-term monitoring of cumulative N leached (not less than a month or a whole cropping season).

Self-Integrated Accumulation (SIA) cores were used to trap the leached NO_3^--N beneath the crop root zone, as described by Bischoff (2009). Cores of 0.1 m diameter and 0.1 m height were cut from PVC pipes. One side of the pipes was fitted with a nylon fine net (50 µm) to prevent loss of content. A mixture of fine (0.001-0.005 m) and medium (0.003-0.015 m) river sand particles were washed thoroughly with running water until the solution ran clear. The sand was then soaked in 2 M HCl for 3 days to destroy soil organic matter. Afterwards the sand was thoroughly washed in clean running water, rinsed with distilled water, then dried and mixed with resin beads (Resinex™ Mx-11, Jacobi Carbons GmbH, Germany) at a ratio of 1:2 (dry weight basis) and the mixture was used to fill the PVC cores.

Profiles each measuring 1 m wide, 1.2 m length and 1.2 m depth were dug at the outer edge of each of the plots. Four tunnels each measuring 0.2 x 0.2 x 0.2 m were dug (2 under the plant rows and 2 in between the plant rows) in each profile at 1 m depth (Supplementary S2). To ensure that the SIA cores were installed in undisturbed soils (since an intact pore system is crucial for water movement in the soil profile) the tunnels were aligned with treated river sand (fine 0.001-0.005 m, and medium 0.003-0.015 m) to fill the space surrounding the cores. This also ensured that any lateral movement of N would be captured and trapped in the sand, since we were only interested in the vertical nitrate-N movement in the sand-resin mixture. The profiles were then refilled with soil which was compacted to normal bulk density. The SIA cores were installed at the start of each cropping season and remained in place for the entire growth period of the crops under investigation.

The SIA cores were retrieved at the end of each cropping season and the sand-resin mixture in the cores was split into three segments i.e. i) top 0.05 m, ii) middle 0.01 m, and iii) the bottom 0.04 m (following Bischoff, 2009). According to Bischoff (2009), leached nitrate-N is trapped in the top 0.05 m segment with minimal amounts being trapped in the middle 0.01 m segment. Nitrate-N and ammonium-N adsorbed by the sand-resin mixture was extracted from the upper and middle samples using 0.5M K_2SO_4 (potassium sulphate) (following Bischoff's 2009 recommendation) and quantified using a segmented flow autoanalyzer (SKALAR® Analytical B.V., Breda, the Netherlands) at 540 nm and 660 nm wavelengths, respectively. Nitrate-N leached through the profile was then extrapolated to hectares, based on the surface area represented by the SIA cores.

4.3.6. N input, output, and surface N balance

4.3.6.1. N inputs and outputs

Nitrogen inputs into a farming system consist of all the N forms that were added to the soils over the crop rotation. These include N from mineral fertilizer (N_f), FYM (N_{FYM}), organic inputs (N_{org}) such as crop residues, compost, green manure crops and mulch, N from atmospheric deposition - wet (rainfall and snow) and dry (absorption of ammonia and other compounds), (N_{ad}), N from irrigation water (I_w), biological N fixation (N_{bf}), N from Seed (N_s), N from litter fall (N_{lf}), N from mineral weathering and deep soil exploitation (N_{mw}), and N from soil sedimentation (N_{sd}) (Fig. 1). In this manuscript total N input over the whole crop rotation (six cropping seasons for the period March 2011- March 2014) was determined by adding all the N from the inputs that were applied to the crops for each cropping season. The crops in the rotation for the period 2011-2013 are as shown in Table 3.

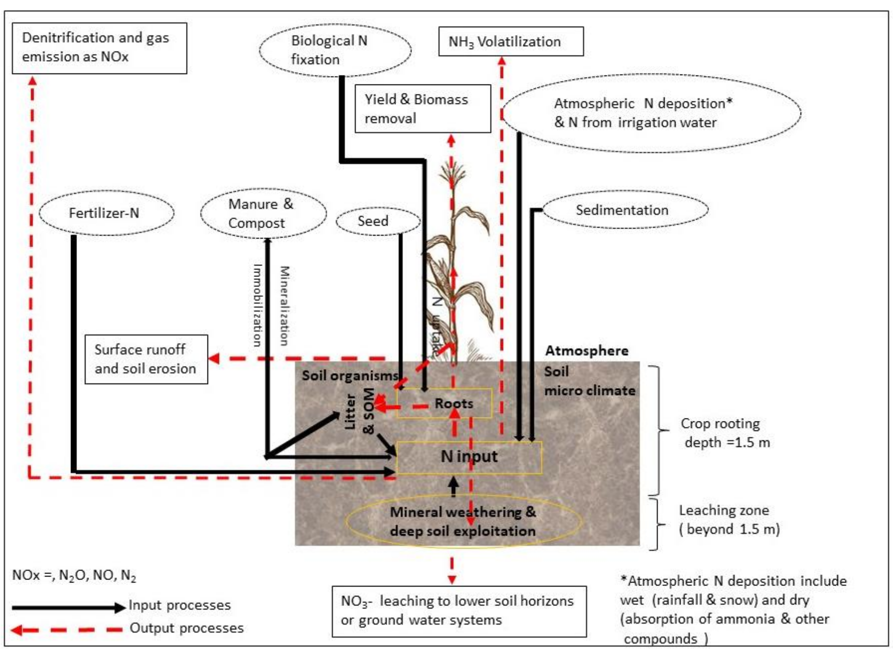


Fig.1: Outline of plant-soil-systems and N input and output (N flows) in a maize cropping system in the long-term system comparison trial plot in Kenya.

In conventional systems (Conv-High and Conv-Low), N applied from fertilizer and FYM (N_{conv}) was calculated as follows:

N_f (kg N ha^{-1}) = $N_{c\,f}$ x $Fertilizer_{DM}$ .... Eq. 1

N_{FYM} (kg N ha^{-1}) = $N_{c\,FYM}$ x FYM_{DM} .... Eq. 2

N_{conv} (kg N ha^{-1}) = $N_f + N_{FYM}$ .... Eq. 3

In organic systems (Org-High and Org-Low) the N applied from organic inputs (N_{org}) was calculated as follows:

N_{org} (kg N ha^{-1}) = ($N_{c\,Mucuna}$ x $Mucuna_{DM}$) + ($N_{c\,Tithonia}$ x $Tithonia_{DM}$) + ($N_{c\,comp}$ x $Comp_{DM}$) ...Eq. 4

Where

$N_{c\,f,}$ $N_{c\,FYM}$, $N_{c\,Mucuna}$, $N_{c\,Tithonia}$, and $N_{c\,Comp}$ are the corresponding concentrations of N in fertilizer, FYM, Mucuna, Tithonia and compost respectively.

N output was calculated based on the N content of all the removed biomass. Total N export for a rotation was determined by adding all the N loss through crop removal per season from the field (Eq. 5). In the high input organic system (Org-High) the different crops (maize, baby corn, French bean and potato) residues were recycled into the systems as compost and/or mulch. N export in Org-High was calculated only from the maize grain, cobs and husks, baby corn cobs, cabbage head and biomass and French beans pods. In conventional systems (Conv-High, Conv-Low) and low input organic system (Org-Low) all the crop biomass from maize, beans and vegetables were removed from the plots but potato biomass was retained.

Total N output ($N_{YBl,}$ kg ha^{-1}) = $N_{c\,yb}$ x YB_{DM} ....Eq. 5

where

$N_{c\,yb}$ is N content of yield and biomass and YB_{DM} is the dry matter of yield and biomass, N_{YBl} = N loss from yield and biomass removal.

4.3.6.2. N balance

Accounting for N inputs and outputs in the soil at plot, farm or regional levels provides N budgets (balances) that measure the flows of N in agroecosystems and account for differences in losses and retention of N thereby providing information on agroecosystem performance and environmental sustainability. In this study, we calculated surface N balance as reported by van Beek et al. (2003) and Prasad and Badarinath (2006)(Eq. 5). The assumptions that were made during the calculation were as shown below.

Assumptions made in N balance calculations:

N inputs from soil mineral weathering, deep soil exploitation and change in N stock were not considered. The N input from seeds, litter fall and sediments was ignored because they are often small. Besides, the plots were not in low land areas to receive run off water and sediments. Atmospheric N (NO_3^- and NH_4^+) deposition was calculated based on rain water analysis collected in Embu by the Crop Nutrition Laboratory Services (CNLS) in Nairobi. Although the study sites are few kilometres from Embu, N concentrations could be similar since both sites have similar agroecological conditions. Hence, values measured for NO_3 (0.02 to 0.5 mg N kg^{-1}) and NH_4 (0.02 to 0.3 mg N kg^{-1}) were averaged and multiplied by the total precipitation received over the 6 cropping seasons in the study sites (Eq. 6). N input from irrigation water was ignored because it was assumed to be negligible. Biological N fixation by Mucuna, French and common beans was calculated according to the procedure of Sainju et al. (2017; 2018). To determine N fixation by Mucuna (Eq. 7) it is assumed that 74% of the total N uptake by Mucuna was fixed whilst the remaining 26% was derived from the soil (Sanginga et al., 1996). Also, because below ground biomass was not measured, it is assumed that the roots constitute one-third of the aboveground biomass hence the value of 0.33 x total Mucuna aboveground biomass N was used to estimate the below ground biomass N . Similarly, to calculate the N fixed by beans (Eq. 8), it is assumed that 50% of N taken up by the aboveground biomass was fixed and the remaining 50% derived from the soil (Rondon et al., 2007). A value of 0.2 x total beans aboveground biomass N was assumed to estimate the belowground biomass N based on the observation of Wandera et al. (2016).

(2016) that root weight of common beans (var. GLP 92) constitute 20 % of the aboveground biomass. Even though there may be possibility of N loss via denitrification, it was not considered because the surface soil was well drained. Although there is the possibility of localized N volatilization occurring due to an increase in pH after FYM or compost application (Choi et al., 2007), ammonia volatilization was not considered because it mostly occurred at pH above 8 (Zhenghu and Honglang, 2000) and in our case the soil pH were below 7. N loss from run off and erosion were excluded in our calculation because the land was flat with a slope less than or equal to 2%.

N deposition from rainfall (kg N ha^{-1}) = $NO_3^-{}_R + NH_4^+{}_R$ (mg l^{-1}) x ∑Rainfall (litres) ....Eq. 6

Where $NO_3^-{}_R + NH_4^+{}_R$ are average mineral N concentrations in rainwater.

N fixation by Mucuna (kg ha^{-1}) = 0.74 x aboveground Mucuna biomass N x 1.33 …………Eq. 7

Where 0.74 is the proportion of N fixed by Mucuna (based on the above assumptions) and 0.33 accounts for root N inputs.

N fixation bean (kg ha^{-1}) = 0.5 x aboveground bean biomass N x 1.2……………………….Eq. 8

Where 0.5 of N fixed by beans (based on the above assumptions) and 0.2 accounts for root N inputs.

The surface N balance (SNB) was assessed for all the farming systems at plot levels using (Eqs. 9 and 10). The balance if it is positive or surplus (i.e. output < inputs) indicates the system is enriching the soil N; and when negative or deficit (i.e. output > inputs) indicate the system is depleting the soil N.

SNB_{Conv} (kg N ha^{-1} yr^{-1}) = $(N_f + N_{FYM} + N_{ad} + N_{bf})$- (N_{YBl})…………………………......Eq. 9

SNB_{Org} (kg N ha^{-1} yr^{-1}) = $[(N_{org} + N_{ad} + N_{bf})$ - $(N_{YBl})]$ ………………………………..….Eq. 10

where

N_{conv} = N in conventional systems i.e. N_f = Fertilizer, N_{FYM} = N from FYM applied in conventional systems, N_{ad} = atmospheric deposition, N_{bf} = biological N fixation; N_{org} = N from organic inputs (compost, Tithonia mulch and plant tea, Mucuna biomass and crop residues), N_{ad} = atmospheric deposition, N_{bf} = biological N fixation

4.3.7. Statistical analysis

Data on NO_3^--N movement in the soil profile were tested for normality using the Shapiro-Wilk test before analysis (Crawley 2007). Analysis to compare NO_3^--N movement in the soil at each sampling date and for each site was done with a linear mixed model using the farming system and soil depth as fixed factors, while replication was treated as a random factor. To account for auto-correlations and possible heterogeneous variances among observations taken on the same plot over time, the linear mixed model was fitted with a random intercept and slope to the data using the *lmer* function from the R (version 2.15.2) of the *lme4* package (Bates et al., 2013). A log-likelihood test indicated that the simpler random intercept model was not adequate for all the three variables analysed. Least squares means and standard errors (at a 95% confidence interval for the farming systems, various soil depths and different time points) were obtained using the *lsmeans* function in the *lmerTest* package (Kuznetsova et al., 2013) of R i386 3.1.1 (R Development Core Team. 2014). In addition, analysis of variance (ANOVA) was performed on cumulative N leached, N input, output and soil surface N balance using a linear mixed-effect model with *lmer* function from the package *lme4* in R statistical software (Bates et al., 2013) with the site and system as fixed effects and replication and the interaction effects as random effects. Least square means were computed using *lsmeans* package, followed by mean separation using adjusted Tukey's method implemented in the "*multicompView package" for cld* function, as developed by Graves et al. (2015) in R software version R i386 3.1.1 (R Development Core Team. 2014).

