EFFECTS OF THREE-STRATA FORAGE CROPPING SYSTEM ON YIELD AND YIELD COMPONENTS OF FOOD CROPS AND SOIL CHEMICAL PROPERTIES IN WESTERN KENYA

DORINE ADONGO OWARE

A Thesis Submitted to the Graduate School in Partial Fulfilment of the Requirements for the Master of Science Degree in Agronomy of Egerton University

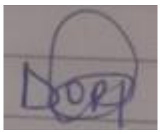
EGERTON UNIVERSITY

JANUARY, 2024

DECLARATION AND RECOMMENDATION

Declaration

This thesis is my original work and has not been presented in this or any other University for the award of a degree.



07/11/2023

Signature Date

Dorine Adongo Oware
KM121/19014/18

Recommendation

This thesis has been submitted with our approval as Egerton University supervisors

…

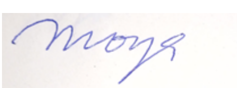
19/11/2023.

Signature Date

Prof. Erick Cheruiyot (PhD)

Department of Crops, Horticulture and Soils

Egerton University



21/11/2023

Signature Date

Prof. Samuel Mwonga (PhD)

Department of Crops, Horticulture and Soils

Egerton University

COPYRIGHT

DEDICATION

I dedicate my work to my supportive mom Mrs. Persila Oware, my siblings Japheth, John, Zadock, William, Phoebe, Eunice and Elsie for their unending love and support. To my husband Erick and son Brighton for always inspiring and encouraging me throughout my academic journey. Your tremendous support, prayers and unending love has pushed me this far. May God bless you all.

ACKNOWLEDGEMENTS

I acknowledge the generous financial support from Education and Training on Sustainable Agriculture and Nutrition across East Africa (EaTSANE-Project). I am indebted to my supervisors Prof. Erick Cheruiyot and Prof. Samuel Mwonga for their patience, continued guidance and support. I am extremely grateful for believing in me over the years. Very special thanks to the EaTSANE project team headed by Dr. Lydia Waswa, Dr. Sahrah Fischer and Dr. Thomas Hilger for the support during the entire research period. I gratefully recognize the efforts of Prof. James Owuoche and Dr. Philip Okwiri who assisted me in data analysis and also believed in my ability and always encouraged me to finish my work. I would like to thank KALRO- Nairobi for allowing me to do soil analysis in their laboratories. To Mr. Shadrack who assisted in the entire process feel highly appreciated. Special thanks also to Egerton University fraternity for giving me a chance to pursue this degree in their institution. I would also wish to express my gratitude to farmers in Teso South, Busia County for providing their farms and actively participating in the research. To Busia County agricultural officers including Mr. Etyang', Mr. Douglas, Madam Catherine and the late Samsom Simuyu, I am forever grateful for the support. Finally, I would wish to thank my friends Christine, Tabitha, Joyce, Nelly, Tracy, Lawrence and Pauline for tremendous support and always believing in me. Thank you all for the strength you gave me. May God bless you all.

ABSTRACT

The exploitation of diverse cropping practices alongside residue incorporation has remained low among small-holder rural farming households in Kenya. A three-year experiment was conducted in Ng'elechom and Obekai in Teso south, Busia County to evaluate the three-strata forage system (TSFS) which integrates forages for animal feeds with food crops thereby enhancing residue incorporation. The objective of this study was to determine the effects of TSFS on yield and yield components of diversified food crops and its impact on the dynamics of soil chemical properties. Food crops including cereals, legumes and African leafy vegetables were evaluated under TSFS and in no TSFS cropping systems. In TSFS system, desmodium, brachiaria grass and pigeon peas were grown in the peripheral area of the farm as forages. The treatments were laid on a randomized complete block design at two locations for 3 years (2019, 2020 and 2021) and performance of agronomic traits measured. After a 3-year field experiment was done, soil samples both in TSFS and in no TSFS were sampled and changes in soil chemical properties analysed. Data from both the field experiment and laboratory analysis were subjected to Analysis of variance (ANOVA) in SAS software and means separated using LSD at 5% level of significance. Results revealed that the effects of cropping system, location and season on crop yields were significant at $p<0.001$. Yield increase of 30.69% and 12.71% was observed in the third season in maize grown in TSFS and in no TSFS respectively. Beans on the other hand recorded a yield increase of 76.52% and 56.25% in TSFS and in no TSFS respectively. The same trend was observed in African leafy vegetables, where yield increase of 49.31% and 39.47% in cowpeas was obtained in TSFS and in no TSFS respectively, during the third season. Crotalaria also recorded a yield increase of 72.36% and 34.39% in the TSFS and in no TSFS, respectively. In TSFS, there was an increase of 17.06%, 23.07%, 8.21% in soil pH, total nitrogen (TN) and soil organic carbon (SOC), respectively. A decrease of 48.27% in soil exchangeable acidity in the TSFS system was observed. However, there was no variation in levels of manganese (Mn) in soil both in TSFS and no TSFS systems. The food crops yielded higher in TSFS than in no TSFS system and therefore this could be an alternative cropping system for curbing food and feed shortage as it improves soil fertility.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS AND ACRONYMS

AEZ	Agro-Ecological Zone
ALV	African Leafy Vegetables
EaTSANE	Education and Training for Sustainable Agriculture and Nutrition in East Africa project
FAOSTAT	Food Agricultural Organization Statistics
LR	Long rains
SOC	Soil organic carbon
SOM	Soil Organic Matter
SR	Short rains
SSA	Sub-Saharan Africa
STN	Soil Total Nitrogen
TSFS	Three-Strata Forage System
WHC	Water Holding Capacity
WHO	World Health Organization

CHAPTER ONE

INTRODUCTION

1.1 Background Information

Diversified cropping system improves productivity and resilience in agricultural systems. Research towards achieving food security through diversified farming system has received little attention despite its importance in crop production stabilization (Michler & Josephson, 2017). In Kenya, agriculture is one of the key sectors that drives the economy as visualized in vision 2030 (Ndung'u *et al.*, 2011). However, the growth in the sector is constrained by inappropriate farming practices which have contributed to decline in soil fertility and low farm productivity. Most soils in Kenya are less productive which has contributed to a decline in crop production and reduction in livestock enterprises due to inadequate animal feeds. Soil erosion is among the threats to decline in soil fertility and is associated with in-appropriate farming practices in Kenya (Gachene *et al*., 2019).

Dry grain maize cultivated annually on estimated area of 197M ha of land globally, it is the second most widely grown crop after wheat (FAOSTAT, 2021). Maize is the preferred cereal crop grown by most farmers in Kenya. It is the staple food and it accounts for nearly 40% of the total cultivated area, 2.4% of total Gross Domestic Product (GDP) and 12.65% of the agricultural GDP (FAOSTAT, 2017). However, maize production in Kenya is below global averages in spite of its importance both at family and national levels. Further, maize production is likely to decline between 5% and 33% by 2050 due to climate change as predicted by climate change models (Nelson & Rosegrant, 2010). The expected decline in production is against a projected population increase of 85 million by 2050. On the other hand, the African leafy vegetables which include pumpkin (*Cucurbita pepo* L.), crotalaria (*Crotalaria retusa* L.) and cowpeas (*Vigna unguiculata*) are increasingly becoming important as subsistence and commercial crops in Kenya (Van *et al*., 2012). They are known for their nutritional attributes and can be used to curb malnutrition challenges (Ntawuruhunga *et al*., 2016). Although the consumption of these vegetables has increased for a decade in both urban and rural areas their production has not been well implemented yet (Matui *et al*., 2016).

In Busia County, the agricultural sector is the main source of income as it employs about 78% of the workforce and contributes about 50% to the household incomes (Government of Kenya, 2013a). Even though agriculture is the main source of income, production has remained low in the recent past. The low agricultural production is associated with declining soil fertility and unfavourable climatic conditions, and this contributes to the high food insecurity level in the County. Research has shown that 84% of crop output in Busia County is used for household consumption since farming is majorly subsistence (USAID, 2014). High consumption of cereals and low consumption of animal and vegetable proteins has led to high incidence of malnutrition of children below 5 years where approximately 15.5%, 13.3% and 14.8% are underweight, stunted and wasted respectively (Jela, 2016). To curb these challenges there is need to improve on cropping pattern and diversify the crops grown so as to enrich diet intake.

Crop plants and residues contribute to about 49% of livestock feed in Busia County hence residue incorporation is generally low (Kinyua, 2019). The low incorporation of crop residues has contributed to most agricultural land remaining bare and the soil easily exposed to erosion. Moisture stress mostly in drier areas coupled with intense soil erosion by either water or wind are among the most problematic hazards in Busia County (Soree, 2017). Growing of livestock feeds and food crops in a sustainable cropping system could enhance crop residue incorporation. Crop diversification with nutrient dense food crops and soil fertility enhancing crops could improve soil fertility and malnutrition challenges. Through this practice, the crops will provide total ground cover while short maturing legumes can act as green manure. Planting of forages as hedgerows for livestock feeds could also narrow the gap of using crop residues as animal feeds.

Three-strata forage system (TSFS) technology integrates diverse food crops such as cereals, legumes and the traditional African leafy vegetables into a sustainable cropping system. The food crops are planted in the core area while the forages on the peripheral areas of the farm thereby providing protection to the food crops. This system enables the farmer to harvest both food crops and forages in the same piece of land. The forages could be annuals or perennials that can stay longer in the soil thereby protecting the soil against erosion and creating an improved fallow during off seasons. The forages could serve as animal feeds and provides an opportunity for the crop residues to be used as composts to improve soil organic matter. The interaction of forages like brachiaria and desmodium with crop pests like stemborers and fall army worm could also protect crops against pest attack following the idea of ‘push-pull’ technology. The aim of this study was to evaluate the performance of food crops grown in the TSFS and in no TSFS and further determine the impact of TSFS on soil chemical properties.

1.2 Statement of the problem

In Kenya, agriculture is one of the key sectors that drives the economy as visualized in vision 2030 (Ndung'u *et al*., 2011). However, the growth in the sector is constrained by inappropriate farming practices which have contributed to decline in soil fertility. Soil erosion is among the threats to decline in soil fertility and is associated with in-appropriate farming practices in Kenya (Gachene *et al*., 2019). Declining soil fertility is also associated with continuous monoculture cropping with little or no fertilizer application. In Busia County, lack of fertilizers is one of the major challenges that famers face and therefore most farmers opt to plant without the use of DAP fertilizers (Ali-Olubandwa *et al*., 2011). Continued application of inorganic fertilizers that supplies mainly nitrogen and phosphorus has also led to mining of other micro- nutrients to deficient levels (Pahalvi *et al*., 2021). There is also competition of crop residues for soil incorporation and livestock feeds. In Busia County, crop plants and residues contribute to about 49% of livestock feed (Kinyua, 2019). This research implies that 100% residue incorporation is generally impracticable among farmers as majority depend on crop residues for livestock feeds. The study therefore aimed at an alternative and sustainable cropping system that allows planting of diverse food crops together with forages and through this, incorporation of diverse crop residues is achieved.

1.3 Objectives

1.3.1 General objective

To contribute to enhanced food, forage and nutritional security through diversifying and integrating food with forage production in Western Kenya.

1.3.2 Specific objectives

i. To determine the effects of a three-strata forage cropping system on yield and yield components of the selected food crops.
ii. To determine the influence of a three-strata forage cropping system on soil chemical properties.

1.4 Hypotheses

i. A three- strata forage cropping system has no significant effect on yield and yield components of the selected food crops.
ii. A three- strata forage cropping system has no significant influence on soil chemical properties.

1.5 Justification

The population of Kenya is projected to increase by 2030, therefore there is need to increase Kenya's annual agricultural production by approximately 75% in order to meet the food demand of 70 million people (FAOSTAT, 2017). Efforts to achieve this are highly hindered by reduced soil fertility as a result of inappropriate farming practices. The three-strata forage cropping system that provides forages and food crops is a sustainable system that has not been fully implemented. In TSFS system, the forages will act as windbreaks thereby reducing the speed of wind while the diverse food crops will provide total ground cover thereby minimizing exposure of soil to agents of erosion. Crop residues incorporation has remained low among most farmers leading to high moisture and soil loss due to erosion. Inadequate animal feeds have also resulted to use of crop residues to feed livestock resulting to low residue incorporation. The use of chemical fertilizers to improve soil fertility has become uneconomical for most farmers due to high cost of production. There is need to explore an alternative sustainable cropping system in order to achieve food, feed and nutrition security.

Chemical fertilizers have been widely used to achieve maximum productivity in conventional agricultural system. However, increased use of fertilizers has been reported to accelerate the acidification of soil thus leading to environmental contamination. Crop rotation is also a better way of improving soil fertility but this has become impracticable due to reducing land sizes as a result of sub-division for human settlement. Crop residue incorporation is beneficial in improving soil health and quality, however, this is yet to be achieved by most farmers due to competition for crop residue as livestock feeds. There is need for alternative cropping system that allows growing of crops together with forages to create opportunity for total incorporation of crop residues. Creating awareness on the benefits of residue incorporation through on-farm trials can encourage the adoption of a three-strata strata forage system by local farmers. It is for this reason that this study was conducted to determine the effectiveness of a three-strata forage cropping system in improving soil chemical properties and crop production.

CHAPTER TWO
LITERATURE REVIEW

2.1 Crop diversification

Climate change and variability affects agricultural sector significantly and there is need to diversify crops grown. Crop diversification involves increasing the number of crops grown per unit area either through practice of planting numerous crops or crop rotation in order to improve productivity (Garbach *et al*., 2017; Kremen *et al*., 2012; Wezel *et al*., 2014). This system enhances sustainability and development of value chains for less important crops thereby contributing to socio-economic benefits (Hufnagel, 2020). Crop diversification practices can include crop rotations involving diverse crops (Reckling *et al*., 2016), mixed farming (Bedoussac *et al*., 2015), planting of perennial grasses and leys which are locally adapted (Hufnagel, 2020).

Maggio *et al*. (2018) found out that diverse cropping systems give higher yields than the mono-cropping systems and its impact on environmental safety were lower. In order to achieve higher and more stable yields, there is need to vary seeding time or changing cropping patterns thereby increasing profitability and thus leading to greater resilience in agro-ecosystems (Urruty *et al*., 2016). Crop diversification is the most environmentally friendly, cost effective and reduces agricultural uncertainties among smallholder farmers (Chibesa, 2020). Arable crop species diversity at national level is directly correlated with greater stability of the total national harvest of all edible crops (Renard &Tilman, 2020).

Diversified cropping system tend to be more agronomically stable as it is usually associated with reduced need for nitrogen fertilizers, reduced weeds and insect pressure (Makate *et al*., 2016). Practicing of crop diversification is an environmentally sound alternative to the control of parasites and soil fertility maintenance (Makate *et al*., 2016). The system also provides habitats for beneficial insects and this reduces some crop pests by rendering host crops less preferred by the pests for their establishment. Crop diversification helps in controlling common crop pests and diseases (Shah *et al*., 2021). Crop mixtures increases natural enemies of insect pests thereby breaking disease cycles.

Improving food, income and nutrition security especially in smallholder farming has become a major challenge due to declining crop yields associated with poor soil fertility as a result of environmental degradation (Zingore *et al*., 2015). Climate smart agriculture as one of the sustainable agricultural practice may reduce the effects of climate change and variation on smallholder farming systems (Wekesa *et al*., 2018). Crop diversification through practices such as integrated soil fertility management, crop rotations and intercropping could improve crop productivity (Rosenstock *et al*., 2016). This system increases resilience and can also serve as an alternative to improve soil fertility and pest control (Truscott *et al*., 2009). The growing of indigenous crops and vegetables contribute to local biodiversity.

2.2 Three-strata forage cropping system (TSFS)

A three-strata forage cropping system is a technology that integrates planting and harvesting of food crops with forages all year round in a sustainable manner (Nitis *et al*., 1993). The forages are planted at the peripheral area around the crops in different layers. The forages can be annuals/perennials that can stay longer in the soil thereby protecting the soil against erosion and creating an improved fallow during off-seasons The forages can be used by farmers directly as livestock feeds on the farm or sold to generate income. The crop residues are incorporated back in the farms to add organic matter into the soil (Hansen *et al*., 2020). The nutrient dense crops can also supply green manure through shedding of leaves, good ground cover and can also be used to reduce malnutrition among children (Kinyua *et al*., 2019).

The TSFS is a modified crop-animal farming system which is highly appropriate and important strategy for feed and food production. The TSFS maintains and sustain soil fertility thereby improving crop yield and dietary feeds to livestock (Sekaran *et al*., 2021). The leguminous forages act as hedgerows thereby protecting soil against erosion (Hombegowda *et al*., 2020). The development of TSFS is appropriate for both highland and lowlands since it provides feeds for livestock use, promote nutrient recycling through biological nitrogen fixation (Huluka & Argaw, 2018). Planting of legumes improve natural fallows during off-seasons and the plants shedding off their leaves also acts as green manure (Kar & Singh, 2023). The TSFS improves the availability of animal feeds throughout the year. The grasses and leguminous forages in TSFS can be harvested through cut and carry or fed to livestock directly (Singh & Kumar, 2012).

In smallholder production systems animals are mainly fed on natural pastures and weeds from fallow lands (Gowing *et al*., 2020). The forages from this system of feeding have low nutritional value to livestock and therefore cannot sustain animal growth. The low input agriculture practiced in Sub-Saharan Africa, is prevalent and cannot deliver enough food and feeds for the coming generation (Gowing *et al*., 2020).

2.3 Selection of food crops grown in the three-strata forage system

The diversified food crops were selected on the basis of nutrient dense vegetables which can provide good ground cover besides the nutritional benefits (Kinyua *et al*., 2019). The legumes and cereals were planted in order to benefit from intercropping system in case of crop failure and to exploit the complimentary benefits between the crops (Sahoo *et al*., 2023). The food crops grown included cereals, legumes and African leafy vegetables. The crops were grown under polyculture system, intercropping and mono-cropping systems.

2.3.1 Maize, beans and pumpkin grown as poly-culture

Polyculture involves growing of three main crops of various groups that is maize (*Zea mays* L.), climbing beans (*Phaseolus vulgaris* L.) and pumpkin (*Cucurbita pepo* L.) closely together **(**Boissele, 2017). The incorporation of these three crops benefit from each other, maize provides a structure for the beans to climb, eliminating the need for poles. Often, all legumes add organic matter into system in association with Rhizobium bacteria (Mohammed *et al*., 2012). The organic matter incorporated plays a role in increasing soil stability, resistance to soil erosion and activities of soil organisms (Chepkoech, 2015). Maize, bean and pumpkin have different shoot structure and hence poses niche complementarity effects (Postma *et al*., 2012). The beans will therefore fix nitrogen to the soil that other plants can be able to use (Gellings & Parmenter, 2016). Pumpkin leaves acts as 'living mulch' which creates a micro-climate to retain moisture in the soil (Gonsalvez, 2016).

This cropping system is important for weed control through smothering effect (Choudhary *et al*., 2014). Weeds compete for resources like water, light and deplete nutrients thus resulting in decline in crop yield if not managed properly (Bhatt *et al*., 2016). Pumpkin has the ability to tolerate shade and cool temperatures (Dumlao *et al*., 2012). It also has creeping growth habit and rapidly covers the soil surface thereby smothering weeds. Pumpkin has the ability to grow well during the dry spell therefore, it is guaranteed to harvest even if the rains are inadequate (Mertz *et al*., 2009). Erratic weather conditions may affect the growth and productivity of maize and beans due to inadequate soil moisture, pests and diseases attack but pumpkins will overcome the two adversities. Polyculture cropping system yielded higher and supported more people per hectare compared to monocultures of the individual crops (Pleasant, 2016).

Maize is the main staple food crop in Kenya, accounting for nearly 40% of the cultivated area, 2.4% of Kenya's GDP, and 12.65% of the agricultural GDP (FAOSTAT, 2017). In Kenya, small holder farmers accounts for more than 75% of the total maize produced although out of the 75% only 20% is sold in the market (FAOSTAT, 2017). A research done by FAO in the year 2016 estimated that in Kenya each person consumes on average 103 kg/year as captured in data for the year 2012-2014, compared to 73 kg/ year for Tanzania, 52 kg/year for Ethiopia, and 31 kg/year for Uganda during the same period (FAOSTAT, 2017). Production of maize in Kenya is below global averages in spite of its importance at both family and nation level. Muraoka *et al.* (2016) found that there is a positive significance on land productivity in Kenyan highlands when a high yielding variety is planted with recommended fertilizer rates.

The increasing demand for maize due to high population increase implies that by 2023, maize will account for the greatest share of about 34% of the total crop area harvested (West *et al*., 2014). The rising demand has often increased maize area and brought about new land into cultivation through sustainable intensification in order to achieve an increase in yield. The crop area has often expanded into more marginal lands with high potential threats to crop diversity and erodible top soils in hilly slopes (Neumann *et al*., 2010). Soil infertility and over-reliance on fossil fuels to produce energy for synthesis of nitrogenous fertilizers and pesticides (Juárez & Sheinbaum, 2020).

Climate change models have predicted that maize yields are likely to decline between 5% and 33% by 2050 and this will depend on severity of climate change (Nelson & Rosegrant, 2010). The largest fall in productivity will be experienced in under-developed countries as a result of climate change with a possibility high rise of maize prices by about 30% (Pandeyi, 2020). Improved agricultural technology is seen as the best strategy for increasing agricultural productivity thereby obtaining sufficient food and alleviating poverty among farmers (Khan *et al*., 2011). In addition, crop productivity is declining as a result of intensive farming which leads to soil degradation through erosion and declining soil fertility as a result of excessive leaching (Kagabo *et al*., 2013).

Beans belong to the genus of *Phaseolus* and family of Leguminaceae and are considered the most important crops after maize country-wide. Beans are used as vegetables for human or animal food (Yamaguchi, 2012). Legumes including beans are capable of fixing nitrogen and hence need less fertiliser than most plants. Maturity of beans take about 55–60 days from planting to harvest (Shurtleff & Aoyagi, 2013). Bean is very nutritious consequently, their seeds have served as raw materials for the production and enrichment of certain foods like breads and other bakery items (Rebello *et al*., 2014).

Climbing beans has high yielding potential under good management it can yield up to 4 to 5 tons/ha unlike 3 tons/ha for bush beans (CIAT, 2004). Climbing bean has high lysine content which is deficient in maize, rice and cassava and thus highly recommended in the diet (Katungi *et al*., 2009). Common beans strongly inhibit the activity of key pancreatic enzymes trypsin and chymotrypsin thereby reducing digestion even in the presence of high amounts of digestive enzymes (Gemede *et al*., 2014).

The production of climbing beans is still limited in Kenya despite the positive attributes. The production sector is constrained by low soil fertility due to restricted access to fertilizers associated with high prices. High cost of stakes, limited use of improved climbing varieties and weak extension services are among the challenges associated with low bean production in Kenya (Katungi *et al*., 2009). It is rich in biomass which when incorporated into the soil can act as good ground cover and also serve as mulch.

Pumpkin (*Cucurbita pepo*) which originated from North America belongs to the family *Cucurbitaceae* which also includes gourds, cucumber, melons and squash. Pumpkin is adapted to a wide range of agro-ecological zones and very rich in multiple nutrients (Moa & Jica, 2000). In Kenya, the production of pumpkin has remained low with smallholder farmers producing less than the potential of 20 tons per hectare (HCDA, 2013). Low pumpkin production is associated with pests and diseases infestation, unavailability of seeds and lack of awareness on the crop’s nutritive value as majority still associate its consumption with poverty (Shava *et al*., 2009).

In Kenya, the demand is high majorly in urban and peri-urban regions and the production is still very low to meet the demand (Ngugi *et al*., 2007). Pumpkin can be used either at homes as food or for commercial purposes. The seeds are rich in protein, carbohydrates and oil containing unsaturated fatty acids (Karanja *et al.*, 2013). They are often grown for recreational purposes due to their attractive shape and colour. Their seed is an excellent source of protein and has anti-fungal and anti-bacterial (Kaur & Sharma, 2018). In addition, it is used to control type 2 diabetes or non-insulin dependent diabetes mellitus through ingestion of crude aqueous extract of pumpkin fruits (Yavad *et al*., 2010).

2.4 Chickpea grown as monocrop

Mono-cropping is an agricultural practice of growing a single crop year after year on the same piece of land. Chickpea is ranked third among the most important food legumes rich in protein (Jain *et al*., 2013). Chickpea contain minerals such as magnesium (Mg), calcium (Ca), potassium (K), zinc (Zn), phosphorus (P), and iron (Fe) (Thavarajah, 2012). It constitutes 20-30% protein, 40-64.6% carbohydrate, 3% fibre, 3-6% oil, 4% ash, and is a good source of absorbable ions like calcium (Ca), phosphorus (P), magnesium (Mg), iron (Fe), potassium (K) and essential Vitamin-B (Abu-Salem & Abou-Arab, 2011).

The high nutritional composition of chickpea helps in improving digestion, boosting mental health and strengthening bones (Mudryj *et al*., 2014). Chickpea is susceptible to fungal, viral and bacterial infections which if not timely managed can cause serious economic losses globally (Nene *et al*., 2012).

2.4.1 Production and economic importance of chickpea in Kenya

A report by KARI, 2011 indicated that 55,000 ha of land was under chickpea production in Kenya and this translated to about 15,000 tons to 18,500 tons of chickpeas produced. An annual increase of 10% has been recorded in chickpea production in Kenya since 2017 when 550 tons of chickpea was produced. Over 270,000 households derive their livelihood from chickpea production both in dry highlands and ASALS of Kenya (Kimurto *et al*., 2014). Chickpea improves soil structure of acidic soils when applied as a green manure (Danga *et al*., 2013).

In Kenya, chickpea is generally grown by smallholder farmers in dry zones of Eastern and Rift-valley provinces (Wafula *et al*., 2021). The plant is developed for its nutritious seeds which are rich in protein and fibre (Sofi *et al*., 2020). Chickpeas are low in fat and making it to be credible crop for weight reduction ((Mudryj *et al*., 2014).). The production of chickpeas in Kenya has been adopted by smallholder farmers in the lowlands. Chickpea creates opportunity of enhancing other legume production as it does not compete with other legumes especially the wet season legumes (Fikre & Ahmed, 2020). In Kenya, chickpea can be grown after the harvest of cereals and grows under residual moisture thus ideal in areas where farmers are planting in one season (Fikre & Ahmed, 2020). The crop residues obtained from chickpeas are used as animal feeds or incorporated back in the soil to improve soil fertility (Shinde *et al*., 2022).

It is more drought-tolerant than other cool season legumes and the demand is projected to increase in future due to global population increase and climate change (Bar-El *et al*., 2017). Chickpea serve as a source of energy and protein rich feed for livestock leading to high nutrition values and less digestive problems in non-ruminants (Abu-Hafsa *et al*., 2022). The green leaves are rich in minerals and therefore are consumed as vegetables while the green immature seeds used as snack and the dry seeds milled into flour. Past studies indicate that chickpea has the ability to improve soil fertility and yield of following cereal crops by 24-68% in a cereal-legume relay cropping system and hence it has become attractive to cereal farmers (Kimurto *et al*., 2014).

2.5 Production of cowpea -amaranth and groundnut –crotalaria as inter-crops

Intercropping as a practice of cultivating two or more crops in the same space at the same time serve to increase production and utilize available growth resources (Lithourgidis *et al*., 2011). The biological benefit is enhanced through efficient light interception by species occupying the same land area when the inter-specific competition is less than intra-specific competition in the same entity (Dolijanovic' *et al*., 2013). Other benefits associated with intercropping include; soil conservation, restriction of growth of weeds, reduced pests and diseases incidences (Muperi, 2016).