4.4. Results

4.4.1. The influence of cropping systems on NO_3^--N movement in the soil profile

Cumulative rainfall amount was highest and well-distributed at Chuka during potato cropping period (905 mm), while more rain was received in the initial 30 DAS during the maize and vegetable cropping period (Fig. 2). Even though the site at Thika received less rain than Chuka, there was highest rainfall during the maize cropping period (637 mm) during the initial 20 DAS at Thika. Rainfall distribution was fairly good during the potato cropping period, while the vegetables experienced a drought spell from 30-90 DAS.

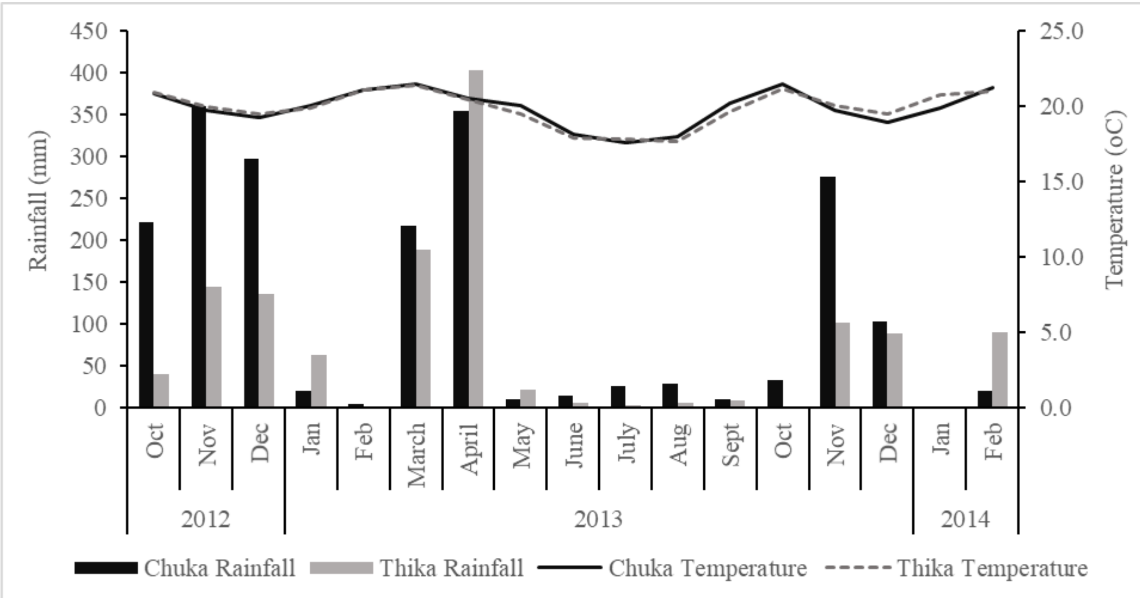


Fig. 2: Cumulative rainfall patterns (from planting to harvesting) during the three cropping seasons in the long-term systems comparison trial at Chuka and Thika in the Central Highlands of Kenya (Musyoka et al., 2019)

Potato: At Chuka site, NO_3^--N concentrations over 0-0.8 m depth ranged from 3 to 16 mg N kg^{-1} soil for all the systems at the time of planting, with higher values at 0.8-1.0 m (Fig. 3). At the vegetative stage, NO_3^--N concentrations at 0-0.8 m depth increased to 11-25 mg N kg^{-1}. There were no significant differences in the NO_3^--N concentration among the systems, with the exception of Org-High, which showed a higher (P<0.001) NO_3^--N concentration at depths of 0.4-0.8 m at Chuka (Fig. 3b). All the farming systems showed lower (P< 0.001) NO_3^--N concentrations in the topsoil at the tuber initiation stage than at the vegetative stage (Fig. 3c). At maturity, NO_3^--N concentrations in the soil profile increased to 23-31 mg N kg^{-1} in all farming systems (Fig. 3d). The soil profile NO_3^--N concentrations at both sites showed similar patterns and trends, but the concentrations at Thika site were generally higher, particularly during vegetative and tuber initiation stages (Fig 3).

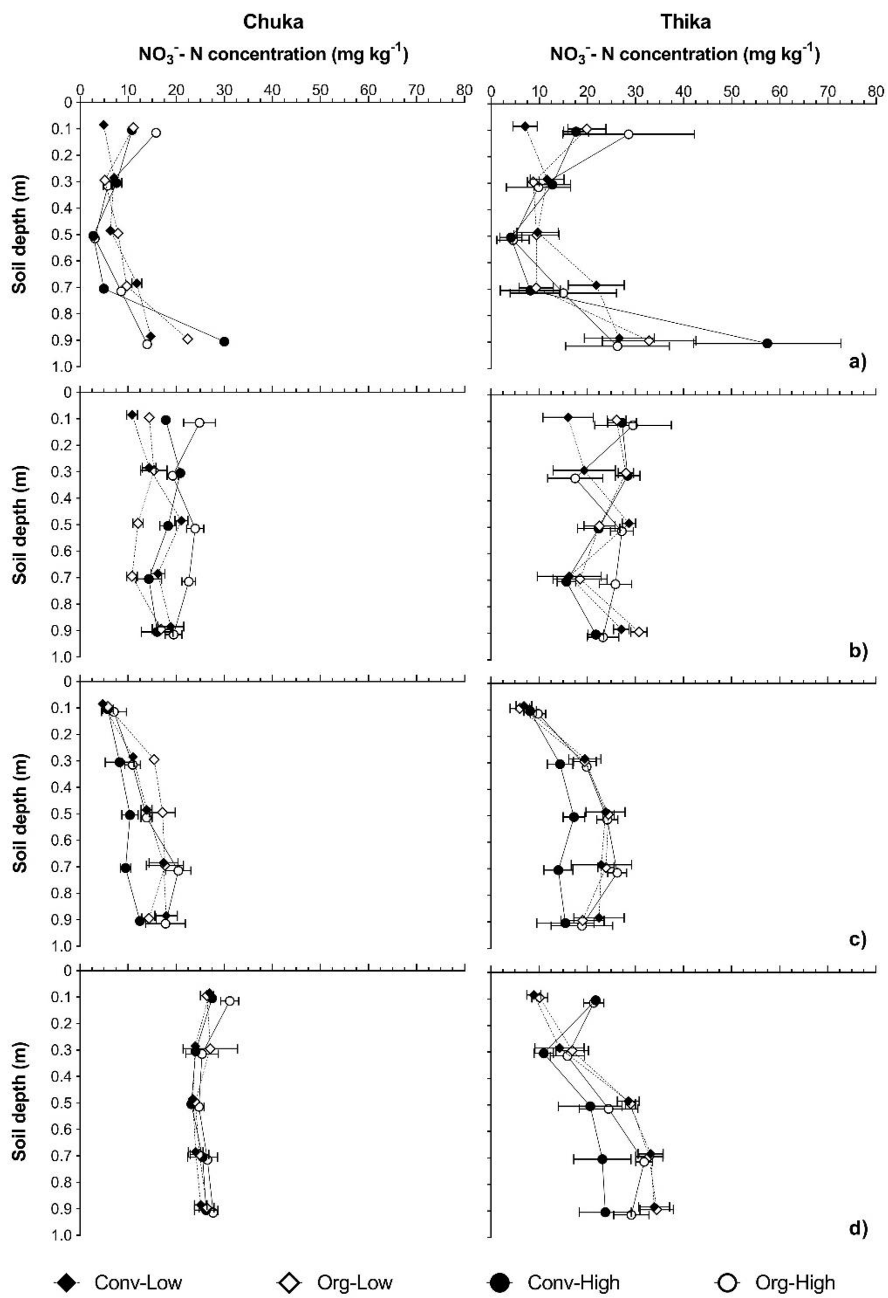


Fig. 3: Soil nitrate-N in the soil layers at different potato growth stages: a) before planting, b) vegetative, c) tuber initiation and d) harvest in the long-term systems comparison trail at Chuka and Thika in the Central Highlands of Kenya

Maize: At Chuka, high NO_3^--N concentrations, of 69-82 mg N kg^{-1}, were observed across the soil profile for all farming systems before planting maize (Fig. 3). These concentrations declined significantly at the vegetative, silking/tasseling and harvesting crop stages to 3-18 mg N kg^{-1}. NO_3^--N concentrations across the soil profile were lower at Thika than at Chuka before planting maize (14-64 mg N kg^{-1}). The NO_3^--N concentration at vegetative, silking/tasseling and harvesting crop growth stages showed similar patterns and trends at the two sites but were generally higher at Thika than at Chuka.

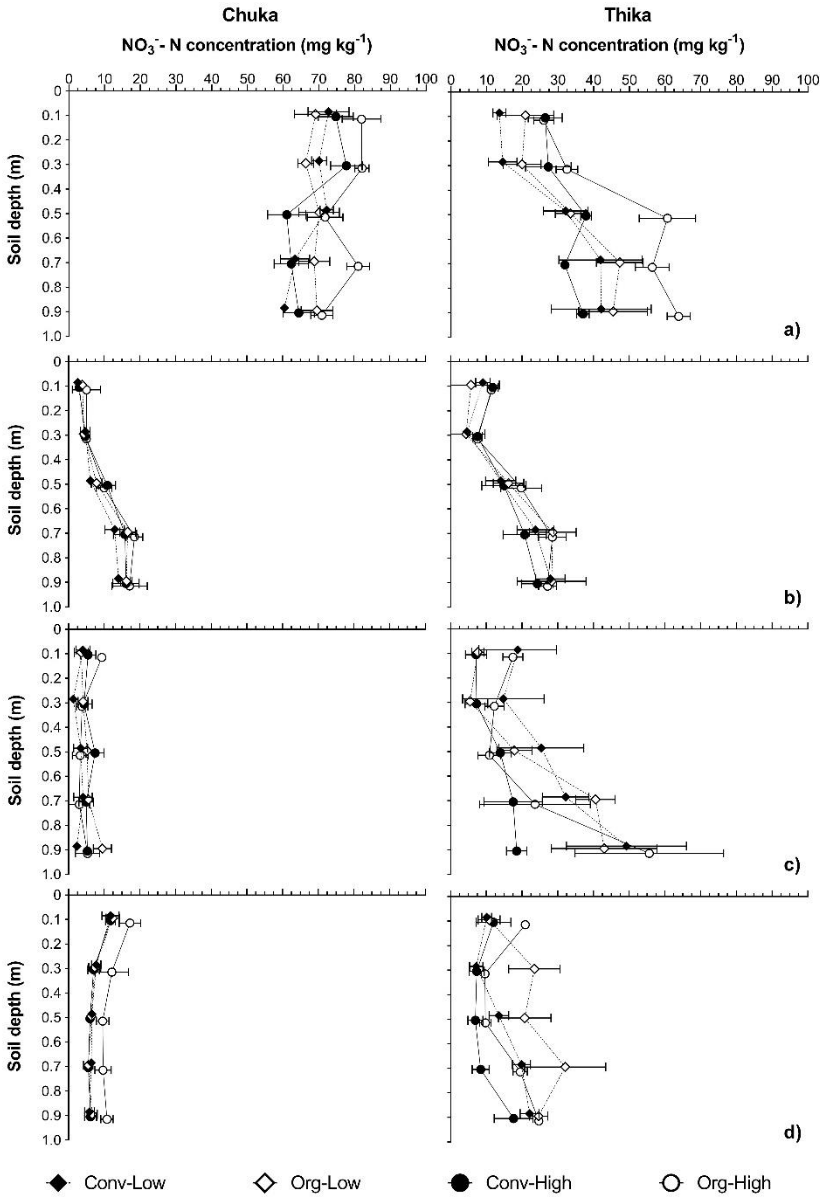


Fig. 4: Soil nitrate-N in the soil layers at different maize growth stages: a) before planting, b) vegetative, c) tasselling/silking and d) harvest in the long-term systems comparison trail at Chuka and Thika in the Central Highlands of Kenya.

Vegetables: *Vegetables*: NO_3^--N concentrations were generally low (<10 mg N kg^{-1}) during the vegetable (cabbage, kale and Swiss Chard) cropping period (Fig. 5). At Chuka, NO_3^--N in the top soil ranged between 3.3-8.9 mg N kg^{-1}. At the vegetative stage, NO_3^--N concentrations in the top soil declined significantly (<4 mg N kg^{-1}) but there was also an increase (P<0.001) in the NO_3^--N concentration at 0.6-1.0 m soil depth. By contrast, at the head formation stage of cabbage (corresponding to the development of harvestable vegetative plant parts for kale and Swiss chard), NO_3^--N concentrations in the top soil increased, with a higher (P<0.001) concentration in Org-High system than the other systems. At Thika NO_3^--N concentrations at 0-0.6 m depth before planting vegetables were lower (3 mg N kg^{-1}) than at Chuka (Fig. 5a). NO_3^--N concentrations were higher at a depth of 0.6-1.0 m (P<0.001) in all the systems at this site. At the vegetative stage, NO_3^--N concentrations in the topsoil depth were higher than those observed at planting (Fig. 5a-b). At the head formation and harvesting stages, NO_3^--N concentrations at 0-0.4 m depth were similar for all the systems at Thika (Fig. 5c-d).