Cowpeas is an annual leguminous crop which matures after a short period of time (Ngalamu & Tongun, 2015). It is majorly grown for its seeds and leaves and residues used as livestock feeds. Cowpeas is a good source of protein, vitamins (A, B and C) and other micro-nutrients such as zinc, magnesium, calcium and iron (Osipitan *et al*., 2021). Cowpea is also used in soups, stews or ground into flour and used in bakery industries (Yavad *et al*., 2018). It can easily be grown as inter-crop with cereals or other African leafy vegetables like Amaranth. A research done by Southern Sustainable Agriculture and Education, showed that intercropping cowpea with vegetable crops increases its yield up to 50% (Kumawat *et al*., 2022). Intercropping cowpeas and amaranth improves their survival and growth due to companion interaction between the two crops (Mndzebele *et al*., 2020).

Groundnuts is a short maturing legume with multiple uses. In Kenya, the crop is grown in an estimated area of 18,000 ha thereby producing up to 21,000 metric tonnes. Groundnut is majorly rich in proteins but also contains oils, vitamins and minerals such as potassium, phosphorus and calcium (Balasubramanian *et al*., 2020). This crop grows best in deep, and well drained sandy soils. The crop does poor in acidic soils and is highly sensitive to salinity and therefore it requires optimum soil pH of between 5.3 to 7.3 (Wafula, 2021). Groundnuts is usually planted as an intercrop either with cereals or African leafy vegetables like crotalaria. Crotalaria is one of the most underutilized indigenous vegetables in Kenya (Mwakha *et al.*, 2020). Slender leaf crotalaria has contributed to dietary improvement and even food security especially for the small holder farmers (Akinola *et al.*, 2020). The leaves are rich in vitamins A and C and can also be used locally as medicine for treating stomach related ailments like abdominal pains and stomach ulcers (Nakaziba *et al.*, 2021). This vegetable is also capable of fixing atmospheric nitrogen, and due to its high biomass production, it can be used as green manure in farms (Silva *et al.*, 2021).

Crops in the intercrop should differ in their nutrient acquisition potential for better utilization of available resources in different soil depths. Intercropping reduces the risk of crop failure that may result from fluctuations of weather variable factors such as inadequate soil moisture that cause one crop to mature relatively earlier compared to the other thereby obtaining yield of at least one crop (Alemayehu *et al.*, 2017).

2.6 Suitability of forages used in the three-strata forage system

The selection of forages depends on their preference in the livestock sector, their adaptability in the region and finally their importance on restoration of soil fertility. The forages used in the study include; silver-leaf desmodium which is a nitrogen fixing legume, brachiaria grass which is fodder grass and pigeon peas being a fodder legume. The forages should also have higher palatability and can be used be variety of animals.

2.6.1 Production and economic importance of silver-leaf desmodium

Silver-leaf desmodium (*Desmodium uncinatum)* is a warm season legume as well as cold tolerant tropical legumes and can survive frost at -10°C. Extreme frost may kill the leaves, however, the plant recovers quickly in warm weather and it is one of the earliest tropical legumes to grow in spring (Heuze *et al.,* 2015). Silver- leaf desmodium is irregular annual/perennial leguminous crop that may grow up to about 1m over the surrounding vegetation. It has shallow root system that node during wet conditions hence rapidly forms dense ground cover under good management (Valenzuela, 2011). The seeds of silver leaf desmodium are olive-green in colour, triangle or oval shaped 3mm long and 2mm wide (Heuze *et al.*, 2015).

Optimal growth is obtained at average temperatures ranging between 25°C and 30°C with rainfall up to 1000 mm. It has been established that heavy rainfall of up to 3000 mm is harmful to its growth (FAO, 2011). It is tolerant to flooding but cannot stand poorly drained soils such as clays, or soil salinity (FAO, 2011). Silver-leaf desmodium is mainly used as mulching material but can also be used as feed for livestock (Assefa, 2012). Silver-leaf desmodium establish slowly in its early growth stages and therefore weed management strategies should be put in place to avoid unnecessary competition (Lissu *et al*., 2016). Desmodium has weak vines hence should be intercropped to provide support to the weak vines and shade.

Silver-leaf desmodium requires beneficial Rhizobium bacteria to grow just like other legumes in order to fix nitrogen from the air that may be available as a free fertilizer to the plant (Miriko, 2018). The fixed nitrogen will reduce the need for nitrogen fertilizer and whose trickle effect is increase in crop yields in a desmodium intercrop (Midega *et al*., 2013).

It is a high quality protein-rich forage and effectively controls some problematic weeds such as *Striga asiatica* and *S. hermonthica* (Pickett *et al.*, 2013). Desmodium has allelopathic nature due to its high content of *phenolic* compounds which inhibit the growth of other plants (Khan *et al*., 2008). Desmodium can be used as an effective biological striga control due to its allelopathic quality (Sodaeizadeh & Hosseini, 2012). Due to the desirable qualities and multiple uses of desmodium it is one of the best legumes used in the three-strata forage cropping system as the innermost stratum which requires nitrogen fixing legume.

2.6.2 Production and economic importance of brachiaria grass

Brachiaria grass (*Brachiaria decumbens*) belongs to grass family mostly grown in the tropics and sub-tropics of Asia and Africa. It can grow in numerous environments but generally brachiaria grass do best in savannas and other open tropical ecosystems (Torres & Morton, 2005). Brachiaria is an annual/perennial grass that grows to a height of 100 cm and lack rhizomes but exhibit branching panicle (Chaudhari *et al*., 2013).

Brachiaria grass are C_4 species and can tolerate drier conditions and their leaves are more exposed to light than some other plants (Baldissera *et al*., 2016). Brachiaria grass grows faster than Napier grass with little moisture requirement due to its tufted growth habit (Nguku *et al*., 2016). In the tropics, brachiaria grass is the single most important forage grass for pastures as it can grow in less fertile and acidic soils (Singh *et al*., 2018).

The crude protein content of Brachiaria grass can range from 9 to 20% thereby giving quality and tasty forage for livestock (García *et al.*, 2019). It has high rate of re-growth after grazing, more nutritious and highly palatable as animal feed (Ondabu *et al*., 2016). Brachiaria grass has high plant vigour thereby producing more biomass even on low fertile soils (Paciullo *et al*., 2010). It conserves water thereby making it drought tolerant (Odokonyero *et al*., 2016).

Brachiaria grass has the ability to produce repellent chemicals that repel pests and hence can be used as mechanism to avoid invasion of crops by pests (Cheruiyot, 2018). It can play a significant role in soil improvement, soil conservation thereby increasing bio-diversity and minimizing greenhouse gas emissions (Da Silva Dias, 2015). Brachiaria also has a wide developed rooting system that enhances water and nutrients uptake from the soil and hence resilient to effects of climate change (Midega *et al*., 2015). Brachiaria cultivars can grow in less fertile and slightly acidic soils (Rao *et al*., 2016).

In low fertile soils, Brachiaria grass has shown to improve the fertility of soil when rotated with food crops (Tesfai *et al*., 2019). Brachiaria grass has the ability to reduce nitrous oxide emissions from the soil through biological nitrification inhibition processes (Simon *et al*., 2020). The major challenges experienced by farmers in the adoption of high quality forages are pests and diseases. The major production constraints in brachiaria Mulato *II* is the arthropod pests. There is little exploitation in breeding programs to narrow the wide genetic variations observed in brachiaria in order to achieve resistant species to common pest and diseases (Cheruiyot *et al*., 2020). However, two brachiaria varieties Mulato II and Piata are important in developing management strategy such as 'push-pull' technology as pest management mechanism.

2.6.3 Production and economic importance of pigeon pea

Pigeon pea (*Cajanus cajan*) is a grain legume crop in the family *Fabaceae* and mainly cultivated in the semi-arid tropics due to its ability to withstand soil moisture stress (Ahmed *et al*., 2016). Pigeon pea is an annual/perennial leguminous crop that compete less with intercropped cereals like maize and short duration beans due to its deep root morphology. Pigeon pea is the third most widely grown pulse crop in Kenya for its high quality protein and high dry matter digestibility (Saxena *et al.,* 2010). Compared to soybean, pigeon pea is not as effective as soybean in accumulating high dry matter and protein levels under adverse growing conditions (Rao *et al*., 2009).

The vigorous root system of pigeon pea has the capacity to explore large soil volume and nutrient recycling from deeper soil profiles (Abebe *et al*., 2016**)**. Pigeon pea is nutritionally well balanced and is an excellent source of proteins 20–30% (Karri & Nalluri, 2017). It also provides carbohydrates and high levels of vitamins A and C (Mbaeyi *et al*., 2016). The biomass from pigeon pea rapidly decomposes to release nitrogen as compared to maize stalks. Residues of high quality organic inputs on the other hand decompose quickly and may release about 70% of the nitrogen within a season under tropical conditions (Ibrahim *et al*., 2018). It is also source of wood for fuel and also used for fencing purposes. The seeds contain various amino acids components that can impose negative effects depending on the animal species (Nwoagu *et al*., 2010).

In a ration of corn-silage for lactating dairy cows, 20% of seeds of pigeon peas can be base fed without any side effect on dry matter intake of 22.5 kg/DM/day in order to achieve milk production of 42 litres/day (Corriher *et al*., 2010). Incorporating heated pigeon pea in the diets of quails increases the growth by approximately 20-30%, however, increased feed consumption lead to degradation of feed conversion efficiency (Emefiene *et al*., 2014).

Pigeon peas is under-utilized despite its importance in income generation and enhancing food security to small-holder farmers. One of the major challenges experienced by smallholder farmers is that this crop has slow initial development and less competitive compared to other grown legumes like cowpeas, soybeans and groundnuts. Both biotic and Abiotic stresses affect pigeon production in Kenya (Nolipher, 2014). Major pests and diseases that affect pigeon peas include blister beetles, aphids, pod borers, pod bugs, bacterial leaf spot and leaf canker (Sarkar, 2020). The crop however, can adapt to wide range of soil types even though it thrives best in well drained, loamy soils with high organic matter content. Pigeon pea can be grown at different altitudes although in Kenya it is commonly grown in lowland to mid-altitude areas (Mligo & Craufurd, 2005). High humidity levels lead to increased diseases invasion especially fungal related diseases (Pande *et al*., 2013).

2.7 Effects of three-strata forage cropping system on soil chemical properties

Soil chemical properties including soil organic matter (SOM), soil pH, soil macro- and micro-nutrients contribute to soil health. The type and method of crop residue incorporated determine the rate of decomposition (Kauer *et al*., 2021; Stegarescu *et al*., 2020). Planting of cover crops with regular field crops improves soil chemical properties and thus addresses the issue of soil health (Carr *et al*., 2013). Increased species diversity improves the overall production per unit area and helps in retention of nutrients (Brooker *et al*., 2015).

Multiple crop species in a single unit area sequester more soil carbon due to the influence of root litter decomposition (Cong *et al*., 2015b). Soil organic carbon (SOC) and soil total nitrogen (STN) can be increased within 0-20 cm of the soil layer through increasing cropping intensity (Liao *et al*., 2015). Enhancing carbon and nitrogen stocks improves soil structure and soil water- nutrient-crop productivity (Naresh *et al*., 2018). This can be used to mitigate emissions of greenhouse gases, such as methane (CH_4) and carbon (iv) oxide (CO_2) in the atmosphere (Bento *et al*., 2018).

Crop rotation and management practices such as tillage cause a substantial influence on the soil as they interfere with the normal soil-environment (Li *et al*., 2022). Microorganisms in the soil are responsible for the decomposition of organic matter inputs in the form of crop residues and plant litter. In the process of breaking down the residues, carbon is incorporated into microbial biomass pool thereby becoming a key component of SOM (Cotrufo *et al*., 2013). The addition of one or more crops to a monoculture increases the amount of total microbial biomass of Carbon and Nitrogen (McDaniel *et al*., 2014). The analysis also reported that by adding one or more crops into a crop rotation increases both soil organic carbon and total nitrogen in the soil. Cover crops help to reduce the use of herbicides in the field for weed control. The incorporation of cover crops into the soil promote the activities of microorganisms.

2.8 Effects of residue incorporation on soil chemical properties

The increased decomposition of crop residues increases soil organic matter (SOM) and soil fertility (Drost *et al*., 2020). The incorporation of residues improves soil moisture content by reducing surface run-off and direct evaporation, water infiltration and improving soil saturated water conductivity (Jin *et al*., 2020). The application of crop residues to soil has been shown to increase the pH of topsoil and sub-soil and the effects can persist for over 26 months (Diacono *et al*., 2011). Crop residues have been identified as source of organic potassium and thus can effectively replace the use of inorganic potassium fertilizers to improve potassium supply and crop yields (Sui *et al*., 2014).

The decomposition of incorporated residues increases soil organic carbon into the soil (Zhang *et al*., 2016). The amount of soil organic carbon is directly associated with the amount of crop residues incorporated (Malhi *et al*., 2011). Chalise *et al*. (2019) found out that increased soil organic carbon and decreased soil bulk density with crop residue incorporation. Soil nitrogen dynamics has also been observed to be directly related to that of soil organic carbon (Moges & Holden, 2008). Ghimire *et al*. (2012), reported that an increase in the amount of residue returned in the soil significantly increased soil organic carbon and nitrogen in the system. The retention of crop residues resulted in 110% increase in the recovery of fertilizer-derived N in vegetative biomass and a significant increase in 41% for total N in the soil-crop system (Murphy *et al*., 2016).

Crop residues are generally rich in organic carbon but also contain nitrogen, potassium, phosphorus and microelements. One of the most affordable and sustainable way of improving soil quality without disturbing its biological balance is through crop residue retention (Turmel *et al*., 2015). The crop residues decomposition increases the amount of organic carbon, potassium and available phosphorus in soils thereby providing nutrients for the microorganisms and the growing crops (Verhulst *et al*., 2010). Residue retention improves the stability of soil aggregates, pores and moisture content (Guo *et al*., 2020). Crop residue retention reduces the negative effects of allelo-chemicals on crop growth (Hussain *et al*., 2021). In some conditions, crop residues have shown the inhibitory effects on some heavy metals found in soil (Fu *et al*., 2021). Furthermore, the crop residues have shown positive effects in reducing the availability of some soil organic pollutants, and improving saline soils (Fu *et al*., 2021).