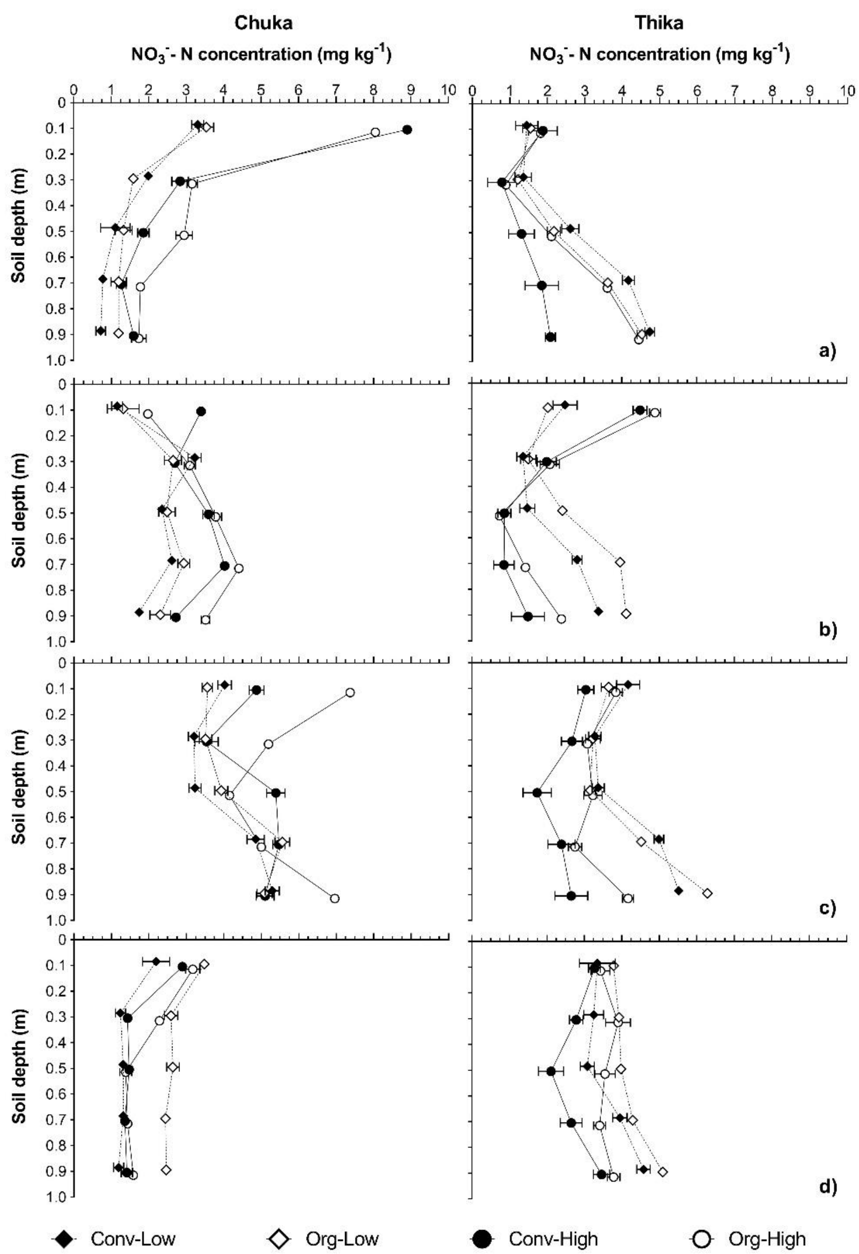


Fig. 5: Soil nitrate-N in the soil layers at different vegetable growth stages: a) before planting, b) vegetative, c) head formation and d) harvest in the long-term systems comparison trail at Chuka and Thika in the Central highland of Kenya

4.4.2. Cumulative NO_3^--N leached under the different cropping and farming systems

A total of 22-38 kg ha^{-1} of NO_3^--N was leached beyond 1 m depth during the potato cropping period, being more (P<0.001) than during the maize (0.9-5.7 kg ha^{-1}) and vegetable (1.9-2.9 kg ha^{-1}) cropping periods (Table 5). Expressed as a percentage of the total N applied, the NO_3^--N leached represented a loss of an average of 80% N from Conv-Low and Org-Low during potato cropping period, significantly more (P< 0.001) than the 15% of applied N leached from Conv-High and Org-High (Table 5). In contrast, there were no significant differences in N leached as a percentage of the total N applied during the maize and vegetable cropping seasons. When the cumulative N lost over the three cropping seasons was expressed as a percentage of the total N applied, more (P<0.001) NO_3^--N was lost from the low input systems (25-50%) compared to the high input systems (4-9%). In addition, significantly more N (P<0.01) was lost through leaching at Thika than at Chuka.

Table 5: Cumulative N leached during potato (October 2012-March 2013), maize (April-September 2013), and vegetable (October 2012-March 2013) cropping season in the long-term system comparison trial at Chuka and Thika in the Central highland of Kenya

		N leached			N leached expressed as percentage of total N applied				
		Potato	Maize	Vegetables	Potato	Maize	Vegetables	Cumulative N leached	Cumulative N leached expressed as percentage of total N applied
		kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	%	%	%	kg ha^{-1}	%
	Crops	31.0 a	2.0 b	2.5 b					
Farming systems									
	Conv-High	27.6	3.37	2.61	20.2 b	3.2	2.0 b	33.6	8.6 b
	Org-High	34.6	1.61	2.59	10.1 b	0.8	1.1 b	38.8	4.9 b
	Conv-Low	32.3	1.65	2.26	83.4 a	3.4	9.7 a	36.2	33.9 a
	Org-Low	29.5	1.25	2.47	78.6 a	10.5	12.7 a	35.9	38.2 a
Sites									
	Chuka	26.1	2.97 a	2.63	37.9	3.6	6.8	31.6	16.3 b
	Thika	36.0	1.00 b	2.34	58.2	5.4	5.6	40.6	26.5 a
Sites x Farming systems									
Chuka	Conv-High	22.9	5.65	2.93	14.3	5.0	2.6	31.5	8.1
	Org-High	31.8	2.28	2.41	9.5	0.9	1.2	36.5	4.6
	Conv-Low	26.5	2.34	2.60	80.3	3.7	11.3	31.5	26.4
	Org-Low	22.8	1.61	2.55	47.5	4.6	12.1	27.0	25.9
Thika	Conv-High	32.3	1.09	2.28	26.0	1.3	1.3	35.7	9.1
	Org-High	37.3	0.94	2.77	10.6	0.7	1.0	41.1	5.3
	Conv-Low	38.0	0.96	1.91	86.4	3.1	8.0	40.9	41.3
	Org-Low	36.2	0.9	2.39	109.7	2.4	13.3	44.8	50.4
Sources of variations									
System		ns	ns	ns	***	ns	***		***
Site		ns	*	ns	ns	ns	ns		**
Site x System		ns	ns	ns	ns	ns	ns		ns

Conv-High conventional high input system, *Org-High* organic high inputs system, *Conv-Low*, conventional low input system, *Org-low* organic low input system, *Ns* not significant
*P<0.05; **P<0.01; ***P<0.001; a, b, c are used to compare means

4.4.3. Impact of the farming systems on surface N balance

N input and output: Over the full rotation of six seasons in three years (March 2011 to March 2014), the total N supplied to Org-High was 57 and 82% higher ($P < 0.001$) than the amount supplied to Conv-High at Chuka and Thika respectively (Table 6). FYM and mineral fertilizer constituted 46 and 48% of the total N applied in Conv-High respectively, with less than 4% from biological N fixation (BNF). In Org-High organic inputs (compost, Tithonia tea, mulch, and Mucuna biomass) provided 88% of the total N applied with 11% being from BNF. The total N inputs over the rotation in Org-Low and Conv-Low were similar, with 55% of the total N applied coming from FYM, while 9 to 16% from biological N fixation (BNF) in Conv-Low and 10 to 37%

in Org-Low. The fraction of atmospheric N deposition was low (ranging from 0.5 to 1.7% of the total N applied) in all the systems. At both sites, a comparable amount of total N applied in Conv-High was exported from the field whilst in Org-High the fraction exported constituted 32 to 41% of the total N applied. The amount of N exported from the low input systems was 60 to 160% above what was applied. The surface N balance over one complete rotation showed negative balance for all the systems except Conv-High at Chuka, and Org-High which showed a positive N balance of 797 and 1263 kg N ha^{-1} at Chuka and Thika respectively – constituting 59-68% of the total N applied in Org-High. There was a strong positive correlation between the N from BNF (r = 0.88; $P < 0.001$) or the N from organic inputs (r = 0.91; $P < 0.001$) and the positive N balance in Org-High.

Table 6: Nitrogen balances in different farming systems after one crop rotation (six cropping seasons for the period March 2011 – March 2014) in the long-term system comparison trial at Chuka and Thika in the Central Highlands of Kenya

	Chuka				Thika				System	Site	System x Site
	Conv-High	Org-High	Conv-Low	Org-Low	Conv-High	Org-High	Conv-Low	Org-Low			
N input											
[1]N in Org inputs (kg ha^{-1})	357	1201	147	118	564	1644	125	158			
[2]N in mineral fertilizer (kg ha^{-1})	414	0	61	0	414	0	61	0			
[3]N in wet deposition (kg ha^{-1})	15	15	15	15	10	10	10	10			
[4]Total N fixation by legumes (kg ha^{-1})	81	143	43	77	40	213	18	20			
Total Inputs (kg ha^{-1})	867d	1359b	266e	211e	1028c	1867a	214e	188e	***	***	***
N outputs (kg ha^{-1})											
[5]Total N export (kg ha^{-1})	856a	562bc	525bc	546bc	1035a	604b	343c	326c	***	ns	**
Soil surface N balance											
[6]N balance (kg ha^{-1})	11c	797b	-259cd	-335d	-40cd	1263a	-134cd	-117cd	***	***	**

Conv-High conventional high input system, *Org-High* organic high inputs system, *Conv-Low*, conventional low input system, *Org-low* organic low input system
[1]N in organic inputs includes N from FYM in conventional systems; Mucuna biomass, tithonia applied as mulch or plant tea, crop residues and mulch;
[2]N in mineral fertilizer includes N applied as diammonium phosphate and calcium ammonium nitrates;
[3]Calculated as N deposit from rainfall
[4]N fixation from French bean in conv-High; Mucuna and French bean in Org-High and common beans in Conv- and Org-Low (Sanginga et al. 1996; Rondon et al. 2007; Wandera et al. 2016)
[5]N output in Baby corn was mainly from harvested cobs, tops removed during grading and stover except in Org-High where baby corn stover was used for composting; N output in maize/bean intercrop in the low input systems was from grain, cobs and above ground stover N output from potato was from tuber as haulms were left in the field; N exported from maize was from grain and above ground stover except in Org-High where N export was mainly from grain and cobs, since maize stover was used in compost preparation and 2 t ha^{-1} incorporated before the vegetable season; N export was mainly from above ground biomass for vegetable season (*calculated based on yield and N uptake levels reported in Musyoka et al., 2017)*
[6] N balance was calculated as Total N input – Total N output
Numbers followed by different letters in a row are significantly different. *Ns* not significant; *P<0.05; **P<0.01; ***P<0.001

4.5. Discussion

4.5.1. The effects of cropping systems on Nitrate-N movement

The high NO_3^--N concentrations at 0 to 0.8 m depth observed at the time of planting the potatoes could have been due to residual effects from the previous crop (baby corn in the high input systems and maize-bean intercrop in the low input systems). The subsequent increase in NO_3^--N concentration during the vegetative growth stages of potato can be attributed to mineralization flushes from the applied inputs (as measured by Musyoka et al., 2019). Zebarth and Milburn (2003) also observed a build-up of NO_3^--N from 0-50 days after planting potatoes when N was applied at planting, and reported that the risk of N losses was lowered with split N applications. The observed decrease in NO_3^--N concentration in the top soil at the tuber bulking stage was partly due to the large N demand of potato during this stage (Musyoka et al., 2017). Increases in NO_3^--N levels of 0.6-1.0 m suggest that there were N losses to lower soil layers, probably due to the high rainfall experienced during the short rain season at both sites. This could also explain the low NO_3^--N concentration observed in the top soil at tuber bulking stage. The NO_3^--N level was higher at Chuka than at Thika during the maturity stage of potato and this was probably due to low N uptake of potato (Musyoka et al., 2017) caused by late blight disease at Chuka, which reduced the ability of the crop to take up nutrients. This could also explain the higher residual N observed after the potato crop. This is in line with the findings of Zebarth et al. (2003) who found higher NO_3^--N levels at planting when the previous crop was potatoes and lower NO_3^--N when the previous crop was maize.

At maize planting, the high NO_3^--N concentrations throughout the soil profile were clearly a residual effect from the potato cropping period. Subsequent lower NO_3^--N concentrations observed at the vegetative stage of maize crop, particularly in the upper soil layer, provide an indication of high crop N demand coupled with poor root development to lower depths at this stage.

Nyamangara et al. (2007) also observed higher NO_3^--N concentrations at lower depths (below 0.4 m) at the vegetative stage of maize crop. On the other hand, the fairly high NO_3^--N concentrations in the soil profile at the reproductive stage of the crop, especially in the low input systems at Thika, can be explained by low N uptake as a result of stunted crop growth due to prolonged drought (Musyoka et al., 2017).

In the vegetable cropping period, generally low NO_3^--N concentrations were observed along the soil profile at most growth stages, which can be explained by the N supply being insufficient to meet crop demand (insufficient-asynchrony) during the reproductive stages of the vegetables, especially in cabbage grown in the high input systems (Musyoka et al., 2019). Kristensen and Thorup-Kristensen (2004) reported that white cabbage developed profuse and extensive roots that grow to a depth of 2.4 m to take up nutrients, which is in line with our observations of low concentrations of NO_3^--N in the lower soil profile. In all the cropping seasons, the potential for NO_3^--N losses was observed at the early stages of crop development, an indication that there is a need to assess N application to coincide with periods of rapid N uptake and reduce the possibility of N losses (Zhaohui et al., 2012; Musyoka et al., 2019).

4.5.2. The effect of farming systems on N leaching and surface N balances

Cumulative NO_3^--N leached during potato cropping (23-32 kg N ha^{-1}) from conventional systems was within the range (5-33 kg N ha^{-1}) reported in Minessota (United States) by Zvomuya et al. (2003) but below the 50 kg N ha^{-1} reported by Haas et al. (2002) in conventional, integrated and organic farming systems under potato cropping in north-western Germany. When cumulative N leached was expressed as a percentage of N applied, the low input systems lost between 79 and 83% more N through leaching than 10-20% in the high input systems. The differences in the percentage of N leached can be attributed to asynchrony between N release and crop N demand

(Musyoka et al., 2019), poor plant development and N uptake in the low input systems (Musyoka et al., 2017).

The low level of cumulative N leached during maize cropping period in all the farming systems could be explained by the low N release from the added inputs at reproductive stage of maize (insufficient-asynchrony, as reported by Musyoka et al. (2019) coupled with low rainfall, resulting in lower drainage. In addition, the immobilization of N observed during the early stages of maize development (Musyoka et al., 2019), especially at Chuka, could have reduced potential N losses at this stage when crop N demand was low. The cumulative NO_3^--N leached during the maize cropping period , expressed as a percentage of total N applied, was between 0.7 and 5%, at the lower end of the range of 3-40% reported by Nyamangara et al. (2003) for maize cropping systems in Zimbabwe. The differences in our results could be attributed to the soil types, which in our study were high clay soils, compared to the sandy soils in their study.

Low cumulative NO_3^--N leached during the leafy vegetable cropping period could have been due to high N demand of cabbage, coupled with insufficient N supply to meet crop demand (insufficient-asynchrony) during the reproductive stages of vegetables (as reported by Musyoka et al., 2019). This is supported by the low NO_3^--N concentrations observed along the soil profile at most growth stages in this study. In addition, low rainfall and uneven distribution resulted in low drainage and could explain the low levels of NO_3^--N leached during this cropping period.

The higher amounts of cumulative NO_3^--N leached under potato than the other two cropping systems could have been due to the high amount and well distributed rainfall received during the potato cropping period, as well as the shallow rooting depth of potato. The higher cumulative NO_3^--N loss revealed significant economic losses of N and highlights the need to improve management practices in all the farming systems. Potential solution would be to reduce N application at planting and vegetative stages of the crop when highest N movement and excess asynchrony occurred and supplying the N at reproductive stages of the crop when crop N demand is highest (Musyoka et al., 2019). There is further a need to take into consideration seasonal effects on the nutrient content of inputs (Musyoka et al., 2019) as this leads to uncertainty of the amount of N applied and were the main cause of the positive soil surface N balances under Org-High.

Even though equal amounts of N were expected to be applied to both Conv-High and Org-High, more N was effectively supplied throughout the entire rotation in Org-High (Table 6). The difference in N inputs could be attributed to contributions of Mucuna and variations in FYM quality due to seasonal effects. From 2007 to 2012, Mucuna N fixation and N contribution from its biomass were not considered as part of the N sources in Org-High, yet Mucuna N fixation and biomass accounted for 12-20% of the total N applied in Org-High. Similarly, the feeds given to animals varied from season to season and this was observed to influence the quality of FYM and composting materials (data not provided). Besides the high N inputs in the Org-High, the above result gave an indication that we can meet the N requirement of crops through the use of compost, nitrogen fixing legumes and N-based shrubs as tea and mulch. However, in order to avoid over application of N (as in Org-High) or under application (as in Org-Low), we have been analyzing the inputs (since 2013 to date) before application. This is however associated with high costs which is unaffordable to small scale farmers. It is therefore important to come out with a model that will guide the application of organic inputs (taken into consideration seasonal effect on the quality of composting materials and FYM).

The high amounts of N exported from Conv-High, Conv-Low and Org-Low could be attributed, apart from yield N offtake, to the complete removal of crop residues from the field for use as animal feeds (Adamtey et al., 2016). The same reason contributes to the negative N balance (net N loss) in the above-mentioned farming systems. This result revealed that the current practices of farmers, as mimicked by Conv-High, Conv-Low and Org-Low, cannot help to achieve sustainable agriculture production. Thus, to improve and maintain soil fertility (N) and to assure successful integration of livestock into farming systems in Kenya and its surroundings, research is needed to better understand which folder crops can serve as alternative sources of feeds as well as educating farmers in management of crop residues and FYM handling to reduce N loss.

In both Conv-High and Org-High, equal amounts of FYM were used (22 t year^{-1}, applied as decomposed FYM in Conv-High and similar amount was combined with crop residues and other materials to produce compost which was used in Org-High) but there was a positive N balance under Org-High where compost constituted between 49 and 68% of the total N applied. Although this can partly be due to the lower amount of N applied in the Conv-High, it could also mean that the use of FYM combined with crop residues (as compost) in addition to nitrogen fixing crops and Tithonia has the potential to improve soil fertility. Our results differs with those reported by Tully and Lawrence (2011) in Costa Rica that N balances were higher and positive in conventional compared to organic coffee systems. Negative partial N balances were also reported in organic and conventional farming systems in high potential regions of central Kenya where only N application via compost and liquid manure was considered as inputs in organic systems and FYM and fertilizer in conventional systems (Onduru et al., 2002). The negative surface N balances observed in conventional systems and Org-Low could result in N mining in the system causing the systems to be unsustainable. There is therefore the need to more efficiently manage these systems , including the introduction of more grain legumes in the rotation and an increase in N application rates in the low input farming systems. In Org-High, the surplus N accumulation could pose a potential risk to the environment. However, the non-significant differences in the cumulative N loss between Conv-High and Org-High means that the surplus N in Org-High was probably stored in the soil in organic forms hence the relatively low N loss. Thus, we can deduce that Org-High is more sustainable and that management practices in soil inputs application and cropping systems design play a crucial role in determining the sustainability of farming systems.

4.5.3. The effects of the environment on N leaching and the soil surface N balance

NO_3^--N levels were higher at Chuka than at Thika at the time of harvesting potato, which can be explained by lower potato yields as a result of late blight (as explained earlier). The (slightly) higher rainfall at Chuka during the maize cropping period contributed to more cumulative leaching of NO_3^--N at this site than at Thika during this cropping period. N input from organic sources were higher at Thika compared to that of Chuka possibly due to differences in FYM quality caused by the type of manure used at the two sites (Musyoka et al., 2019). On the contrary, N input via BNF was higher at Chuka due to higher Mucuna, common and French bean yield as a result of higher rainfall at this site. Higher N output at Thika compared to Chuka in the high input systems could have been due to higher N removal via baby corn (2012, LR), potato (2012, SR) and maize (2013 LR) yields which was higher in Conv-High at Thika compared to Chuka. In Org-High the differences in N output was also due to potato (2012, SR) and maize (2013 LR) yield which was high at Thika (Adamtey et al., 2016; Musyoka et al., 2017).

4.6. Conclusion

Similar amounts of NO_3^--N were leached from the conventional and organic farming systems. The cumulative amount of N leached from the high and low input farming systems was also similar. There was lower N leaching during the maize and vegetable cropping periods when compared to potato cropping period. Leaching was very high at the early growth stages of all the crops. Irregular rainfall amount and distribution, asynchrony between N release and crop demand, poor crop development and N uptake were the major identified factors that influence N leaching in the various farming systems. The two conventional systems and Org-Low all showed negative soil surface N balances, indicating the risk of N mining in the long-term. In contrast, the large positive N balances in Org-High (as a result of the influence of Mucuna and variations in compost quality) could result in N losses from this system when the prevailing conditions are conducive to such loss. Based on these results, we recommend reducing the rate of N application for potato in all the farming systems as well as carrying out split application of N at reproductive stage. Additionally, we recommend reducing the N applied when planting maize, but increasing the supply of N during its reproductive stage. This would reduce excessive soil residual N with this crop, which was one of the main factors for the observed excess-asynchrony. There is need to increase N application rates in the low input systems to avoid impoverishing the systems in the long-term on one hand and to develop a model to guide application of organic inputs with the aim of reducing over application and the risk of N loss in Org-High. The planting of nutrient trap crops during off-season (where applicable) in Org-High can also help to reduce nutrient loss, and trap crops can then be incorporated back into the soil in the subsequent cropping season.

4.7. Acknowledgement

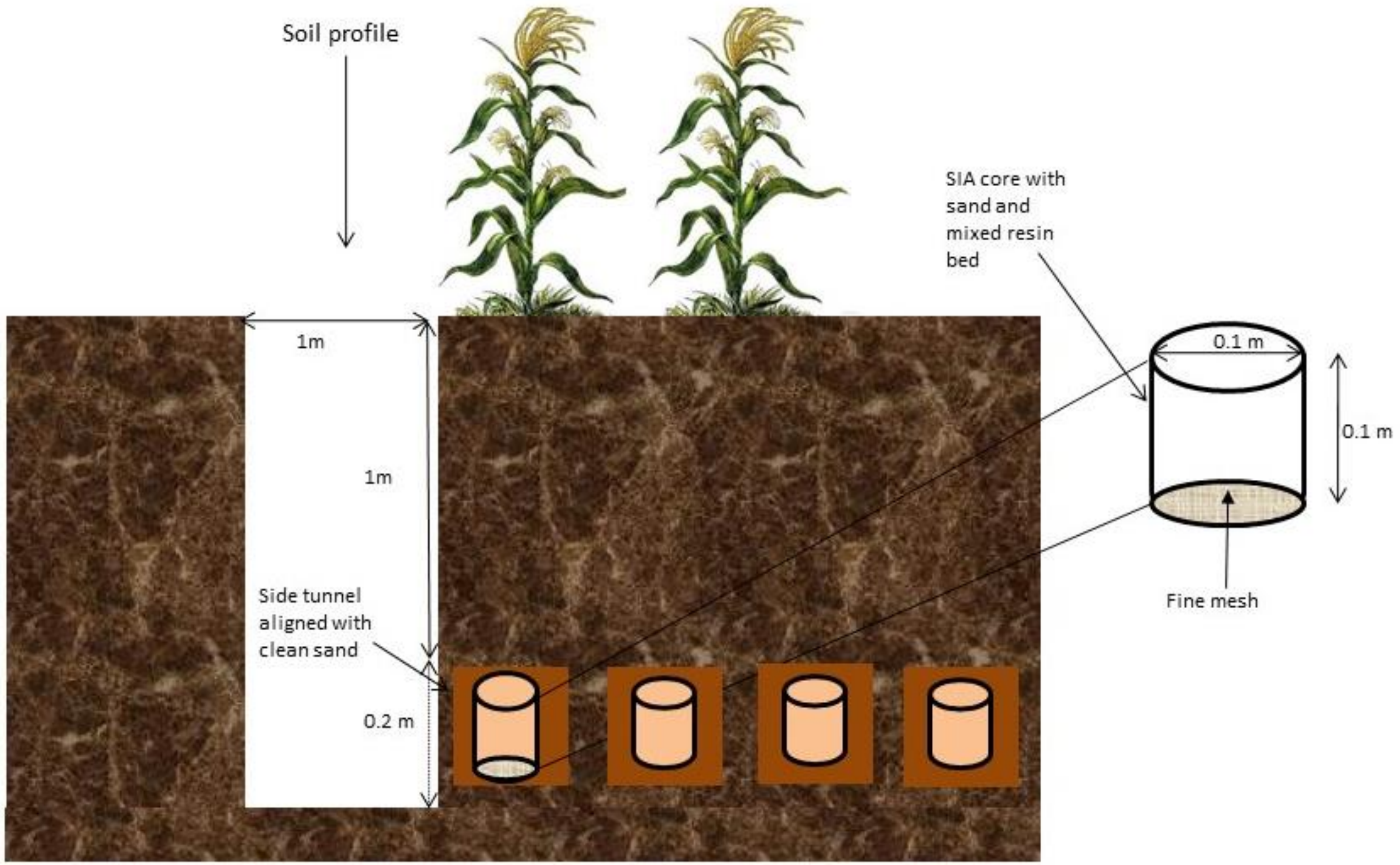
We gratefully acknowledge the financial support for this research provided by the Biovision Foundation, The Swiss Coop Sustainability Fund, Liechtenstein Development Service (LED) and the Swiss Agency for Development and Cooperation (SDC). We also gratefully acknowledge financial support for the core research agenda of ICIPE provided by UK Aid from the UK Government; the Swedish International Development Cooperation Agency (SIDA), the Swiss Agency for Development and Cooperation (SDC) and the Kenyan Government. We appreciate the support of Terraquat Ltd Company in providing training on the methodology used, which is patented (Pat. No. 19726813) in the Federal Republic of Germany. The support offered by the Kenya Agricultural and Livestock Research Organization (KALRO) at Muguga during laboratory analysis is much appreciated. We also appreciate the support provided by the SysCom Kenya team (the late Peter Owuor, Jane Makena and Felistas Mutua) during data collection. The support of Dr. Dionys Foster at the initial stages of the trial establishment and Beate Huber, among others) is also highly appreciated. Statistical guidance was provided by Dr. Daisy Salifu of ICIPE and Dr. Juan Laso of Hohenheim University is also appreciated. Dr. Nicholas Parrott's (TextualHealing.eu, Hendaye) empathetic English language editing helped improve the clarity of the text. *The views expressed herein do not necessarily reflect the official opinions of the donors.*

4.7. Supplementary material

S1: Initial soil characteristics at the start (in 2007) of the long-term systems comparisons trial sites at Chuka and Thika in the sub-humid zones of the Central Highlands of Kenya

Site	Farming systems/	pH	CEC	OC	Total N	Olsen P	Extractable			Sand	Clay	Silt
							K	Ca	Mg			
		H_2O 1:2.5	cmolc kg^{-1}	…..g kg^{-1}….		------mg kg^{-1}------				………%.......		
Chuka	Org-High	5.72	18.8	24.7	2.0	33.3	507	380	58	8.5	74.5	17.0
	Conv-High	5.81	17.8	21.7	2.1	24.8	507	356	55	8.8	73.0	18.3
	Org-Low	5.73	16.8	22.0	2.1	26.8	468	332	53	8.8	75.0	16.3
	Conv-Low	5.82	16.5	24.5	2.1	30.5	468	332	53	11.8	73.5	14.8
Thika	Org-High	5.46	11.0	23.0	1.6	10.5	468	156	46	5.0	83.6	11.4
	Conv-High	5.33	10.5	22.1	1.5	12.5	507	120	41	5.6	80.8	13.6
	Org-Low	5.45	10.8	22.8	1.7	13.5	507	140	43	4.2	81.4	14.4
	Conv-Low	5.45	11.8	22.4	1.6	12.3	507	148	53	6.8	76.2	17.0

Conv-High conventional high input system, *Org-High* organic high inputs system, *Conv-Low*, conventional low input system, *Org-low* organic low input system, K, Ca, and Mg are ammonium acetate extractable bases.