Diverse crop residues have been found to be important for the redistribution of alkalinity within soils there by increasing soil pH. Xiao *et al*. (2013), found out that the incorporation of crop residues into the soils increased soil pH upon decomposition. A previous research on the contribution of crop residues to changes in soil pH under field conditions showed that residues (10 g dry matter) increased soil pH and temporal changes in alkalinity depended on the residue and soil type (Butterly *et al*., 2013). Wang *et al*. (2017), found out that chickpea and canola residue amendments increased soil pH at 0-10 cm in the podzol by up to 0.47 and 0.36 units and in the cambisols by 0.31 and 0.18 units, respectively, at 48 months when compared with non-residue amended control.

The incorporation of crop residues increases soil organic matter in the soil through decomposition. The organic matter helps in adsorbing and retaining nutrients in a form that can easily be accessed by plants. Hijbeek *et al*. (2017) found out that there is a positive correlation between crop yield and soil organic matter content in the soil. Crop residue incorporation and nitrogen fertilizer application significantly improved soil nitrogen and maize grain yield over non-residue incorporation (Uzoh *et al*., 2019). Crop residue incorporation as a source of organic matter resulted in 12% and 16% higher yield in maize and sugar beet respectively compared to other sources (Piccoli *et al*., 2020).

Diverse crop residues have been found to be important for the redistribution of alkalinity within soils there by increasing soil pH. The incorporation of crop residues into the soils increased soil pH upon decomposition (Xiao *et al*., 2013). A previous research on the contribution of crop residues to changes in soil pH under field conditions showed that residues (10 g dry matter) increased soil pH and temporal changes in alkalinity depended on the residue and soil type (Butterly *et al*., 2013). Chickpea and canola residue amendments increased soil pH at 0-10 cm in the podzol by up to 0.47 and 0.36 units and in the cambisols by 0.31 and 0.18 units, respectively, at 48 months when compared with non-residue amended control (Wang *et al*., (2017).

CHAPTER THREE

MATERIALS AND METHODS

3.1 To determine the effects of three-strata forage cropping system (TSFS) on yield and yield components of selected food crops

3.1.1 Experimental site description

This study was conducted between September-December 2019 (short rains), April-August 2020 (long rains) and April-August 2021 (long rains) cropping seasons in two locations. The two locations were Ng'elechom (0^o 34.66'N, 34^o 10.05'E) and Obekai (0^o 30.04'N, 34^o 12.96'E) within Teso South Sub-County in Busia County, Kenya (0^o 27'N, 34^o 19'E). The soils in Ng'elechom are gleyic acrisols consisting mainly of unconsolidated sand deposits while Obekai has humic cambisols with high clay content and good drainage (Jaetzold *et al*., 2012). Both locations lie within lower midland cotton zone (LM3), Obekai has an altitude of 1202 meters above sea level (m.a.s.l) while Ng'elechom has 1128 m.a.s.l (Jaetzold *et al*., 2012). The two locations receive bimodal rainfall with long rains occurring between March to August while short rains start from September to December (Jaetzold *et al*., 2012). However, over recent years the rainfall pattern is not definite due to the effects of climate change. The two locations receive an annual precipitation range of 1,000 mm-1,500 mm and have daily mean temperature range of 14-30^{o}C (Jaetzold *et al*., 2012).

3.1.2 Plant genotypes

A set of diverse food crops were selected and grown which included cereal (maize), legumes (climbing beans, chickpeas, groundnuts) and African leafy vegetables (cowpeas, pumpkin, amaranth and crotalaria) (Table 3.1). The food crops were selected on the basis of the regional adaptability, nutrient dense and provision of good ground cover especially the African leafy vegetables like pumpkin. In TSFS, the strata forages planted were desmodium (*Desmodium uncinatum*), brachiaria grass (*Brachiaria decumbens*) and pigeon peas (*Cajanus cajan*). All the planting materials were certified except for the brachiaria sets, amaranth, crotalaria, and pumpkin seeds which were sourced from local farmers.

Table 3.1: Selected planting materials in the three-strata forage system (TSFS) trial

Plant Material	Variety	Source
1. Maize	*Duma* 043	Kenya seed
2. Climbing beans	Kenya Safi	Kenya seed
3. Pumpkin	Local variety	Farmers
4. Chickpeas	*Saina* K1	Egerton University
5. Cowpea	Ken Kunde 1	KALRO
6. Amaranth	'giant head'	Farmers
7. Crotalaria	Local variety	Farmers
8. Groundnuts	Red Oriata	KALRO
9. Desmodium	Silver-leaf variety	Kenya seed
10. Pigeon peas	Egerton Mbaazi 3	Egerton University
11. Brachiaria grass	Mulato II	Farmers

3.1.3 Experimental design and treatment application

The experiments were laid out in randomized complete block design (RCBD) with three replications per location. The eight selected food crops were grown under two different cropping systems as polyculture, monocrop and intercrops (Table 3.2). In TSFS, the crops were enclosed by layers of different forages at the peripheral area of the plots while in no TSFS the crops were left open (Fig. 3.1). The plots were sub-divided into four with each having a different crop. The crop residues were incorporated in TSFS during the second and the third seasons. In both cropping systems, crop rotation was practiced during the second and third seasons as a way of randomizing the crops at plot level.

Table 3.2: Experimental layout and Treatment application

Treatment (cropping systems)	Crop(s)	Residue incorporation	Spacing
1.TSFS	Maize + Beans + Pumpkin	Yes	75 cm x 25 cm and 1 m x 1 m for pumpkin
2. TSFS	Chickpeas	Yes	60 cm x 20 cm
3. TSFS	Cowpeas + Giant amaranth	Yes	60 cm x 20 cm
4. TSFS	Crotalaria + Groundnuts	Yes	60 cm x 20 cm
5. No TSFS	Maize + Beans + Pumpkin	No	75 x 25 cm and 1 m x 1 m for pumpkin
6. No TSFS	Chickpeas	No	60 cm x 20 cm
7. No TSFS	Cowpeas + Giant amaranth	No	60 cm x 20 cm
8. No TSFS	Crotalaria + Groundnuts	No	60 cm x 20 cm

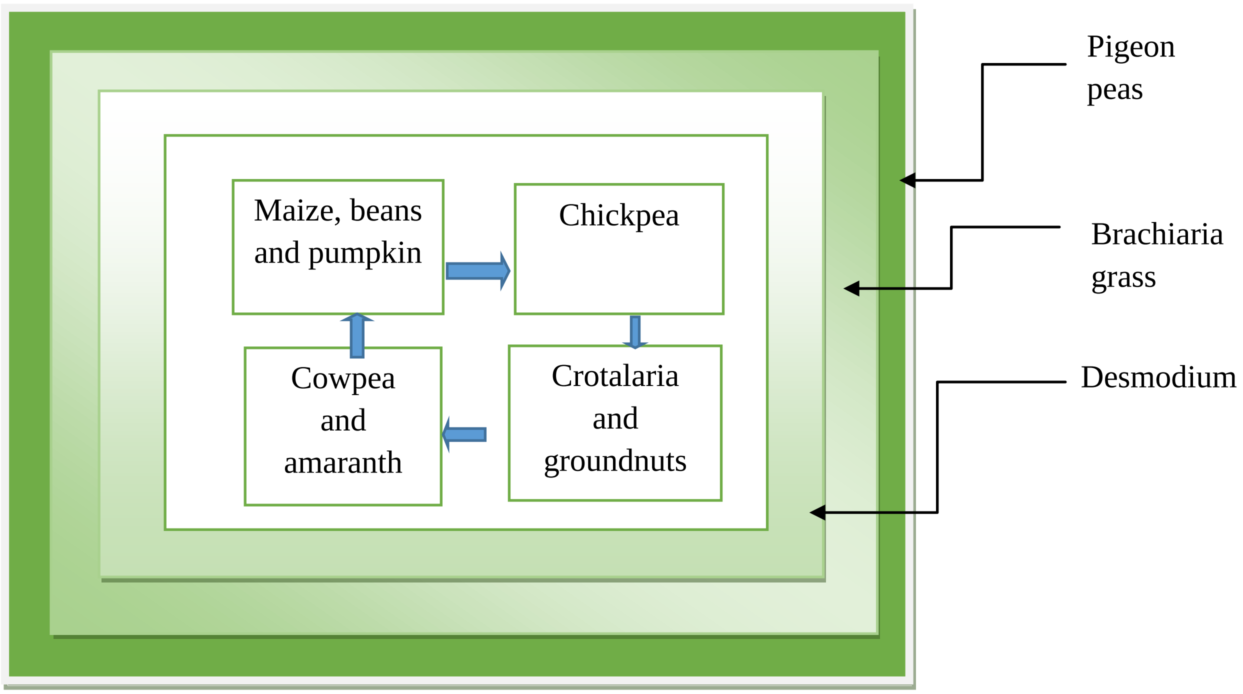


Figure 3.1: TSFS cropping system, the arrows show how crop rotation was practiced

3.1.4 Field preparation, experimental layout and agronomic management

The land was prepared by oxen-driven plough and seedbed prepared to improve the soil tilth depending on the seed size. In the first plot of polyculture system consisting of maize, beans and pumpkin, one maize seed was sown per hill at a spacing of 75 cm × 25 cm to give a plant population of 54,595 plants/ha. The climbing beans were also sown one seed per hill in between the maize rows at a spacing of 75 cm × 30 cm (44,445 plants/ha) and pumpkins were planted at a spacing of 1.5 m × 1.5 m (4,445 plants/ha) in an alternate row of maize and beans.

In the second plot chickpeas were planted as a sole crop at a recommended spacing of 40 cm x 20 cm (125,000 plants/ha). In the third plot an inter-crop of cowpeas and amaranth, cowpeas were planted at a spacing of 60 cm × 20 cm (83,334 plants/ha) with double row of amaranth drilled in between and later were thinned to a spacing of 60 cm × 20 cm (83,334 plants/ha) two weeks after emergence. Lastly, an inter-crop of crotalaria and groundnut, crotalaria seeds were drilled and later thinned to a spacing of 60 cm × 20 cm (83,334 plants/ha) two weeks after emergence with double row of groundnuts at spacing of 60 cm by 20 cm (83,334 plants/ha).

All the plots measured 4.5 m × 4.5 m and thus the application of fertilizer was equal with 6 furrows of fertilizer in each plot. A compound fertilizer, grade 23-23-0 (NPK), was used during planting which supplied an equivalent of 11.5 kg N/ha and 11.5 kg P_2O_5/ha. A 50 cm alley way was maintained between the crops and forages. The inner-most stratum consisted of silver-leaf desmodium planted at a spacing of 30 cm × 30 cm to achieve a seeding rate of 2.5 kg/ha. The second stratum consisted of *Brachiaria ruzizinsis* variety *Mulato*. The brachiaria sets were planted at a spacing of 50 cm apart, distance between the inner and the second stratum was 50 cm. A medium maturing pigeon peas variety *Mbaazi*-1 was planted in the outer-stratum at a spacing of 50 cm × 10 cm at a seed rate of 12 kg/ha. The crops were hand weeded twice in the 4th and 9th week after emergence. Thunder (*Imidacloprid* 100 g/L + *Betacyfluthrin* 45 g/L) was used at the rate of 100 ml/ha for protection against common insect pests in pigeon peas during flowering. There was no pesticide used on the food and vegetable crops.

A field trial experiment was set earlier (April-August 2019) before the beginning of the first season of the experiment. This was done in order to give TSFS enough time to establish. After the first cycle of cropping season all the residues obtained from crops both in the TSFS and those in no TSFS were combined, chopped into smaller pieces and incorporated back in the plots inside the TSFS. However, the plots in no TSFS were left bare, this was done with assumption that residues were used as animal feeds a practice that is common with local farmers. The same crops were planted during the second and the third cropping seasons and similar set of data taken.

3.1.5 Data collection

Data was collected on growth, physiological response, yield and yield components; the data collected for each crop depended on the value of the parameter in assessing its performance. The data were collected in randomly selected plants within the plots. Five plants of each crop species in a plot were randomly selected and the parameters taken. The data collected on pumpkin, chickpeas and pigeon peas in the three seasons at both locations were excluded from the analysis owing to crop failure at a flowering and pod formation stages due to heavy rains (Appendix 5).

For maize, the plant height was determined at 30 days after planting and at maturity by measuring the height from the ground level to the leaf collar of the highest fully expanded leaf. The chlorophyll content in leaves and stomatal conductance were measured 60 days after sowing using chlorophyll meter and leaf porometer, respectively. The above ground biomass was determined at maturity after harvesting the cob, 100 seed weight was obtained through physical counts and grain yield determined and expressed in tons/ha on dry weight basis at 13% moisture content.

For the legumes planted (beans, groundnuts and cowpeas) the plant heights were determined at 30 days after planting and at maturity by measuring the height from the ground level to the leaf collar of the highest fully expanded leaf. The chlorophyll content in leaves and stomatal conductance were measured 60 days after sowing using chlorophyll meter and leaf porometer, respectively. The above ground biomass was determined at maturity after pod picking, number of pods counted per plant and grain yield determined and expressed in tons/ha on dry weight basis at 13% moisture content.

The harvest index of the maize and the legumes were determined by calculating the ratio of grain yield to total biomass using the following formula.

$$\text{Harvest index(HI)} = \frac{\text{Grain yield}}{\text{Total biomass}} \qquad \text{(Equation 1)}$$

The African leafy vegetables (cowpeas, giant amaranth and crotalaria) data on chlorophyll content, stomatal conductance in leaves were measured using chlorophyll meter and leaf porometer, respectively, 60 days after planting. The fresh leaves of cowpeas and crotalaria were harvested in the entire plot twice during the growing seasons at 30 and 45 days after emergence and their respective weights recorded. After which, the vegetables were left to flower and achieve physiological maturity. The grain yield for the giant amaranth and cowpeas were measured at maturity (85 days after sowing) and yield expressed in tons/ha.