S2: Diagram showing the installation of the self-integrating accumulators' cores in the long-term systems comparison trail at Chuka and Thika (with two cores placed directly under the rows of plants and two between the rows) in the Central Highlands of Kenya

S3: Nitrate to ammonium N ratio in different soil layers at critical crop growth stages of potato, maize and vegetables at Chuka and Thika in the Central Highlands of Kenya

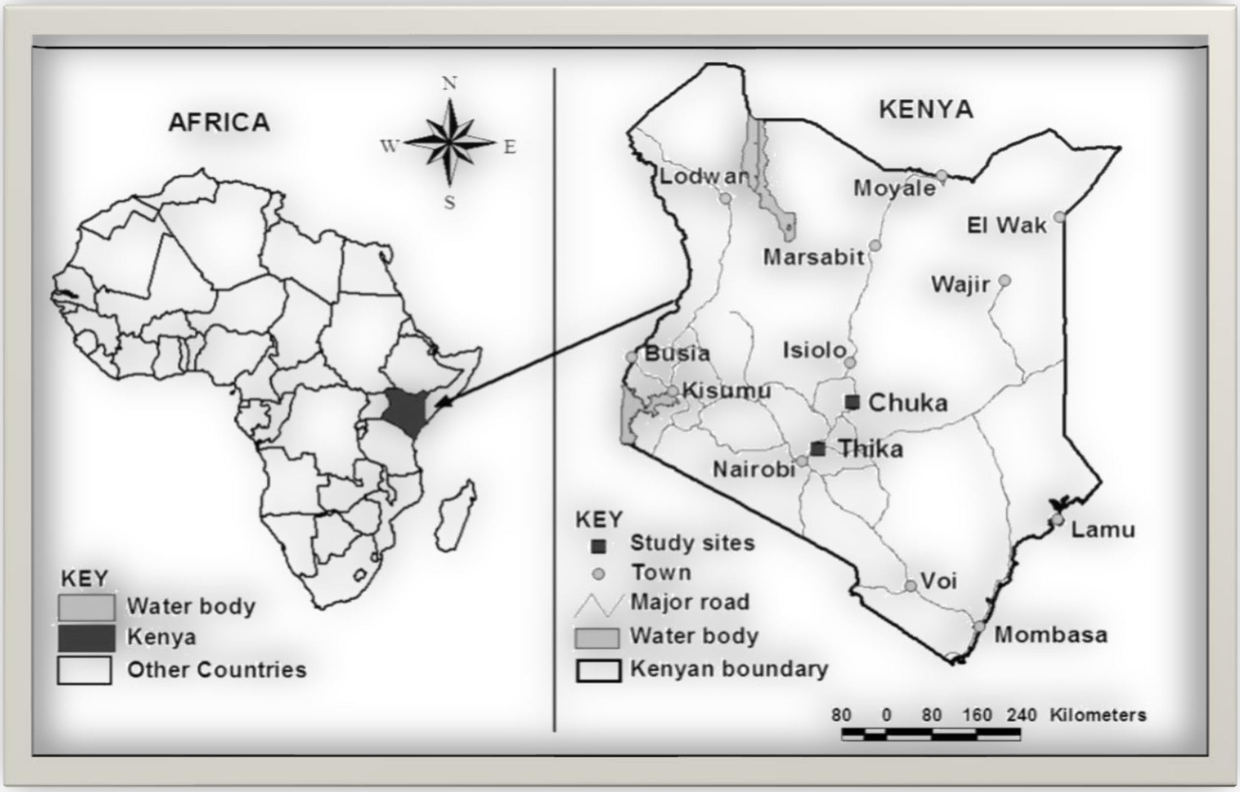
Potato		Before planting				Vegetative				Tuber initiation				Harvesting			
Site	Depth	Conv-High	Org-High	Conv-Low	Org-Low	Conv-High	Org-High	Conv-Low	Org-Low	Conv-High	Org-High	Conv-Low	Org-Low	Conv-High	Org-High	Conv-Low	Org-Low
Chuka	0-20	1.3±0.3	13.1±10.4	1.0±0.2	1.3±0.5	32.2±20.5	6.2±1.2	4.2±1.8	8.6±4.1	1.4±0.3	1.2±0.3	0.7±0.2	1.6±0.7	3.8±0.7	6.2±0.4	4.3±0.7	2.7±0.3
Chuka	20-40	1.4±0.3	1.0±0.2	0.7±0.1	0.6±0.03	10.8±2.2	12.1±1.8	9.0±1.8	8.9±2.8	1.4±0.7	0.6±0.4	0.8±0.2	0.5±0.2	2.4±0.9	4.3±1.2	2.3±0.2	2.3±0.3
Chuka	40-60	0.5±0.2	0.4±0.1	0.6±0.2	0.5±0.1	13.6±2.6	88.2±58.5	10.0±1.9	5.9±2.1	3.7±2.8	0.7±0.5	4.3±2.3	1.5±0.4	1.3±0.6	2.5±0.5	1.3±0.1	1.4±0.3
Chuka	60-80	0.4±0.04	0.5±0.1	0.3±0.1	0.4±0.02	58.6±26.3	84.9±59.6	12.9±5.3	5.6±1.1	1.1±0.4	1.5±0.3	3.4±1.1	3.0±0.8	1.9±0.5	3.5±0.6	2.1±0.6	1.9±0.4
Chuka	80-100	0.5±0.04	0.4±0.05	0.5±0.1	0.4±0.02	44.2±23.4	53.3±39.2	21.6±16.1	14.0±7.6	2.3±0.3	3.4±0.6	3.5±1.5	4.6±1.4	5.9±1.9	5.2±0.4	3.9±0.7	5.3±1.4
Thika	0-20	9.8±2.0	7.4±2.2	4.4±1.0	9.6±2.2	8.7±7.1	5.9±4.7	5.9±4.9	8.0±6.8	102.9±49.0	10.4±.3.1	24.2±13.1	5.9±1.7	2.8±0.5	1.9±0.5	1.0±0.2	1.0±0.2
Thika	20-40	9.0±4.2	1.6±0.8	6.2±1.7	16.2±7.3	6.4±5.1	0.5±0.2	7.1±6.0	7.6±6.4	104.0±83.4	66.4±36.4	26.9±7.1	10.3±2.6	1.6±0.3	2.1±0.3	1.9±0.6	2.4±0.7
Thika	40-60	1.9±1.1	3.0±1.6	5.3±1.4	5.2±2.2	3.7±2.8	8.2±6.8	8.2±6.7	7.7±6.6	38.42±21.3	30.0±13.4	53.5±31.4	24.0±2.9	2.8±0.9	3.1±0.7	4.5±0.6	4.5±1.1
Thika	60-80	5.0±2.3	6.5±2.9	11.3±2.8	4.6±1.4	2.7±2.1	10.5±6.7	0.8±0.2	0.6±0.3	21.5±10.1	44.8±19.6	92.1±46.3	133.9±99.4	3.4±0.9	4.7±0.4	5.8±1.0	5.4±0.6
Thika	80-100	43.7±29.4	5.0±1.7	23.2±8.0	17.1±9.4	5.2±4.3	7.9±6.3	0.5±0.1	9.0±7.5	42.6±18.5	62.8±47.7	50.4±16.0	131.4±104.4	3.6±0.8	4.8±0.9	6.3±1.1	6.1±0.5

Maize		Before planting				vegetative				Tasselling				Harvesting			
Site	Depth	Conv-High	Org-High	Conv-Low	Org-Low	Conv-High	Org-High	Conv-Low	Org-Low	Conv-High	Org-High	Conv-Low	Org-Low	Conv-High	Org-High	Conv-Low	Org-Low
Chuka	0-20	1.5±0.04	1.4±0.1	1.4±0.04	1.6±0.2	1.2±0.3	3.7±1.8	1.1±0.2	1.3±0.2	15.3±6.8	3.1±0.7	3.4±0.9	1.8±1.3	2.5±1.0	0.7±0.2	1.9±1.0	3.3±1.4
Chuka	20-40	1.3±0.05	1.4±0.06	1.3±0.05	1.3±0.01	1.4±0.4	2.0±0.2	2.0±0.4	1.2±0.2	8.4±2.7	10.7±4.1	1.3±0.5	4.4±1.5	0.9±0.4	4.2±1.8	3.3±2.1	3.6±2.1
Chuka	40-60	1.2±0.07	1.3±0.04	1.2±0.02	1.2±0.06	5.4±1.5	4.2±0.7	2.5±0.3	2.4±0.2	1.7±0.5	9.3±3.2	3.6±2.6	2.6±1.2	0.4±0.03	5.9±4.6	1.5±0.6	1.3±0.7
Chuka	60-80	1.2±0.05	1.2±0.05	1.2±0.03	1.1±0.02	6.5±1.5	5.4±0.8	4.6±0.8	5.3±0.5	2.0±0.6	13.6±5.7	1.8±0.6	4.3±1.5	1.6±1.1	2.3±1.4	0.5±0.7	3.5±1.9
Chuka	80-100	1.1±0.03	1.3±0.06	1.2±0.05	1.2±0.03	7.1±1.7	9.5±3.8	5.4±1.0	5.9±1.1	1.0±0.3	2.3±0.5	1.3±0.2	15.0±10.2	3.5±1.6	2.5±1.7	1.4±0.6	2.5±1.0
Thika	0-20	1.0±0.03	0.5±0.08	0.5±0.1	0.8±0.4	3.7±0.4	2.9±0.2	2.9±1.1	1.5±0.06	6.2±1.1	4.5±0.4	10.6±4.6	3.3±0.5	4.1±1.9	2.3±0.4	0.9±0.1	1.0±0.2
Thika	20-40	0.6±0.2	0.7±0.05	2.5±1.6	0.6±0.2	2.5±0.5	1.9±0.1	1.0±0.06	2.4±0.02	2.1±0.3	4.8±2.3	3.2±1.0	8.7±3.1	1.3±0.2	1.5±0.4	1.0±0.2	1.8±0.7
Thika	40-60	1.1±0.2	1.0±0.07	1.0±0.2	1.0±0.2	4.2±1.5	5.6±1.3	4.3± 1.1	6.1±3.0	2.6±0.7	12.1±6.7	11.6±4.4	17.6±7.0	1.2±0.2	1.6±0.3	1.5±0.1	10.4±4.7
Thika	60-80	1.2±0.1	1.0±0.2	1.1±0.3	1.7±0.3	6.8±1.3	8.3±1.6	8.5±2.5	9.2±1.8	14.7±10.6	33.4±9.6	18.3±8.8	14.0±6.4	0.9±0.3	2.7±0.5	2.2±0.1	8.3±4.5
Thika	80-100	1.0±1.6	1.0±0.1	0.9±0.2	2.1±0.4	5.1±	18.8±9.0	9.1±1.4	15.6±4.9	61.5±4.4	160.5±84.6	44.3±24.5	17.1±8.6	1.8±0.3	2.8±0.5	3.8±0.8	4.4±0.9

Vegetables		Before planting				Vegetative				Head formation				Harvesting			
Site	Depth	Conv-High	Org-High	Conv-Low	Org-Low	Conv-High	Org-High	Conv-Low	Org-Low	Conv-High	Org-High	Conv-Low	Org-Low	Conv-High	Org-High	Conv-Low	Org-Low
Chuka	0-20	7.4±1.9	5.4±2.2	2.3±0.6	3.4±1.4	7.1±1.6	4.4±1.7	3.7±0.3	3.7±0.9	2.0±0.6	3.1±0.7	1.7±0.2	1.8±0.6	13.5±4.1	31.3±14	25.0±13	16.8±1.2
Chuka	20-40	2.7±0.4	2.1±0.8	1.9±0.5	1.8±0.7	6.0±1.5	7.3±1.7	11.9±4.0	5.0±0.5	1.4±0.3	2.6±0.5	2.0±0.6	2.3±0.7	8.2±2.4	28.3±11	44.3±29	23.2±7.5
Chuka	40-60	2.0±0.3	1.2±0.1	1.1±0.4	1.4±0.2	8.0±1.5	10.6±2.0	5.8±1.4	6.6±1.4	1.3±0.3	1.6±0.3	1.5±0.3	1.7±0.5	12.8±5.5	8.8±1.3	23.1±8.5	22.3±7.4
Chuka	60-80	1.4±0.5	1.4±0.6	1.2±0.3	1.1±0.4	9.3±1.4	11.1±1.3	7.5±1.2	8.2±1.8	1.4±0.4	1.9±0.4	1.7±0.4	1.9±0.5	13.1±3.3	18.2±6.5	10.8±4.4	28.8±11.8
Chuka	80-100	1.5±0.3	2.0±0.5	0.8±0.3	1.2±0.4	11.4±3.0	9.1±1.9	4.7±0.6	7.2±1.3	2.0±0.6	1.8±0.4	2.5±0.8	1.9±0.5	15.2±3.5	16.0±3.0	12.6±3.6	16.5±5.1
Thika	0-20	2.8±0.4	3.6±0.5	3.2±0.3	4.4±1.6	89.6±34	26.6±7.1	16.9±3.4	53.5±34	5.4±2.0	4.3±7.0	5.7±1.4	38.1±27	2.7±0.6	6.4±4.3	2.5±1.0	4.4±0.5
Thika	20-40	2.4±0.6	2.8±0.7	2.8±0.9	2.4±0.4	11.4±4.7	6.8±2.1	7.7±1.6	13.8±7.5	7.5±2.1	2.0±2.8	6.1±1.6	11.9±3.5	1.4±0.3	5.7±3.4	2.4±0.7	2.8±0.4
Thika	40-60	11.2±4.5	5.0±1.1	5.1±2.6	5.2±0.9	6.0±2.0	3.0±0.7	23.8±7.5	15.1±4.6	5.6±2.0	1.8±0.9	7.8±2.5	13.8±5.0	1.3±0.3	2.4±1.1	2.7±0.8	2.2±0.5
Thika	60-80	12.5±3.0	7.2±1.5	8.8±4.6	10.1±4.0	2.6±0.4	8.9±1.8	17.8±3.2	41.1±6.9	24.0±16.0	2.4±0.7	10.3±3.5	39.4±17	1.8±0.4	3.5±2.1	3.3±2.1	5.6±0.8
Thika	80-100	15.7±3.1	13.2±4.1	7.7±2.9	8.9±2.5	10.6±5.9	11.9±3.8	27.0±5.4	25.3±4.4	7.9±4.6	24.4±1.3	18.6±7.0	32.2±11	6.4±2.4	8.6±5.9	4.7±2.2	4.5±1.3

Conv-High conventional high input system, *Org-High* organic high inputs system, *Conv-Low*, conventional low input system, *Org-low* organic low input system

CHAPTER 5



AFRICA
N
W
E
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KEY
Water body
Kenya
Other Countries
KENYA
Lodwar
Moyale
El Wak
Marsabit
Wajir
Busia
Isiolo
Kisumu
Chuka
Thika
Nairobi
Lamu
Voi
Mombasa
KEY
Study sites
Town
Major road
Water body
Kenyan boundary
80 0 80 160 240 Kilometers

5.0. Nitrogen dynamics in organic and conventional farming systems: synthesis and outlook

5.1. Answers provided to research questions and objectives

5.1.1. Are organic systems in Central Kenya more efficient in N use?

NUE has been considered as key agro-environmental indicator. Increasing NUE is key to increase food security especially in intensive agricultural systems (Spiertz, 2010; Hirel et al., 2011). One of the options to improve NUE is associated with cropping patterns and farming systems (Spiertz, 2010). Thus, the common focus has been to produce more yield with less N in high input systems while in low-input systems the focus has been to increase yield and yield stability by adding more N (Spiertz, 2010). In the current study, the generated results revealed that NUE was similar in organic and conventional farming systems in maize and vegetable systems. However, during potato season, NUE was lowest in organic high input systems possibly due additional N applied as *Mucuna* biomass. This is an indication that NUE varies with crop type, the rate and form of N application. In addition, NUE was higher in high input systems compared to the low input systems which could be associated with rate of N application as well as other biotic and abiotic induced stresses associated with the systems especially in the rainfed low input systems. Although there were no significant differences in N released from soil alone and soil amended with inputs between Conv-High and Org-High during potato season, it is notable that there was appreciably higher N in Org-High compared to Conv-High. In addition, NUE was higher in low input systems as reported by He et al. (2013) who showed that NUE decreases with increase in N supply. Further, N loss was similar between conventional and organic systems during potato season which implies that other factors could have affected NUE in the systems. The low NUE during potato cropping season could have been due to excess-asynchrony between N demand and N released as NUE has been reported to be affected by synchrony of N release and crop N demand (Sharma and Bali, 2018). In addition, large pre-plant N application results in lower NUE due to the associated N loss while mid-season N application results in improved NUE (Sharma and Bali, 2018). Large pre-plant N application could have been the course of low NUE during potato season where all the N was applied at planting. The similar NUE between Conv-High and Org-High farming systems during maize and vegetable cropping seasons could have been due to similar patterns of N release coupled with N application at peak N demand of maize and vegetables. Even though higher N was applied in Org-High compared to Conv-High, data of N release rate revealed that the system depended on soil residual N as there was N immobilization in Org-High and minimal N release in Conv-High system during maize season, while similar amounts of N were released in Conv-High and Org-High during vegetable season. The lower NUE in maize observed at the drier Thika site could have been a combined effect of N and moisture stress as reported by Hammad et al. (2012) compared to the more wet and fertile Chuka site. Further, decline in N availability at reproductive stages of maize as shown by insufficient asynchrony during these stages may have limited crop growth resulting in lower yields and NUE. This is in line with the findings of Moser et al. (2006) that pre-anthesis drought reduced yield and harvest index. Water and moisture stress also affected N uptake by vegetables as observed by an insufficient-asynchrony at reproductive stages of the vegetables. Lammerts van Bueren and Struik (2017) reported that NUE of vegetables is affected by the availability of N as head forming vegetables depends on prolonged photosynthesis and hence prolonged N uptake and this could have affected NUE of cabbage, kale and Swiss Chard. Thus, the data revealed that NUE is not only affected by farming systems but also crop type and therefore any attempt to improve NUE should consider efficiency of N uptake by the specific crop and the ability of the crop to convert the N taken up into economic yield. This is in line with the findings of Lammerts van Bueren and Struik (2017) that improvement of NUE depends on different crop physiological and agronomic traits. Further, NUE may be affected by imbalanced application of nutrients and this need to be assessed if NUE is to be improved (Fairhust, 2012). Nitrogen use efficiency in organic systems was therefore similar to that of conventional during maize and vegetable seasons but was poorer than that of conventional for potato crop.

5.1.2. Nitrogen use efficiency in high and low input systems

During potato season, NUE was highest in low input systems at Thika and was similar to Conv-High at both sites. This could have been associated with N application rates to potato. However, during maize cropping season NUE was highest in high input systems at Thika and lowest in the low input systems at the same site possibly due to drought experienced at this drier site. Hirel et al. (2007) reported that differences in NUE of maize under high N fertilization are associated with NUpE while under low N supply, NUE is governed by NUtE and this could have been the case at Thika where N uptake could have been hampered by drought. In addition, N availability at flowering is one of the determinants of yield (Hirel et al., 2007) and hence NUE. Research by Ertiro et al. (2017) revealed that drought reduced yield while drought coupled with N stress increased anthesis-silking interval in different maize lines in Kenya. In our study, there was insufficient N synchrony at tasseling and silking stages of maize coupled with drought and this could have affected yields hence lowering NUE of maize under rainfed low input systems at the more-drier, less fertile Thika site. Research has also shown that adaptation to N stress is dependent on crop type (Hirel et al., 2007). For example, maize and potato have different adaptations to N stress such that in Maize leaf area index and radiation use efficiency are decreased while in potato only the decrease in the amount of light intercepted is experienced (Hirel et al., 2007) and this could explain the differences in NUE of potato and maize under high-N and low-N input conditions. This therefore reveals that there is a need for breeding crops with improved ability to take up N under low and organic input conditions to enhance NUE under these farming systems (Gallais and Coque, 2005; Coque and Gallais, 2006; Kubota et al., 2017). In addition, management practices such as crop rotations with legumes, use of controlled N release products, split N application (Abbasi et al., 2013), no-tillage, cover crops and catch crops may be useful in improving NUE in organic and conventional systems (Worku et al., 2007; Kubota et al., 2017). Worku et al. (2007) in his study on N utilization under low and high input conditions in Kenya and Zimbabwe found that higher grain yield under low-N was associated to post anthesis N uptake and identified environmental and genotype interactions on hybrids with specific adaptation to either low-N or high-N conditions. He also found maize varieties that produced high yield under either low-N or high-N conditions. This knowledge is paramount if food security is to be improved under low input subsistent farming systems in SSA and opportunities exists in improving NUE under low-N or high-N conditions.

5.1.3. Do conventional systems lead to higher N losses?

Nitrogen supply is one of the major drivers of food security; however, its controlled supply is essential for environmental protection. N supply is affected by farming systems and other land use management activities such as tillage, cropping patterns among others. In addition, maintaining synchrony of N supply and crop demand not only for single crops but for crop rotations is important in reducing N loss and hence environmental protection. Thus, the current study revealed that there was N asynchrony at early stages of crop development in both organic and conventional systems resulting in leaching losses. However, N losses were similar between Conv-High, Org-High, Conv-Low and Org-low but when converted to percentage of the applied N, low inputs systems lost more N compared to high inputs. This supports views of Masso et al. (2017) that the challenges of N management in SSA is related to insufficient N application coupled with high N loss which directly affect NUE of the crops. Kristensen et al. (1994) and Aronsson et al. (2007) also found similar N losses between organic and conventional systems in which animal manure or green manure crops were used. However, this is contrary to the findings of Kimetu et al. (2004) and Benoit et al. (2014) who found that N leaching losses were much lower in organic compared to conventional systems in the tropics and temperate regions respectively, while Bergström et al. (2008a) reported higher N leaching loss in organic systems in temperate regions. The performance of the systems is associated with N application intensities, crop yields and use of cash crops (Hansen et al., 2000; Benoit et al., 2014). The comparable N loss between conventional and organic systems at high and low input levels could be associated with higher N uptake in high input systems compared due to low N uptake due to abiotic and biotic stresses and hence higher proportional N loss in low input systems.

5.1.4. Do organic systems result in improved N balances?

Surface N balances were negative for Conv-High, Conv-Low and Org-Low for the entire rotation, an indication of N mining in the systems. Our study revealed that organic systems can lead to improved N balances as observed by the positive surface N balance in Org-High. However, further research is required that includes other N input and output aspects such as N input via irrigation and N loss via denitrification, runoff volatilization, dissolved organic N loss. This is in line with Surekha and Satishkumar (2014) who also reported positive N balances in organic systems compared to conventional and integrated rice farming systems. Positive N balances observed in organic farming systems need to be assessed as they may lead to N accumulation in the soil which may result to higher N loss in the long-term and therefore there is a need to address N application rates in this system. In addition, the findings also confirm that conventional and organic farming systems at low and high input levels had similar effects on N loss through leaching under tropical conditions although the conventional system as practiced in SSA is an integrated farming system. Therefore, good N management must aim to reduce soil inorganic N accumulation, increase soil organic N accumulation and reduce N mining in the farming systems and this influence agronomic efficiency of the applied N (Masso et al., 2017).

5.1.5. Organic resources and N availability in organic and integrated farming systems

The current study revealed that N release from amended soil was similar between Conv-High and Org-High and between Conv-Low and Org-Low possibly due to the integrated nature of the conventional system tested in these trials. This supports claims that use of organic sources such as *Tithonia, Mucuna* and manures resulted in higher yields compared to integrated use of organic and synthetic fertilizers an indication of availability of nutrients to support higher crop yields (Vanlauwe et al., 2011; Mucheru-Muna et al., 2014). Organic sources of N applied to the systems differed between seasons resulting in high net mineralization at the early stages of the crop during potato and cabbage seasons and high N immobilization during maize cropping season. The observed trends were mainly dependent on N, C: N and lignin: N ratio an indication that N release was dependent on the organic resource quality. Thus, farming systems dependent on organic resource inputs should consider testing of organic inputs to ensure that timing and amount of N release is in tandem with the crop demand. In addition, since manure is one of the key sources of nutrients in the systems, there is a need to access potential ways of improving manure quality to enhance nutrient content. Chivenge et al. (2009) observed negative interaction effects of application of high N organic resources with fertilizers in a clay and sandy soils in Central highlands of Kenya. Thus, high N release is associated with class I organic inputs (>2.5% N, <15% lignin and <4% polyphenols) and this could have been the case during potato season resulting to higher N release and mineralization (Vanlauwe et al., 2005). Class III (<2.5% N, <15% lignin and <4% polyphenols) organic inputs are considered to have a slower mineralization and hence when combined with synthetic fertilizers results in increased yields (Vanlauwe et al., 2002). In addition, there were large amounts of available N before planting due to residual effect from previous cropping season an indication that crop rotation may have an impact on N supply to the following crop but this was dependent on the crop. High available N was observed during the early stages of the crop growth when N demand is low as reported by other authors (Nyamangara et al., 2003; Zebarth and Milburn, 2003; Chikowo et al., 2004). The high available N in all the systems could also be associated with high soil moisture content as most of the rainfall was received 20-30 days after planting. Wang et al. (2017) reported that irrigation facilitated N uptake by maize possibly due to its influence on the mineralization process. Further, the current rotation where potato was followed by maize and then vegetables revealed the impact of crop rotation on N availability where shallow rooted crop (potato) resulted in higher residual effects while the two deep rooted crops (maize and cabbage) resulted to mopping of available N in the soil profile and this needs to be considered when designing the crop rotation. Maize has been reported to have high N uptake (Smale et al., 2011) which agrees with our finding and this may explain the low nitrate-N found in the soil profile during vegetable cropping season. This may call for a review of the rotation as designed although the rotation was designed on the precept that maize is a staple food crop in SSA. Higher N demand than availability was observed at reproductive stages of maize and vegetables and hence there is a need to review timing of N application to meet crop demand at these critical stages. Mucheru-Muna et al. (2014) reported higher yields when *Tithonia diversifolia* and *Calliandra calothursus* were applied as sources of N compared to where N was applied as synthetic fertilizer or in combination with organic inputs even though this did not translate into improved soil fertility possibly due to negative interaction effects of application of high N organic resources (class A) with fertilizers as reported by Chivenge et al. (2009). This reveals that there is a potential trade-off between yield gains and improved soil fertility.