3.1.6 Data analysis

All the quantitative data collected were analysed using the following model:

$$Y_{ijk} = \mu + S_i + R_{j(i)} + T_k + ST_{(ik)} + C_l + SC_{il} + TC_{kl} + M_m + SM_{im} + STCM_{ijklm} + \varepsilon_{ijkl\,mn}$$

μ = the overall mean,

S_i = effect due to cropping system in the ith observation,

$R_{j(i)}$ = effect due to replication in the jth observation,

T_k = effect due to crops in the k^{th} observation,

$ST_{(ik)}$ = effect due to interaction between cropping system and crops in the ith and k^{th} observations,

C_l = effect due to season in lth observation,

SC_{il} = effect due to interaction between cropping system and season in the ith and lth observations,

TC_{kl} = effect due to interaction between crops and season in the kth and lth observations,

M_m = the effect due to location in the mth observation,

SM_{im} = the effect due to interaction between cropping system and location in the ith and mth observations,

$STCM_{iklm}$ = the effect due to interaction between cropping system, crops, season and location in the ith, kth, lth and mth observations,

ε_{ijkl} = random error

All the data collected were first subjected to Shapiro-Wilk's test (W) to check if the distribution of the values were statistically different from the normal distribution. The data were then subjected to Analysis of Variance (ANOVA) using PROC GLM followed by PROC SORT procedure in SAS to compare the performance of each crop both in TSFS and no TSFS. The data were analysed using PROC GLM in SAS to compare the TSFS and no TSFS cropping systems in the two locations. Fisher's protected least significant difference (LSD) test at 5% level of significance was adopted for mean separation following the formula below (Williams *et al*., 2010).

$$W = \frac{(\sum_{i=1}^{n} a_i x_{(i)})^2}{\sum_{i=1}^{n}(x_i - \overline{x})^2} \quad \text{.................. (Equation 2)}$$

Where a_i is the constant generated from the means, variance and covariance of order statistics, *n* is the sample size and $x_{(i)}$ is the ordered sample values.

$$\text{LSD} = t\alpha_{\underset{df}{error}} \text{ x } \sqrt{\frac{2MSE}{r}} \quad \text{....................... (Equation 3)}$$

where; t is the t-value, α is the level of significance, d.f is the degree of freedom, 2MSE is the two mean square errors and r is the number of replicates.

3.2 The effects of three-strata forage (TSFS) cropping system on soil chemical properties

The experiment detailed in section 3.1 was maintained for three years, after which soil chemical properties were measured. In determination of soil chemical properties, soil samples were taken at a depth of 0-30 cm. Soil sampling using soil auger was randomly done from each of the plots within the TSFS and those without TSFS cropping systems. The samples were air-dried and sieved through 2 mm (10 mesh) and analyzed for: soil PH, exchangeable acidity, total nitrogen, soil organic carbon, phosphorus, potassium, calcium, magnesium, manganese, copper, iron, zinc and sodium levels for each cropping system.

3.2.1 Determination of soil pH

Soil pH was determined using a pH electrode meter in soil water ratio of 1:2.5 (Okalebo *et al*., 2002). A 20 g of air-dried and sieved soil was weighed into 50 ml plastic bottle for both soils obtained from TSFS and in no TSFS cropping systems and in each plastic bottle 50 ml of distilled water was added. A mechanical shaker was used to shake the content for 30 minutes then the soil suspension allowed to settle for additional 10 minutes. The pH meter was turned on then allowed to warm for 15 minutes after which it was standardized using pH buffer 7.0 and 4.0. The pH of the soil suspension was determined and the pH value recorded to the nearest 0.1 unit. The electrode was then removed from the soil suspension and cleaned with distilled water.

3.2.2 Determination of exchangeable acidity in soil

In both cropping systems, exchangeable acidity was determined following the procedures of Mclean (1965). 10 g of air-dry (2 mm) soil was placed into a 50 ml plastic beaker and 25 ml of 1 M KCl added into the beaker. The contents were stirred using a clean glass rod and allowed to stand for 30 minutes. The mixture was then filtered through Whatman No. 42 paper and leached with 5 successive 25 ml aliquots of 1 M KCl. 5 drops of phenolphthalein indicator were added into the solution and titrated with 0.1 M NaOH to the first permanent pink colour of end point. The titration readings were corrected for a blank of titration of 150 ml KCl solution. The same procedures were repeated for soils obtained in no TSFS cropping system. The exchangeable acidity was calculated using the formula below:

EA (cmol (+) Kg-1) = (ml NaOH sample - ml NaOH blank) × 10 ……………… (Equation 4)

3.2.3 Determination of total soil nitrogen

Total nitrogen was determined following the Kjeldahl procedure as described by Bremner (1960). The procedure consists of three steps; digestion of the soil samples followed by distillation and finally titration. 2 g of soil samples from TSFS cropping system were weighed and placed in a digestion flask, 15 ml of concentrated sulphuric acid (H_2SO_4), 7 g of potassium sulphate and copper as a catalyst were added. The mixture was heated at 400^0C for 90 minutes until white fumes were seen.

The mixture was then left to cool for 30 minutes and 250 ml of water was added. Sodium hydroxide (NaOH) was also added to the mixture in order to raise the pH so as to convert the ammonium (NH_4^+) ions to ammonia gas (NH_3). Ammonia gas was distilled and vapor trapped in special trapping solution of about 15 ml HCl in 70 ml of water. The trapping flask was removed and the condenser rinsed with water to ensure that all NH_3 is dissolved.

Indicator dye was added to the acid, a standard solution of NaOH was put in the burret and bit by bit it was added into the solution of the acid and dye. The end-point was indicated once the dye turned orange and this indicated that all the acid had been neutralized by the base. The volume of the neutralizing base used was recorded. The same procedure was repeated in soils obtained from the no TSFS cropping system. In order to calculate the percentage (%) nitrogen, the number of moles of acid in the trapping flask and the moles of base (NaOH) added were calculated as shown below.

Moles of acid= molarity of acid × volume used in the flask

Moles of base=molarity of base × volume added from the burret

In order to calculate the number of moles of ammonia from the soil sample, the moles of base added were subtracted from the moles of acid present at the beginning. The amount of N in grams was calculated following the formula below:

N (grams) = moles of N × Atomic mass of N

$$\% \text{ N} = \left(\frac{N \text{ in grams}}{\text{grams of soil sample}} \right) \times 100\% \quad \text{……………} \quad \text{(Equation 5)}$$

3.2.4 Determination of soil organic carbon (SOC)

The soil organic carbon was determined using Walkley-Black colorimetric method (Matus *et al.*, 2009). The soil samples were passed through 0.5 mm sieve to obtain finer particles. 0.5 g of soil was weighed and placed in a 500 ml conical flask, 10 ml of 1 N potassium dichromate ($K_2Cr_2O_7$) was then added into the flask with a burette. 15 ml of concentrated sulphuric (H_2SO_4) was added then swirled gently on a fume hood for one minute until the soil and reagents were mixed. It was allowed to stand for 30 minutes and then 200 ml of distilled water, 5 ml of concentrated phosphoric acid (H_3PO_4) and 10 drops of diphenylamine indicator added.

A similar procedure was repeated for the blank with 10 ml of potassium dichromate and 20 ml of concentrated H_2SO_4 without soil. The sample and the blank were then back-titrated with 0.5 N ferrous ammonium sulphate ($Fe(NH_4)_2SO_4$) until the colour changed from dark blue to green at the end-point and the amount of $Fe(NH_4)_2SO_4$ used recorded. A similar procedure was repeated for soils obtained in no TSFS cropping system. Soil organic carbon was then calculated using the formula below and results recorded.

Organic carbon (%) = (B-S) × 0.3 × V/ (wt. × B) …………………… (Equation 6)

Where, B= blank titre (20.5 mls), S= sample titre, V= volume of 1 N $K_2Cr_2O_7$ (10 mls), Wt. = weight of sample used (0.5 g), 0.3= 1 N $K_2Cr_2O_7$= (3 grams of carbon/1000) × 100%

3.2.5 Determination of available phosphorus in soil

The available P was determined using Olsen method (Okalebo *et al.*, 2002). A 2.5 g of air-dried (2 mm) soil was weighed and placed into a 250 ml polythene shaking bottle. 50 ml of the Olsen's extracting solution (0.5 M 42 NaHCO3 pH 8.5) was added to the bottle. The bottle was well closed using a stopper and placed on a mechanical shaker for 30 minutes. After shaking, the suspension was filtered through Whatman No. 42 paper with a pore size of 2.5 µm. Charcoal was then added in order to obtain a clear filtrate. This filtrate was used for the colorimetric P measurements. 10 ml of each P standard solution was placed on a pipette and 10 ml of the sample filtrates and 2 reagent blanks placed into 50 ml volumetric flasks. 5 ml 0.8 M boric acid was added to each flask. Beginning with the standards and blanks, 10 ml of the ascorbic acid reagent was then added to each flask and filled to the 50 ml mark with distilled water. The contents were closed using a stopper and placed on a mechanical shaker. The absorbance of the solution was measured using a spectrophotometer after an hour, at a wavelength setting of 880 nm. P in ppm in the solution was obtained from the standard P curve. Similar procedures were repeated on soils from no TSFS cropping system. The concentration of phosphorus in the soil sample was calculated as follows and results converted into ppm.

$$P \text{ (mg kg-1)} = \frac{(a-b) \times v \times f \times 1000}{1000 \times w} \text{ ……………………….. (Equation 7)}$$

where a = the concentration of P in the sample, b = the concentration P in the blank, v = volume of the extracting solution, f = dilution factor, w = weight of the soil sample.

3.2.6 Determination of potassium, magnesium and sodium in soil

Potassium, magnesium and sodium levels in soil were determined using Mehlich-III (weak organic acid) method (Mehlich, 1984). 3 g of air-dried soil samples were weighed and placed on 50 ml centrifuge tube. In 1 litre of volumetric flask with 500 ml of distilled water, 55 g of ammonium fluoride (NH_4F) was weighed and added into the volumetric flask. 29 g of ethylene diamine tetra-acetic acid (EDTA) was added into the flask and left for 30 minutes to dissolve and the sample marked as stock solution. 700 ml of water was placed into the volumetric flask and ammonium nitrate (NH_4NO_3), 50 ml of stock solution, 57 ml of glacial acetic acid and 41 ml of 10% of nitric acid added and left for 30 minutes to dissolve. Dilution, filtration and colorimetric readings were made depending on the nutrient element and values recorded.

3.2.7 Determination of calcium, manganese, copper, iron and zinc in the soil

The soils from each cropping system was analyzed separately. Micro nutrients like Ca, Mn, Cu, Fe and Zn were determined through spectrophotometric method (Waiman *et al*., 2012). 15 grams of air-dried soil sample was weighed and placed in volumetric flask and 20 ml of Di-ethylenetriamine extracting solution added. The mixture was placed in electrical shaker for 2 hours. The sample was then filtered and the extract analyzed by inductively coupled plasma atomic emission spectrophotometer and results reported as parts per million (ppm).

3.2.8 Data analysis

All the data collected from laboratory analysis were first subjected to Shapiro-Wilk's test (W) to check if the distribution of the values were statistically different from the normal distribution. The data were then subjected to Analysis of Variance (ANOVA) using PROC GLM followed by PROC SORT procedure in SAS to compare the differences in soil chemical properties in the TSFS and no TSFS cropping systems in the two locations. Fisher's protected least significant difference (LSD) test at 5% level of significance was adopted for mean separation following the formula below (Williams *et al*., 2010). The model below was used in the analysis

$$Y_{ijk} = \mu + S_i + R_j + T_k + ST_{ik} + \varepsilon_{ijkl}$$

μ = overall mean,

S_i = effect due to location in the ith observation,

R_j = effect due to replication in the jth observation,

T_k = effect due to cropping system in the kth observation,

ST_{ik} = effect due to interaction between location and cropping system in the ith and kth observations

ε_{ijkl} = random error

Pearson's correlation coefficient (r) analysis was used to assess the associations among the soil chemical properties (Shrestha, 2020.) using the following formula:

$$r = \frac{n(\sum xy)-(\sum x)(\sum y)}{\sqrt{[n\sum x^2-(\sum x)^2)(n\sum y^2-(\sum y)^2]}} \text{ ……………… (Equation 8)}$$

Where; r = Pearson's correlation coefficient, n = the number of samples, x = the independent variable and y is the dependent variable.

CHAPTER FOUR

RESULTS

4.1 The effects of three-strata forage cropping system (TSFS) on yield and yield components of selected food crops

Results showed enhanced crop performance in the TSFS plots than those planted in the no TSFS. Yield and yield components of grain crops like maize, beans and groundnuts were significantly higher at $p<0.001$ in the TSFS compared to the no TSFS (Table 4.1). The same trend was also observed in African leafy vegetables (cowpeas, amaranth and crotalaria). Growth and physiological responses in crops were higher in crops grown in the TSFS compared to those in no TSFS system.

4.1.1 The effect of TSFS on yield and yield components of maize, beans and groundnuts

The results showing the effect of TSFS on yield and yield components of maize, beans and groundnuts are presented in Table 4.1. From the results obtained, maize yielded 6.97 t/ha in TSFS compared to 6.01 t/ha in no TSFS cropping system. However, there were no significant differences in number of grains per cob and harvest index between crops grown inside the TSFS and those in no TSFS (Table 4.1). The results revealed that bean crop in TSFS system, had higher ($p<0.001$) biomass and the number of pods per plant than those in no TSFS. A yield increase of 23.6% was observed in beans grown in TSFS compared to those in no TSFS (Table 4.1). However, the TSFS had no significant impact on harvest index (HI) and 100 seed weight of bean crop (Table 4.1). Biomass, pods per plant, 100 seed weight and yield of groundnuts were higher in groundnuts grown in TSFS compared to those in no TSFS (Table 4.1). The groundnuts yielded 0.49 t/ha higher in TSFS compared to those in no TSFS (Table 4.1).