N release was not in synchrony with N demand in both organic and conventional systems. This is in line with the findings of Evanylo et al. (2008) who found that N release from compost was not in synchrony with sweet corn. The findings of this study revealed that there is a need to review rate and timing of N application to minimize risks of N loss from the systems. While this may be easy to plan in conventional systems, timing of N application in organic systems is difficult as most N is applied in organic form and N availability is dependent on organic input quality. However, plant teas (prepared from leaves and soft twigs soaked for 7-10 days to bring the most N into solution) of class I organic resources such as *Tithonia* has been found to supply N in available forms but assessment of potential of N loss via volatilization need to be done. Chikuvire et al. (2013) reported similar yields of rape crop fertilized using ammonium nitrate and *Tithonia* plant tea an indication that possibilities of delaying N application at planting and split application at the time of high demand in organic systems also exists (Alaru et al., 2014). These results therefore will be important in fine tuning timing of N application in both high and low input farming systems to ensure increased N synchrony and therefore improve yields and yield stability in the long-term.

5.2. Implications of the research outcomes for food security

Green revolution forward thrust in the 19th and 20th centuries was based on application of nitrogen which allowed genetic expression of crop potential (Sinclair and Rufty, 2012). Research clearly shows that N and water availability coupled with improved crop varieties may increase production and thus improve food security. My current research has revealed that nitrogen and water stress were the major constraints to productivity especially in the rain-fed low input systems. This is line with what has been reported by Sinclair and Rufty (2012) "that the wagon of yield increase is pulled by N and water availability on one side and that improved genetics take advantage of the improved resources". Nitrogen is therefore fundamental to global food security (Sutton et al., 2013). Additionally, my current results revealed crop failure in low input rain-fed farming systems especially at the drier Thika site during maize and vegetable seasons, a scenario that is common with small holder farmers. Thus, agricultural intensification under small scale holder farmers and in view of climate change impacts must include more drought tolerant crops and other crop management options such as mulching, crop rotation to improve food security (Daryanto et al., 2017). Tittonell and Giller (2013) indicated that small holder farmers may not benefit from the high yields offered by genetic improvement of crops due to low nutrient supply and low soil organic matter resulting to degradation and non-responsive soils and that this has become a poverty trap. This means that any efforts to improve food security under low input farming system measures should include strategies that improve management and N use efficiencies in these systems or else breeding for drought and low N environments must be included. High input farming systems resulted in higher maize and cabbage yields as a result of higher N rates, split N application and supplementary irrigation, an indication that food security in this region could be improved when input applications are supported with supplementary irrigation during periods of drought. However, recommended N application rates for potato resulted in lower yields especially in organic farming systems. Hence, there is a need to reduce N application in potato and move to split N application to reduce N applied at planting and supply N at peak N demand (Muthoni, 2016) in the production systems if sustainable food production is to be achieved. In addition, synchronization of N availability and plant uptake is critical (Sinclair and Rufty, 2012). This research has shown that N uptake is low at early stages of the crop while the demand is high at reproductive stages. Thus, minimizing N supply during the early stages of the crop and increasing N supply at high N crop demand period would reduce N loss and movement to lower soil horizons as observed in this research; this would then improve NUE and increase yields and ensure environmental safety. Eighty percent of N supplied to potato in the low input systems was leached below 1 m depth indicating that food insecurity in SSA is exacerbated by loss of applied nutrients in addition to high N removal by crops, drought and low nutrient application. Zhang et al. (2017) assessed N foot prints and virtual N factors in China and found that 39-67% of N is lost during food production phase of cereals, tubers and vegetables and hence N loss has major impact on food production. There is therefore a need to improve the farming systems to reduce N loss. There is a lot of debate on yield gap between organic and conventional systems with some reporting that organic systems yields are higher compared to conventional systems (Badgley et al., 2007b; Auerbach et al., 2013; Te Pas and Rees, 2014) while others report lower yield in organic systems (Bergström et al., 2008a; Seufert, 2012; Ponisio et al., 2015). In the current study, maize and vegetable yields were similar in organic and conventional systems while yields of potato were higher in conventional systems compared to organic systems an indication that the yield gap between conventional and organic systems is dependent on crop type and agroecological zones (de Ponti et al., 2012; Seufert, 2012). Further, it is noted that the crop varieties used in the current study for organic systems are those bred for conventional farming systems condition and hence there is a need for breeding crops for organic and low input conditions in the tropics (Lammerts van Bueren et al., 2011).

Adamtey et al. (2016) reported that organic system produced similar maize and baby corn yields and profit margins (with premium prices in organic systems) as conventional system revealing that organic systems are an option in securing food production and improving livelihood in the tropics. The yield gap observed between high and low input farming systems under maize and cabbage reveals that an opportunity exists to improve yields by increasing N availability, reducing N loss and water stress in the low input farming systems. This is in line with the findings by others that conversion to organic farming systems increased production in Peru (Parrott and Marsden, 2002), Uganda (Gibbon and Bolwig, 2007) and Asia (Giovannucci, 2007). However, the performance of the systems may be dependent on local conditions and hence may not be easy to extrapolate to other locations unless the conditions are similar (Hewlett and Melchett, 2008). Further, since food security is also related to sustainability of the farming systems, additional data on the impact of the farming systems on soil biology and fertility, health and nutrition may be necessary to make conclusive deductions on the impact of the systems on food security.

5.3. Limitations of the study

The study did not assess dissolved organic nitrogen (DON) due to limitation of availability of a well-equipped laboratory. Research has shown that up to 26% of N lost through leaching is in the form of DON suggesting that the observed N lost through leaching could have been much higher if DON loss was assessed. Ion-exchange resins (IER) have been shown to capture both dissolved organic N and dissolved inorganic N (DIN, (Langlois, 2003) and hence the method used could have enabled DON to be determined. In addition, denitrification was also not assessed in the study even though research shows that pockets of anaerobic environment exists and this could have resulted to denitrification especially during potato season when high rainfall was received (Muriuki et al., 2001). Denitrification could occur if field capacity exceeds 60% as oxygen deficit increases causing the microbes to utilize oxygen in nitrate-N and as a result releasing N_2O or N_2 gas (Signor et al., 2013). Krause et al. (2017) reported higher N_2O in organic systems compared to conventional in Europe. N loss through runoff was also not studied as this was planned to be studied by a different student but this study did not take place. The SIA method used in this study was suitable for cumulative leaching for a period of time but is not be useful for single leaching event assessments, which could have been very useful in determining the critical time when N loss through leaching was highest during the crop growth stages. Further, not all of the applied N in the organic systems was available for the crops studied in organic systems compared to conventional systems where most of the N was supplied in more available N and hence the challenge in comparison of the systems. Organic input quality varied with season complicating the situation further such that N applied was not always equal as originally envisaged. Thus, N balances could have been underestimated or over estimated as N supply from irrigation water and loss via volatilization, denitrification, runoff and DON were not taken into consideration (Majumdar et al., 2016).

5.4. Recommendation for future studies

I recommend site specific long-term studies to evaluate effects of the farming systems on soil physical, chemical and biological characteristics as well as fine tune organic systems. Future studies should explore the effects of management systems on water retention and availability to the crop as there could be differences in water retention in the systems given the differences in organic inputs applied that could increase SOM (Hu et al. 2018). The study also recommends that N application rates and timing for potato production in organic systems should be reduced for efficient NUE. There is a need to reduce N applications at planting and increase N supply at reproductive stages of crops possibly use of plant teas in organic and CAN in conventional systems to minimize N supply during the early stages of the crop and thus improve N synchrony. In addition, seasonal variability of compost and manure quality and N supplied to the systems through *Mucuna* or crop residues should be considered to ensure that N and P applied are similar between Conv-High and Org-High and between Conv-Low and Org-Low. There is a need to improve manure quality as research showed that the nutrient content of most manure and compost materials were low. For example, Diogo et al. (2010) revealed that improved animal feeding and manure handling more than doubled nutrient content of manure. Future N balances should consider measurements of N inputs from irrigation water, seeds and N output such as volatilization, erosion/runoff, DON and N_2O in the farming systems especially since all the systems received compost or manure.

6.0. References

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Curriculum Vitae

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M. Phil (Soil Science) 2002, BSc (Forestry),

Personal data

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Educational background

1. PhD in Agricultural sciences – Hohenheim University, Germany, 2019
2. M.Phil. Soil Science - Moi University, Kenya, 2002
3. BSc. Forestry, Second Class Hons, Upper Division - Dept. of Forestry, Moi University, Kenya, 1997
4. KCSE (B plain) Naromoru Girls High School - 1991

Work Experience

September 2006 to date

Senior research assistant and trial Coordinator – **"*Long-term Farming System Comparisons in the Tropics*" (ICIPE).** The project is a long-term trial comparing conventional and organic farming systems considering high and low input level for commercial and subsistence farmer respectively. The systems are being compared on a holistic ecosystem approach taking into account soil fertility, product quality, financial benefits and sustainability. The research is implemented in collaboration with Tropical Soil Biology and Fertility institute of CIAT, Kenya Agricultural Research Institute- Thika, and Kenyatta University (Dept. of Soil Science), Kenya Institute of Organic Farming and Kenya Organic Agriculture Network. My main responsibilities include:

- Facilitation of project implementation in Kenya.
- Management and coordination of field trials including supervision of technicians and students.
- Develop sampling procedures, data collection, compilation and analysis
- Supervision of technicians and students
- Development of research reports, and progress reports for partners and donors.
- Financial management

May 2005 to August 2006

Technical Manager: Crop Nutrition Laboratory Services (CNS) Limited:

Crop Nutrition Service is a private service company offering crop nutrition and soil fertility management and consultancy services in East Africa region.

Primary Responsibilities

- Technical support and backstopping the technical field team to ensure quality service delivery to our clients;
- Promoting good agricultural practices for enhanced sustainable production and food security.
- Research and developing innovations for increased food production. This includes applying research finding by agricultural research institutions to local small-scale farmers with appropriate innovations for easy adoption.
- Developing proposals. I successfully developed several proposals for technical interventions for both small holder and large-scale farmers. As part of my accomplishments, Crop Nutrition Services was selected as service provider in regard to establishment of EUREP GAP compliance by small and large-scale horticultural farmer in export production.
- In charge of soil nutrient mapping projects (GIS projects), which entails geo-referencing, data analysis and generation of nutrient maps. This forms the basis for site-specific recommendations for fertilizer requirements and appropriate crops hence avoid the common generalised blanked recommendations.

- Database management. This entails processing and generating clients' reports with technical interpretation and recommendation.

June 2003 to September 2004:
Project Research Officer: FARM AFRICA (UK International NGO)

The projects sought to establish a pro-poor mechanism for farmer-to-farmer communication and extension embracing active farmer participation in extension services under the Meru Dairy Goat Project in Meru Central and Meru South districts and ended in July 2004.

<u>Specific tasks included:</u>

Overall in charge of implementation of the project Agricultural Knowledge and Information System.

Liaison with collaborating institutions (CBOs, Ministry of livestock and fisheries, World Agroforestry Centre (ICRAF), University of Reading)

Preparation of work plans and ensure their implementation;

Development of protocols for data collection and field operation guidelines;

Data analysis, documentation of research findings and implementation of the field trials;

Preparation of technical and financial progress briefs to donors and collaborating institutions (University of Reading and ICRAF, Nairobi);

Responsible for budget control in the process of research implementation;

May 2002 to May 2003: Project Research Coordinator, Best Bet Project Sustainable Agriculture Centre for Research, Extension and Development in Africa (SACRED AFRICA)

The project sought to establish the best 'bet' agricultural technologies for crop production and soil fertility management in seven districts in Western Kenya, co-implemented by six organizations (NGOs and Research Institutions). I was charged with the overall responsibilities for coordination of the project.

<u>Primary Responsibilities</u>:

- Providing technical backstopping to six collaborating NGOs and Research Institutions and acted as the liaison person on all matters regarding the implementation of the project.
- Development of protocols for project implementation, monitoring and evaluation, including database management.
- Development of technical progress reports and financial budgeting, control and reporting.
- Ensure practical community participation and adoption of the identified appropriate (Best Bet) technologies for increased food production and poverty eradication.
- Data analysis, report writing and developing scientific publications.

June 1999 – September 1999

Data Management: Agricultural Research Fund (ARF) Moi University

- Data analysis for Agricultural Research Fund

January 1998 to September 1998
Research Assistant:
World Agroforestry Research Centre (ICRAF)
Responsibility

- Research Assistant in a pilot project evaluating the use of improved fallow systems for nutrient replenishment in Western Kenya. I was charged with responsibility of designing field studies, sample collection, preparation for analysis, analysis of ash content (done at ICRAF laboratories in Nairobi for 1 month), data analysis and writing of a paper for publication

Other Accomplishments

1) Editor, Quarterly Newsletter for Sustainable Agricultural Centre for Research, Extension and Development in Africa (SACRED Africa), an International NGO, May 2002 to May 2003.
2) Participated in strategic planning and SWOT (Strength, Weaknesses, Opportunities and Threats) analysis for Participatory Ecological Land Use Management (PELUM); a network of NGOs involved in land use and related activities, 21st – 25th October 2003.
3) Laboratory Analysis; Plant and manure analysis at, Kenya Agricultural Research Institute (KARI), Muguga. Samples for Rockefeller Funded Project. March 1st to April 4th, 2001)
4) Data Management; Data analysis for Agricultural Research Fund (ARF) project, Moi University, Research Conducted from 1995 to 1999.Undertook data management, statistical analysis and reporting for Agricultural Research Fund (ARF) project, Moi University, conducted from 1995 to 1999, June 1999 – Sept 1999.

Publications and research outputs

1) Beesigamukama, D., Mochoge, B., Korir, N., Fiaboe, K. K. M. Khamis, F. M., Subramanian, S., Musyoka, M. W., Baldwyn, T., Ekesi, S., Tanga, C. M. 2019. Impact of sawdust amendment of organic waste on black soldier fly larvae yield and nutrient quality of rearing residues for fertilizer production. *To be submitted to Journal of economic Entomology.*
2) Karanja, E. N., Fliessbach A., Kambura A. K., Musyoka M. W., Adamtey, N., Fiaboe, K. K. M., Mwirichia, R. K. 2019. Diversity and structure of prokaryotes within organic and conventional farming systems: A comparative long-term field experiment in Central Highlands of Kenya. *Submitted to Journal of Basic Microbiology.*
3) Karanja, E. N., Fliessbach A., Adamtey, N., Kambura A. K., Musyoka M. W., Fiaboe, K. K. M., Mwirichia, R. K. 2019. Impact of organic and conventional farming systems on soil fungal diversity in Central Highlands of Kenya. *To be submitted in Journal of Scientific African*

4) Adamtey, N., Eshetu Bekele, David Bautze, Martha Wangu Musyoka, Edward Karanja, Komi Fiaboe, Anne W. Muriuki, Monicah Mucheru-Muna, Amritbir Riar, Laura Armengot, Gurbir S. Bhullar, Juan Guillermo Cobo, Andreas Gattinger, Paul Mäder, Georg Cadisch, Andreas Fliessbach, Bernard Vanlauwe 2018. Organic farming is more effective at improving soil fertility in the tropics than conventional farming: Evidence from the long-term farming systems comparison trials in Kenya. *Submitted to Georderma*.
5) Musyoka, M.W., Adamtey, N., Muriuki, A.W., Bautze, D., Karanja, E.N., Fiaboe, K.K.M., Cadisch, G., 2019. Nitrogen leaching losses and balances in conventional and organic farming systems in Kenya. Nutrient cycling in agroecosystems. *Nutr Cycl Agroecosystems 114, 237–260. doi.org/10.1007/s10705-019-10002-7*
6) Musyoka, M.W., Adamtey, N., Bünemann, E.K., Muriuki, A.W., Karanja, E.N., Mucheru-Muna, M., Fiaboe, K.K.M., Cadisch, G., 2019. Nitrogen release and synchrony in organic and conventional farming systems of the Central Highlands of Kenya. Nutrient Cycling in agroecosystems. *Nutrient Cycling in Agroecosystems 113:283–305. doi.org/10.1007/s10705-019-09978-z*
7) Anyango, J. J., Bautze, D. Fiaboe, K. K. M., Lagat, Z. O., Muriuki, A. W., Stöckli, S., Riedel, J. Onyambu, G. K, Musyoka, M. W. Karanja, E. K., Adamtey, N. 2018. The abundance, incidence, diversity and activities of termites under conventional and organic farming systems in the Central Highlands of Kenya. *Submitted to BMC Ecology Journal*
8) Atandi, J.G.; Haukeland, S., Kariuki, G.M., Coyne, D.L., Karanja, E.N., Musyoka, M.W., Bautze D., Fiaboe, K.K.M. and Adamtey, N. (2017) Characteristics of soil nematode communities as affected by organic and conventional farming systems under various cropping systems. In: Book of abstracts in Proceedings of the 21st Symposium of the Nematological Society of Southern Africa (NSSA). P. 57. Durban, South Africa, 07-11th May 2017.
9) Adamtey N., M.W. Musyoka, E.N. Karanja, D. Bautze, F.M. Matheri, A.W. Muriuki and K.K.M. Fiaboe (2017) Overall Long-term Farming Systems Comparisons in the Tropics. SysCom Kenya horizontal evaluation workshop, 6-8 June, Nairobi, Kenya.
10) Musyoka M.W., E.N. Karanja, F.M. Matheri, A.W. Muriuki, K.K.M. Fiaboe, D. Bautze, and N. Adamtey (2017) Farming Systems Comparisons in the Tropics - Kenya (SysCom Kenya). SysCom Kenya horizontal evaluation workshop, 6-8 June, Nairobi, Kenya.
11) Musyoka M.W., E.N. Karanja, F.M. Matheri, A.W. Muriuki, G. Cadisch, K.K.M. Fiaboe, D. Bautze and N. Adamtey (2017) Effect of organic and conventional farming systems on nitrogen use efficiencies of potato, maize and vegetables in the sub humid region of the central highlands of Kenya. SysCom Kenya horizontal evaluation workshop, 6-8 June, Nairobi, Kenya.

12) Karanja E.N., R.K. Mwirichia, A. Fliessbach, K.K.M. Fiaboe, A. K. Kambura, M.W. Musyoka, D. Bautze and N. Adamtey (2017) Diversity of prokaryotic communities within Organic and Conventional Farming systems in Central Highlands of Kenya. SysCom Kenya horizontal evaluation workshop, 6-8 June, Nairobi, Kenya.
13) Anyango J.J., Z.O. Lagat, K.K.M. Fiaboe, A.M. Muvea, A.W. Muriuki, S. Stöckli, M.W. Musyoka, E.N. Karanja, D. Bautze and N. Adamtey (2017) Effect of farming systems on termite abundance and damage on maize crop. SysCom Kenya horizontal evaluation workshop, 6-8 June, Nairobi, Kenya.
14) Mwangi E., C. Ngamau, J. Wesonga, E.N. Karanja, M.W. Musyoka, F.M. Matheri, K.K.M. Fiaboe, D. Bautze and N. Adamtey (2017) Phosphorus fluxes and vegetable growth as influenced by rock phosphate management under acid soils. SysCom Kenya horizontal evaluation workshop, 6-8 June, Nairobi, Kenya.
15) Atandi J.G., S. Haukeland, D.L. Coyne, G.M. Kariuki, E.N. Karanja, M.W. Musyoka, K.K.M. Fiaboe, D. Bautze and N. Adamtey (2017) Characterizing Soil Nematode Communities Under Organic and Conventional Farming Systems in Chuka, Kenya. SysCom Kenya horizontal evaluation workshop, 6-8 June, Nairobi, Kenya.
16) Mapili M.M., V. Madadi, J. Irungu, N. Adamtey, K.K.M. Fiaboe, S.O. Wandiga, E.N. Karanja, M.W. Musyoka, D. Bautze and B. Torto (2017) Effect of Organic and Conventional Farming systems on the concentration of pesticide residues in environmental and food samples. SysCom Kenya horizontal evaluation workshop, 6-8 June, Nairobi, Kenya.
17) Karanja E.N., M.W. Musyoka, K.K.M. Fiaboe, M. Waweru, S. Ndung'u, A.W. Muriuki, M.M. Mucheru, D. Bautze and N. Adamtey (2017) Identification of beneficial uses of biomass for organic vegetable production. SysCom Kenya horizontal evaluation workshop, 6-8 June, Nairobi, Kenya.
18) Karanja E.N., M.W. Musyoka, K.K.M. Fiaboe, M. Waweru, S. Ndung'u, A.W. Muriuki, M.M. Mucheru, D. Bautze and N. Adamtey, (2017) Effects of different types of manures and composting techniques on carrot (*Daucus carota*) and bean (*Phaseolus vulgaris*) yield. SysCom Kenya horizontal evaluation workshop, 6-8 June, Nairobi, Kenya.
19) Atandi, J. G., Haukeland, S., Kariuki, G. M., Coyne, D. L., Karanja, E. N., Musyoka, M. W., Fiaboe, K. K.M., Bautze, D., Adamtey. N., 2017. Organic farming provides improved management of plant parasitic nematodes in maize and bean cropping systems. Agriculture, Ecosystem and Environment 247, 265-272
20) Musyoka, M. W., Adamtey N., Muriuki A. W. and Cadisch, G., (2017) Effect of organic and conventional farming systems on nitrogen use efficiency of potato, maize and vegetables in the Central highlands of Kenya. *European Journal of Agronomy 86, 24-36.* *doi.org/10.1016/j.eja.2017.02.005*

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34) A. Muriuki, M. Musyoka, A. Fliessbach, D. Forster (2012) Resilience of Organic Versus Conventional Farming Systems in Tropical Africa: The Kenyan Experience, Presented at Tropentag International Conference September 19-21, 2012, Germany
35) Muriuki, A.W., M.W. Musyoka, C. Zundel, B. Vanlauwe, J. Kamau and R. N. Farray (2011*).* Organic versus conventional farming: Maize performance in consecutive years at KARI-Thika, Central Kenya. Paper presented at the 11th workshop on Sustainable Horticultural Production in the Tropics under the theme 'Analysis of horticulture course content and research agenda' held at Pwani University College, Kilifi. December 7th – 10th 2011.
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37) Muriuki, A.W., M.W. Musyoka, J. Cobo, C. Zundel, B. Vanlauwe, M. Mucheru-Muna and J. Kamau (2011). Organic versus conventional agriculture: Maize performance in a long-term farming systems comparisons trial. Paper presented at the 4th National Council for Science & Technology Conference held at Kenyatta International Conference Centre, Nairobi. May 3rd to 6th, 2011.
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51) Waigwa, M. W and Okalebo, J. R. (1998) Decomposition and nutrient release rates from residues/ prunings of, *M. dura* wheat straw and *Acacia mearnsii* in the Ferrasols of Uasin Gishu, Kenya. Soil Science Society of East Africa 13th-19th December 1998 conference proceedings.
52) Waigwa, M. W. (1997) Decomposition and nutrient release rates of *Milletia dura,* wheat straw and *Acacia mearnsii* (B.Sc. Research Project)

Scholarships

1999-2002: Forum of Agricultural Resource Husbandry, the Rockefeller Foundation for MPhil programme

Relevant short training courses / workshops attended

1. Martha W. Musyoka. The role of DOC and DON in plant-soil C and N cycling to be held in Uppsala April 23-27th 2012.
2. Martha W. Musyoka, Brigitte Nyambo, A. Muriuki, B. Vanlauwe, [4]M. Mucheru, M. Waweru, and S. Ndung'u (2011). What can organic agriculture contribute to sustainable development: long-term farming systems comparison trials in Kenya. *icipe* research week. Celebrating 40 years of Research. 16th November 2011.
3. M. Musyoka[1] and S. Ndungu[2] (2011). Developing the Organic Sector-Best Practices from Africa: Building Strategies for Africa: Adding Value through Organic Farming. Brussels 11-12th July 2011. European Commission
4. African Organic Conference 2009. "Fast tracking sustainable development in Africa through harnessing Organic Agriculture and Bio-technology" May 19-22nd, 2009

5. Infonet Planning platform. Theme: Co-Creating a Farming Information Hub for the next Decade. 25-28th August 2008 at *icipe*, Nairobi.
6. Training in GIS applications, spatial data concepts, ArcGIS data model, spatial coordinate system and map generation and display, and nutrient mapping, held at Oakar Services ltd, Nairobi, on 22-23rd March 2006.
7. Scaling up the promotion of Fodder trees held at World Agroforestry Centre (ICRAF) on 7-10th June 2004
8. Farmer-to-Farmer Research Validation workshop held at Transit Motel on 28–30th October 2003
9. Engendered Poverty Reduction Strategic Plan and Gender district plan strategic planning meeting. Park Villa, Webuye. December 4-5th, 2002
10. Forum for organic Resource Management and Agricultural Technologies Workshop held at Village market on 17-19th November 2002.
11. Strategic planning for Participatory Ecological Land Use Management (PELUM) NGO's network. Training and participation in five year (2002-2006) strategic planning and SWOT analysis for several NGOs under PELUM, Tourist Hotel, Naivasha. October 22-26th, 2002
12. Soil fertility in western Kenya workshop, Savona Isle Hotel, Kakamega. October 3-4th, 2002
13. Forum for organic Resource Management and Agricultural Technologies Workshop held at Village market on 7-9th November 2001, Theme: Strengthening Kenyan Partnership in Organic Resource Management.
14. Biometrics Workshop-Data Analysis using Genstat organized by the Rockefeller Foundation (FORUM) at Egerton University, Njoro, Kenya, December 2000.
15. Soil Science Society of East Africa Conference held at Continental Hotel, Mombasa on the December 4-8th, 2000.
16. The 4th regional meeting organized by the Forum of Agriculture and Crop Husbandry in Malawi and presented a paper on "The use of manure and Crop residue to improve Minjingu Rock Phosphate for Phosphorus replenishment in acid soils of western Kenya" (July 10-14th 2000)
17. Soil Science Society of East Africa Conference at Tanga, Tanzania and presented a paper. (December 13-19th, 1998)

Hohenheim/July 2019

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Martha Wangu Musyoka

Statutory declaration

I hereby declare that I have written this thesis independently without using other resources than stated herein. Further, I declare that the research work has not been presented in other university for any degree or academic certificate.

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Hohenheim/July 2019

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