Table 4.1: Yield and yield components of maize, beans and groundnuts in both the three-strata forage system (TSFS) and no TSFS cropping systems

Crop	Cropping system	Biomass (g/ plant)	Grains/cob (Maize) and pods/plant in legumes	Harvest Index	100 seed weight (g)	Yield (t/ha)
Maize	TSFS	218.76a	423a	0.53a	346.75a	6.97a
	No TSFS	197.34b	404a	0.52a	322.08b	6.01b
	LSD(0.05)	21.42	31.65	0.01	13.40	0.64
Beans	TSFS	134.35a	16.54a	0.43a	298.31a	1.57a
	No TSFS	121.51b	13.08b	0.41a	287.45a	1.27b
	LSD(0.05)	6.32	0.96	0.03	3.21	0.24
Groundnuts	TSFS	97.08a	17.02a	0.20a	363.61a	2.10a
	No TSFS	86.95b	14.34b	0.18b	327.59b	1.61b
	LSD(0.05)	5.63	0.93	0.01	0.19	0.19

Means followed by the same letter within a column are not significantly different at ($p<0.05$)

4.1.2 The effect of TSFS on growth and physiological responses in maize, beans and groundnuts

The results showing the effect of TSFS on growth and physiological responses in crops are presented in Table 4.2. The crops grown in TSFS had higher growth vigor 30 days after planting that resulted into higher plant height at maturity compared to those in no TSFS (Table 4.2). In maize crop, chlorophyll content and stomatal conductance in leaves were higher than those in no TSFS (Table 4.2). The same trend was also observed in beans and groundnut crops (Table 4.2).

Table 4.2: Growth and physiological response in maize, beans and groundnuts as influenced by TSFS cropping system

Crop	Cropping system	Plant vigor (cm) 30 days after planting	Chlorophyll content (µmol m^{-2}) 60 days after planting	Stomatal conductance (mmol m^{-2} s^{-1}) 60 days after planting	Plant height (cm) at maturity
Maize	TSFS	51.93a	51.60a	25.42a	120.60a
	No TSFS	50.94a	49.88b	23.64b	111.40b
	LSD(0.05)	1.87	1.12	0.90	4.81
Beans	TSFS	27.36a	24.42a	22.79a	82.98a
	No TSFS	25.88b	23.68b	21.71b	79.86b
	LSD(0.05)	1.71	3.31	1.09	4.20
Groundnuts	TSFS	19.32a	25.81a	20.75a	50.57a
	No TSFS	18.36a	24.75b	19.48a	49.12b
	LSD(0.05)	0.98	1.10	1.29	1.90

Means followed by the same letter within a column are not significantly different at ($p<0.05$)

4.1.3 The effects of location and season on the performance of maize, beans and groundnuts

The results showing the effect of location and season on crop performance are presented in Table 4.3 and Table 4.4, respectively. The crop environment emerged as a major contributor to crop response in TSFS. Results showed that variation existed between the two locations for the agronomic traits evaluated. Plant vigor, plant height at maturity, biomass, grains per cob, HI, 100 seed weight and yield of maize were higher in Obekai than Ng'elechom. Maize crop yielded higher in Obekai (7.56 t/ha) than Ng'elechom (5.43 t/ha). However, no significant impact observed on chlorophyll content and stomatal conductance in maize leaves (Table 4.3). In beans, plant vigor, chlorophyll content, plant height, biomass, number of pods per plant,100 seed weight and yield were higher in Obekai compared to Ng'elechom. Beans yielded 0.14 t/ha more in

Obekai than in Ng'elechom. The same trend was observed in groundnuts, the yields obtained in Obekai was 2.27 t/ha compared to 1.43 t/ha obtained in Ng'elechom. However, there was variation on chlorophyll content in leaves, plant height, biomass and HI of groundnuts between the two locations (Table 4.3).

The performance of crops in the TSFS was also influenced by the changes in growing seasons, all the crops yielded higher during the third season compared to the first and second seasons.

Table 4.3: Growth, physiological responses, yield and yield components of maize, beans and groundnuts in two locations

Crop	Location	Plant vigor (cm) 30 days after planting	Chlorophyll content (µmol m^{-2}) 60 days after planting	Stomatal conductance (mmol m^{-2} s^{-1}) 60 days after planting	Plant Height (cm) at maturity	Biomass (g/plant)	Grains/cob and pods/plant	Harvest Index	100 seed weight (g)	Yield (t/ha)
Maize	Obekai	53.27a	51.24a	24.59a	140.36a	247.76a	453.91a	0.54a	360.31a	7.56a
	Ng'elechom	49.59b	50.27a	24.49a	91.34b	165.22b	384.81b	0.51b	308.53b	5.43b
	LSD(0.05)	1.87	1.12	0.90	4.81	4.45	31.65	0.02	13.40	0.64
Beans	Obekai	28.15a	25.72a	24.57a	81.44a	133.74a	14.92a	0.31a	265.81a	1.49a
	Ng'elechom	25.09b	22.39b	23.87a	75.40b	122.14b	13.67b	0.32a	234.93b	1.35b
	LSD(0.05)	1.71	3.31	1.09	4.20	6.32	0.96	0.03	2.45	0.24
Groundnuts	Obekai	19.86a	25.70a	21.03a	50.17a	92.54a	16.57a	0.18a	368.17a	2.27a
	Ng'elechom	17.82b	25.66a	19.19b	48.51a	91.48a	14.78b	0.20a	323.03b	1.43b
	LSD(0.05)	0.98	1.10	1.29	1.90	5.63	0.93	0.01	16.35	0.19

Means followed by the same letter within a column are not significantly different at ($p<0.05$)

Table 4.4: Growth, physiological response and yield in crops obtained in three different growing seasons (SR 2019, LR 2020 and LR 2021)

Crop	Seasons	Plant height (cm) 30 days after planting	Chlorophyll content (µmol m^{-2}) 60 days after planting	Stomatal conductance (mmol m^{-2} s^{-1}) 60 days after planting	Yield (t/ha)
Maize	SR 2019	48.90c	24.57b	111.74b	5.60b
	LR 2020	50.49b	27.54a	115.56b	6.85a
	LR 2021	52.83a	28.56a	121.16a	7.03a
	LSD (0.05)	1.38	1.10	5.89	0.78
Beans	SR 2019	72.07b	20.53c	18.87b	1.04c
	LR 2020	74.95a	24.79b	20.75a	1.25b
	LR 2021	88.24a	25.84a	23.05a	1.99a
	LSD (0.05)	5.14	4.06	1.34	0.29
Groundnuts	SR 2019	47.39b	22.35b	19.10b	1.74b
	LR 2020	48.54b	23.03b	19.78b	1.84ab
	LR 2021	51.10a	25.68a	20.41a	1.98a
	LSD (0.05)	2.33	1.35	1.58	0.23

Means followed by the same letter within a column are not significantly different at ($p<0.05$), SR- Short rains, LR- Long rains

4.1.4 The performance of maize and beans in TSFS and in no TSFS over seasons

In TSFS cropping system, maize yielded 6.06 t/ha, 6.51 t/ha and 7.92 t/ha during the SR 2019, LR 2020 and LR 2021 seasons, respectively while in the no TSFS, maize yielded 5.43 t/ha, 5.86 t/ha and 6.12 t/ha during the SR 2019, LR 2020 and LR 2021 seasons, respectively. This translated to about 31% and 13% yield increase from the SR 2019 to the LR 2021 in TSFS and in no TSFS cropping system, respectively (Fig 4.1a). In the TSFS cropping system, beans yielded 1.15 t/ha, 1.34 t/ha and 2.03 t/ha during the SR 2019, LR 2020 and LR 2021 seasons, respectively while in the no TSFS, 1.12 t/ha, 1.15 t/ha and 1.75 t/ha of beans were obtained during the SR 2019, LR 2020 and LR 2021 seasons, respectively. This translated to about 77% and 57% yield increase from the SR 2019 to the LR 2021 season in TSFS and in no TSFS cropping system, respectively (Fig 4.1b).

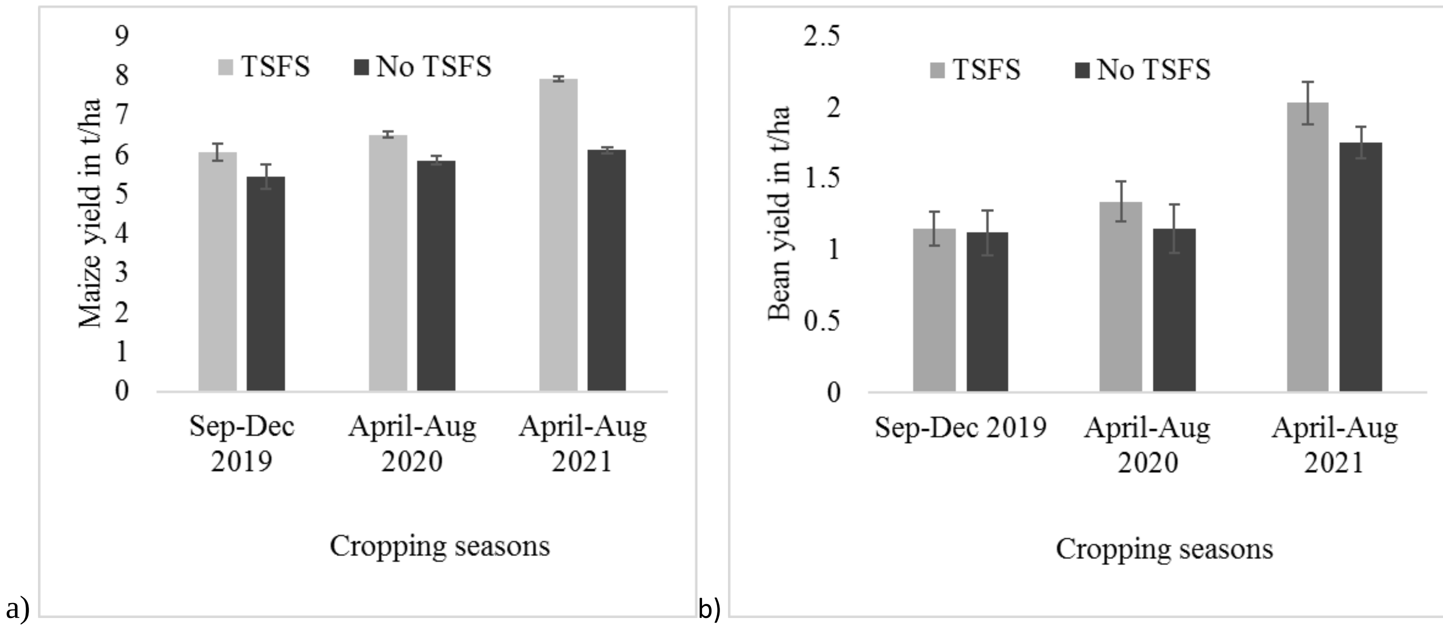


Figure 4.1: The yield of maize and beans in TSFS and in no TSFS during the SR2019, LR 2020 and LR 2021 seasons

4.2 Response of African leafy vegetables to the TSFS system

African leafy vegetables in the study were amaranth, cowpeas and crotalaria. They yielded higher in the TSFS cropping systems than in no TSFS system. Plant vigor, chlorophyll content and yield (t/ha) were notably higher in the TSFS than in the no TSFS. In cowpeas, the stomatal conductance in leaves was higher in plants grown in the TSFS than in no TSFS. However, there were no variation in plant height and biomass for both cowpeas and amaranth grown in TSFS and in no TSFS system (Table 4.5).

Table 4.5: Growth, physiological response, yield and yield components of amaranth and cowpeas in TSFS and in no TSFS cropping systems

Crops	Cropping system	Plant vigor (cm)	Chlorophyll content (µmol m^{-2})	Stomatal conductance (mmol $m^{-2}s^{-1}$)	Plant Height (cm)	Biomass (g/plant)	Yield (t/ha)
Amaranth	TSFS	23.41a	21.81a	25.15a	129.22a	183.56a	1.58a
	No TSFS	22.01b	19.88b	25.11a	115.67a	179.72a	1.17b
	LSD(0.05)	1.29	0.98	1.77	16.68	8.15	0.15
Cowpeas	TSFS	28.65a	69.21a	26.03a	69.27a	103.97a	2.04a
	No TSFS	26.48b	63.71b	24.55b	66.75a	97.63a	1.71b
	LSD(0.05)	1.73	2.84	0.83	4.32	12.82	0.36

Means followed by the same letter within a column are not significantly different at ($p<0.05$)

4.2.1 The effect of location and season on the performance of amaranth, crotalaria and cowpeas

The leafy vegetables performed differently in the two locations. Cowpeas and amaranth yielded slightly higher in Obekai than Ng'elechom (Fig 4.2). The harvestable leaves of crotalaria and cowpeas in grams/m^2 obtained during the third season were higher than the second and first seasons (Fig 4.3a). A yield increase of about 49% and 40% was observed in cowpeas grown in the TSFS and in no TSFS cropping system, respectively. Crotalaria on the other hand recorded a yield increase of about 72% and 34% in the TSFS and in no TSFS, respectively (Fig 4.3a). The fresh weight obtained during the second harvest were higher compared to the first harvests (Fig 4.3b).

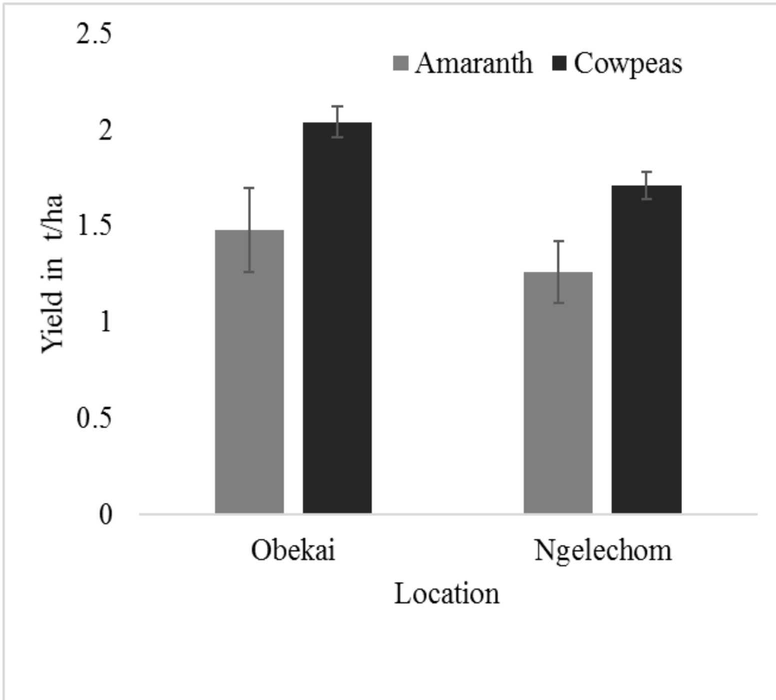


Figure 4.2: The performance of amaranth and cowpeas (t/ha) in Obekai and Ng'elechom locations

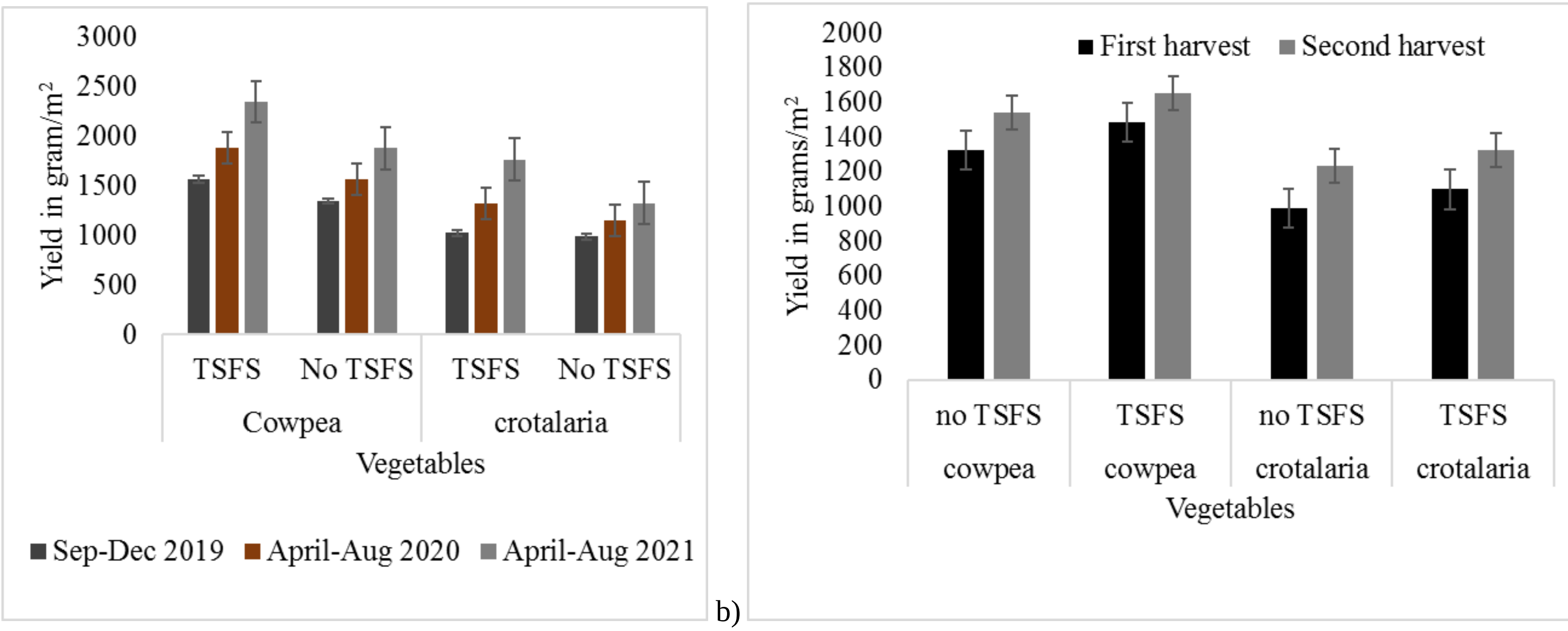


Figure 4.3: Yield comparison of cowpea and crotalaria (grams/m2) across SR 2019, LR 2020 and LR 2021 seasons (a) and differences in yield between 1st and 2nd harvests (b)

4.3 The performance of strata forages in TSFS cropping system

The TSFS had forages alongside crops unlike in the no TSFS cropping system. The two forage species performed differently in the two locations. Brachiaria grass yielded higher in Ng'elechom (8.79 tons/ha) than in Obekai (7.14 tons/ha) (Fig. 4.4). Desmodium on the other hand performed higher in Obekai (2.81 tons/ha) than in Ng'elechom (2.6 tons /ha) (Fig. 4.4). The differences in soil type between the two locations could have contributed to variations in performance of the forages.

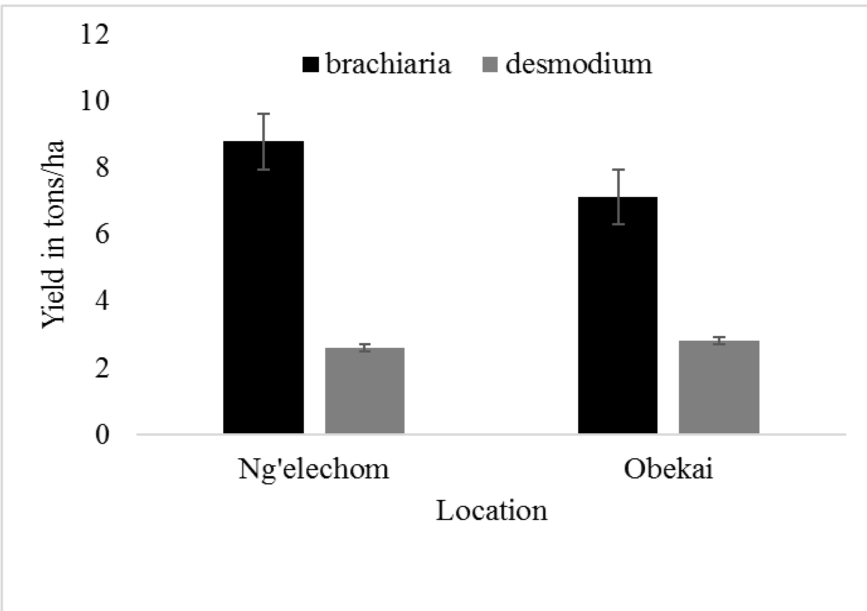


Figure 4.4: Fresh biomass of brachiaria grass and desmodium in Obekai and Ng'elechom locations

4.4 The effects of TSFS cropping system on chemical properties of soil

The results showing the effects of TSFS on soil chemical properties are presented in Table 4.6. Phosphorus, magnesium, iron and sodium levels were higher in the TSFS than in no TSFS. The TSFS system, however, had no significant impact on the levels of potassium, calcium, manganese and zinc (Table 4.6). Soil pH, total nitrogen and soil organic carbon were higher in TSFS system than in no TSFS, however, exchangeable acidity and copper levels were higher in no TSFS system than in the TSFS (Fig. 4.5).

Table 4.6: The effects of TSFS cropping system on soil chemical properties

Cropping system	P (ppm)	K (meq %)	Ca (meq %)	Mg (meq %)	Mn (meq %)	Fe (ppm)	Zn (ppm)	Na (meq %)
No TSFS	27.04***	0.18	0.37	1.05***	0.25	59.78*	1.53	0.18***
TSFS	33.41***	0.20	0.41	1.10***	0.22	65.66*	1.73	0.20***

*, ***, Significant at p<0.05 and p<0.001 respectively, TSFS; three-strata forage system

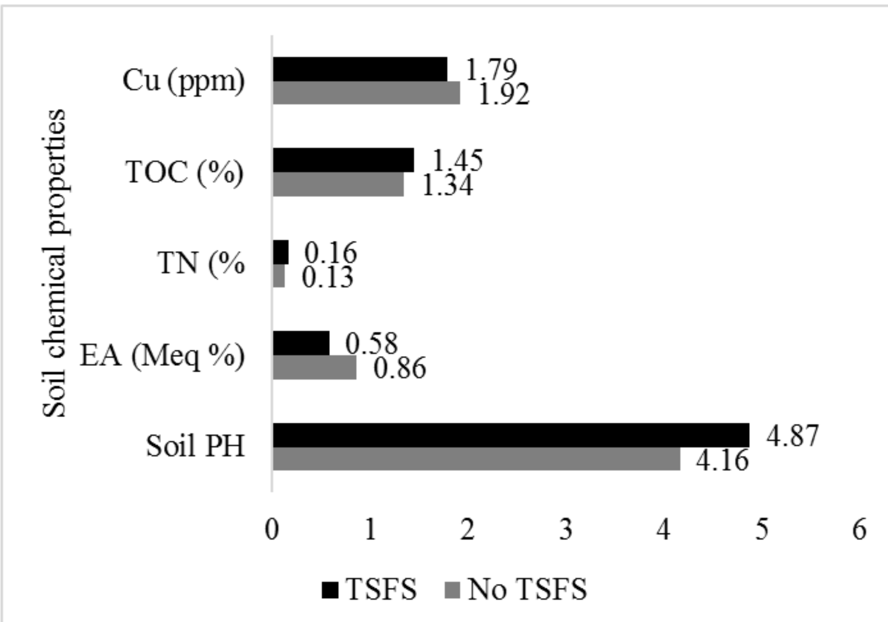


Figure 4.5: Chemical properties of soil as influenced by TSFS and no TSFS cropping systems after 28 months

4.4.1 The effects of location and TSFS system on soil chemical properties

Combined analyses of variance over the TSFS system revealed that location exhibited significant effects at (*P*<0.001) on all the measured soil chemical properties except for manganese (Table 4.7). Total nitrogen, soil organic carbon, phosphorus, calcium, magnesium, copper and zinc levels were higher in soils in Obekai than those in Ng'elechom while exchangeable acidity, potassium and sodium levels were higher in soils in Ng'elechom than Obekai (Table 4.8).

Table 4.7: Effects of interaction between location and cropping systems on soil chemical properties

Location	Cropping system	Soil pH	Exchangeable acidity (meq %)	TN (%)	TOC (%)	P (ppm)	K (meq %)	Ca (meq %)	Mg (meq %)	Mn (meq %)	Cu (ppm)	Fe (ppm)	Zn (ppm)	Na (meq %)
Ng'elechom	No TSFS	3.92***	1.19***	0.13***	1.16***	29.33***	0.22***	0.28***	0.95***	0.30	1.77***	72.07***	1.34***	0.19***
Ng'elechom	TSFS	4.20***	0.76***	0.10***	1.42***	29.41***	0.17***	0.30***	1.17***	0.19	1.72***	76.58***	1.27***	0.21***
Obekai	No TSFS	4.40***	0.52***	0.14***	1.51***	24.76***	0.14***	0.45***	1.16***	0.21	2.06***	47.49***	1.72***	0.16***
Obekai	TSFS	5.54***	0.39***	0.21***	1.48	37.42***	0.24***	0.51***	1.04***	0.25	1.87***	54.74***	2.19***	0.19***

***, Significant at $p<0.001$

Table 4.8: The effects of location on the chemical properties of soil

Location	Soil pH	EA (meq %)	TN (%)	TOC (%)	P (ppm)	K (meq %)	Ca (meq %)	Mg (meq %)	Mn (meq %)	Cu (ppm)	Fe (ppm)	Zn (ppm)	Na (meq %)
Obekai	4.36a	0.46b	0.17a	1.49a	31.09a	0.19b	0.48a	1.10a	0.23a	1.96a	65.66a	1.95a	0.18b
Ng'elechom	4.06b	0.97a	0.12b	1.29b	29.37b	0.20a	0.29b	1.06b	0.24a	1.75b	59.78b	1.30b	0.21a
LSD(0.05)	0.08	0.08	0.01	0.05	1.94	0.01	0.02	0.02	0.01	0.03	0.78	0.05	0.01

Means followed by the same letter within a column are not significantly different at ($p<0.05$); TN-Total Nitrogen, EA-Exchangeable acidity, TOC-Total Organic Carbon, P-Phosphorus, K-Potassium, Ca-Calcium, Mg-Magnesium, Mn-Manganese, Cu-Copper, Fe-Iron, Zn-Zinc, Na-Sodium

4.4.2 The correlation among soil chemical properties in TSFS cropping system

Pearson's correlation results indicate a positive relationship among different soil chemical properties in the two cropping systems (Table 4.9). The soil pH values in no TSFS cropping system showed significant positive correlation with calcium (r = 0.66) while in TSFS a positive correlation with nitrogen (r = 0.68), potassium (r = 0.79), manganese (r = 0.73) and zinc (0.63) was shown. In no TSFS cropping system, the exchangeable acidity was significantly correlated with all soil properties except nitrogen, zinc and sodium while in the TSFS there was a positive correlation of exchangeable acidity with iron (r =0.59). There was significant positive correlation between total nitrogen with calcium (r = 0.70) and zinc (r = 0.52) in no TSFS system while in TSFS it positively correlated with potassium (r = 0.87), calcium (r = 0.64), manganese (r = 0.79) and zinc (r = 0.83). A significant positive correlation between total organic carbon and magnesium (r= 0.66), manganese (r = 0.55) and copper (r = 0.61) were observed in no TSFS system while in TSFS it positively correlated with phosphorus (r = 0.47) and copper (r = 0.55).

In both cropping systems, phosphorus showed a significant negative correlation with calcium (r = -0.41) and sodium (r = -0.46) in no TSFS and TSFS, respectively. Potassium on the other hand had a significant positive correlation with manganese (r = 0.87) in no TSFS while in TSFS it positively correlated with manganese (r = 0.96) and zinc (r = 0.92). Calcium correlated positively with magnesium (r = 0.46) and zinc (r = 0.46) in no TSFS, however, in TSFS a positive correlation with manganese (r = 0.51) was observed. In both cropping systems, magnesium had a significant negative correlation with manganese (r = -0.66) and (r = -0.63), in no TSFFS and TSFS respectively. Magnesium also showed a negative correlation with iron (r = -0.71) and zinc (r = -0.75) in no TSFS system and TSFS respectively. In no TSFS system, manganese had significant negative correlation with copper (r = -0.61) and a positive correlation with zinc (r = 0.89) in TSFS. There was no significant correlation between copper and other soil chemical properties in TSFS while in no TSFS system it correlated with zinc (r = 0.48) and sodium (r = -0.6). Fe, Zn and Na had no significant correlations with other elements.

Table 4.9: Correlation coefficient (r) between chemical properties of soil in no TSFS and TSFS cropping systems

	PH	EA	TN	TOC	P	K	Ca	Mg	Mn	Cu	Fe	Zn	Na
Without Strata (No TSFS)													
PH	1												
EA	-0.68***	1											
N	Ns	Ns	1										
C	0.41*	-0.66***	Ns	1									
P	-0.48*	0.50**	Ns	Ns	1								
K	ns	0.51**	0.59**	-0.63**	Ns	1							
Ca	0.66***	-0.56**	0.70***	Ns	-0.41*	ns	1						
Mg	ns	-0.63**	Ns	0.66***	Ns	-0.58**	0.46*	1					
Mn	ns	0.44**	Ns	-0.55**	Ns	0.87***	ns	-0.66***	1				
Cu	ns	-0.53**	Ns	0.61**	Ns	-0.66***	ns	ns	-0.61**	1			
Fe	ns	0.41*	Ns	-0.45**	Ns	ns	-0.54**	-0.71***	ns	ns	1		
Zn	ns	Ns	0.52**	0.43**	Ns	ns	0.46*	ns	ns	0.48*	ns	1	
Na	ns	Ns	Ns	Ns	Ns	ns	-0.62**	ns	ns	-0.64***	ns	ns	1
With Strata (TSFS)													
PH	1												
EA	-0.59**	1											
N	0.68***	-0.50*	1										

C	ns	Ns	Ns	1									
P	ns	Ns	Ns	0.47*	1								
K	0.79***	Ns	0.87***	Ns	Ns	1							
Ca	0.59**	-0.43*	0.64***	Ns	Ns	0.59**	1						
Mg	-0.50**	Ns	-0.61**	Ns	Ns	-0.65***	ns	1					
Mn	0.73***	Ns	0.79***	Ns	Ns	0.96***	0.51**	-0.63***	1				
Cu	ns	-0.57**	Ns	0.55**	Ns	Ns	ns	ns	ns	1			
Fe	ns	0.59**	-0.59**	Ns	Ns	Ns	-0.51**	ns	ns	ns	1		
Zn	0.63***	Ns	0.83***	Ns	Ns	0.92***	ns	-0.75***	0.89***	ns	ns	1	
Na	ns	Ns	Ns	Ns	-0.46*	Ns	ns	ns	ns	ns	ns	ns	1

* ** *** significant at $p<0.05$, $p<0.01$ and $p<0.001$ respectively; ns-not significant, EA exchangeable acidity, TN Total Nitrogen, TOC Total Organic Carbon, K Potassium, Ca Calcium, Mg Magnesium, Mn Manganese, Cu Copper, Fe Iron, Zn Zinc, Na Sodium

CHAPTER FIVE

DISCUSSION

5.1 The effects of three-strata forage system (TSFS) on yield of the selected food crops

The selected food crops grown yielded higher in the TSFS than in no TSFS. The contribution of the TSFS to enhanced crop productivity is attributed to positive interaction between strata crops and crop pests. Planting of brachiaria grass and desmodium as hedgerows help in curbing common pests which could attack crops thereby increasing crop yields in TSFS cropping system. These results are in agreement with Hailu *et al*. (2018), who reported that planting of desmodium and brachiaria grass as intercrops with maize proven to be effective for controlling stemborers, fall army worm and the parasitic striga weed. The 'push-pull' companion cropping systems reduced the maize damage mean score of fall armyworm by 168%, compared to the control and this translated to 46.80% and 51.11% increase in maize grain yield and biomass yield, respectively (Yeboah *et al*., 2021).

Desmodium species improves soil fertility as it fixes nitrogen thereby improving soil organic matter content into the soil. The nature of its trailing vines conserve soil moisture as it provides good ground cover. These results are in agreement with Toniutti *et al*. (2017), who reported that inclusion of desmodium species results to symbiotic relationship with the rhizobia thereby fixing nitrogen into the soil hence plays an important role in sustainable agriculture. The inclusion of pigeon peas also acted as windbreaks thereby protecting the crops within the TSFS from external factors like strong winds and this made the crops to perform better as compared to those in the no TSFS system.

The higher yield obtained in a TSFS cropping system could also be as a result of crop residue incorporation. The crop residues act as habitat and substrate for soil flora and fauna and hence increase soil nutrients upon mineralization (Pal, 2016). Other benefits include, soil surface cover thereby decreasing soil erosion and also aids in soil moisture retention, which could not be guaranteed in the no TSFS. The vigorous crop growth can be explained on the basis of the differences in soil organic matter. Consistent addition of crop residues season after season is expected to sustain an improved soil structure which serves to increase both water infiltration and storage (Turmel *et al*., 2015). A well-structured soil sustains root growth by enabling the growing plants to capture a sufficient proportion of the available nutrients (White *et al*., 2013a, b).

The forages included in the TSFS could be used as feed to replace the common practice of removal of crop residues by local farmers to feed livestock. The trend in crop performance seemed to be dependent on residue incorporation. The crop residues incorporated decomposed yielding organic matter in the soil. The organic matter helped in adsorbing and retaining nutrients in a form that can easily be accessed by plants. Hijbeek *et al*. (2017) found out that there is a positive correlation between crop yield and soil organic matter content in the soil. These results are consistent with the findings of Uzoh *et al*. (2019) who also reported that crop residue incorporation and nitrogen fertilizer application significantly improved soil nitrogen and maize grain yield over non-residue incorporation. Crop residue incorporation as a source of organic matter resulted in 12% and 16% higher yield in maize and sugar beet respectively compared to other sources (Piccoli *et al*., 2020).

The TSFS with integrated forages for feed had added advantage over the no TSFS cropping system. The addition of forage crops could be added advantage to the farmers since it guarantees ready feeds that can be used directly in the homesteads or sold for income. The two forage species performed differently in the two locations. Brachiaria grass yielded higher in gleyic acrisols soils with low fertility in Ng'elechom than humic cambisols in Obekai. Brachiaria grass is adaptable and more resistant in soils with low fertility due to its capacity to absorb and accumulate silicon in aerial parts. Brachiaria grass does well in sandy soils compared to clay and loamy due to its high tolerance to both alkalinity and salinity. Desmodium on the other hand tolerates slight acidity and hence performed better in humic cambisols soils in Obekai than acrisols soils in Ng'elechom. Pitman & Sotomayor, (2000), reported that desmodium has the capacity to tolerate aluminium toxicity in soil and this makes it to tolerate slight acidity as well.

In regard to location, there was variation in growth, physiological responses, yield and yield components of the selected food crops. Even though the two locations lie within the same agro-ecological zone (LM3 zone), the crops grown in Obekai performed slightly higher than those grown in Ng'elechom. The observed differences could be due to differences in soil type. Obekai has humic cambisols soils which are well drained and contain high content of humic top soils which supported the crop growth unlike Ng'elechom with gleyic acrisols soils consisting of unconsolidated sand deposits. Cambisols soils contain high content of clay (Abdissa *et al*., 2011) while acrisol type of soil has very low inherent chemical fertility and water holding capacity (Pardo *et al*., 2003).

During the LR 2021 season, a significant yield increase was observed in crops grown both in the TSFS and in no TSFS cropping system. Even though yield increase was observed in both systems, crops grown in TSFS yielded higher compared to those in no TSFS.

Consistent addition of crop residues over the seasons could have increased water infiltration and storage. The accumulation of organic matter due to more residues incorporation also improved soil structure that supported plant growth thereby resulting to higher yield increase during the LR 2021 season. Turmel *et al*. (2015), found out that consistent addition of crop residues season after season is expected to sustain an improved soil structure which serves to increase both water infiltration and storage (Turmel *et al*., 2015). During LR 2021 season, a well-established forages acted as hedgerows in the cultivated plots thereby creating a barrier preventing soil loss. A vetiver (*Chrysopogon zizanioides*) hedgerow can reduce up to 31-69% and 62-86% of runoff volume and soil loss, respectively compared to non vetiver hedgerow (Aziz & Islam, 2023).

The long rains in the third season supported the plant growth and general performance of crops. The crops are dependent on water during their entire lifecycle in order to survive and thrive and therefore water availability for crop use enhanced good production. These results are in agreement with the findings of Mkonda (2014), who reported that there is a relationship between rainfall variability and crop production. The window of time between the time of residue incorporation and the third season also gave the soil microorganisms opportunity to breakdown the residues into usable nutrients thereby adding organic matter into the soil. The available nutrients were utilized by plants during the third season thereby increasing yield of the selected crops. The nutrient content in crop residues is not readily available to plants primarily after incorporation hence there is need for mineralization in order to convert them into a form available for plants (Chen *et al*., 2014).

5.2 The effect of residue incorporation on growth and physiological response in plants

From the results obtained, the crops grown in the TSFS had higher growth rate than those in no TSFS system. Chlorophyll content in leaves of crops in the TSFS system were slightly higher than those in no TSFS. The crop residues added in the soil increased nitrogen content which contributed to nitrogen found on leaves and hence chlorophyll increase in plant leaves. The availability of enough nutrients in the soil further resulted into higher growth rate. These results are in agreement with findings elsewhere (Aminifard *et al*., 2012; Sikuku *et al*., 2016).

Crop residue retention improves the physical and chemical composition in soil thereby promoting growth and development in plants. It also improves soil water storage by increasing infiltration thereby reducing losses associated with run-offs and evaporation. About 40% of crop residues contain organic carbon which is involved in regulating soil properties and soil stability through the formation of large soil aggregates. In a previous research by Ali *et*. (2020), found out that a treatment of 5% raw garlic stalk incorporated in soil increased soil organic carbon by 52% and 50% in 2016 and 2017, respectively. The retention of residues can also help in reducing organic carbon loss (Chen *et al*., 2016). The incorporation of soil residues also improves soil health thereby promoting plant growth. Crop residues has the capacity to alleviate the pressure of saline-alkali soils thereby improving their quality (Fu *et al*., 2021).

Crop residues also increases soil organic matter thus providing favourable environment for the growth and proliferation of the beneficial micro-organisms in the soil (Zhang *et al*., 2021). The quality of soil health depends on the type of residues incorporated. Wheat straw return lowers the diversity of fungus community in the soil while in corn straw there was higher fungal pathogenic risks that were observed (Su *et al*., 2020). It was also reported that long-term combination of rice straw and inorganic fertilizers in paddy rice had positive impacts on the diversity of fungus family (Nie *et al*., 2018).

5.3 The effects of TSFS on the chemical properties of soil

5.3.1 Soil pH

Most essential elements and nutrients are available in soils with pH range of between 5.5 and 7.2. In this study, though all soils were acidic ($pH<6.4$) in all cropping systems, soils in the TSFS cropping system ended with significantly higher pH than those in no TSFS cropping system after LR 2021 season. The general acidity of the soils in the study areas could be due to acidic parent material from which soil particles are made or high mean annual rainfall. High mean annual rainfall removes basic cations from the surface horizons through leaching thereby making the soils to be acidic (Wei *et al*., 2019). The variation in pH could be due to differences in management practices between the two systems. In the TSFS, the forages acted as hedgerows thereby reducing the effects of run-off during rainy seasons unlike the no TSFS system. Soil pH showed significant correlations with most crop nutrients in the soil. This was expected because the availability plant nutrients in the soil is dependent on the soil pH.

The incorporation of crop residues could also be a factor in higher soil pH in the TSFS cropping system. Diverse crop residues have been found to be important for the redistribution of alkalinity within soils there by increasing soil pH. This observation is in agreement with the findings of Xiao *et al*. (2013), who found out that the incorporation of crop residues into the soils increased soil pH upon decomposition. A previous research on the contribution of crop residues to changes in soil pH under field conditions showed that residues (10 g dry matter) increased soil pH and temporal changes in alkalinity depended on the residue and soil type (Butterly *et al*., 2013). Wang *et al*. (2017), found out that chickpea and canola residue amendments increased soil pH at 0-10 cm in the podzol by up to 0.47 and 0.36 units and in the cambisols by 0.31 and 0.18 units, respectively, at 48 months when compared with non-residue amended control.

5.3.2 Exchangeable acidity

This is the measure of H^+ and Al^{3+} ions retained or fixed on soil colloid after the active acidity is measured (McCarty, 2003). In this study, the exchangeable acidity in soils was higher in no TSFS cropping system than the TSFS cropping system. In no TSFS system, the crops were not enclosed in strata forages and therefore during off-seasons the farm was left bare. This could expose agricultural land to agents of erosion like the run-offs thereby sweeping away top fertile soil. Soil erosion leads to poor soil structure and water infiltration thus high concentration of H^+ in soil-water solution. The higher the concentration of H^+ in the soil water solution the lower the pH value and the higher the acidity of the soil. The acidity of the soil affects soil chemical reactions such as the solubility of Al, Fe, Mn and Zn thereby leading to their toxicity to crops (Liu & Hanlon, 2012).

The high exchangeable acidity in no TSFS cropping system implied that the residue incorporation could have contributed to the observed variation. The effect of climatic conditions like high rainfall amount could have resulted into leaching of nutrients thereby reducing soil pH and increasing the level of exchangeable acidity in the soil in no TSFS. The more the exchangeable cations held by soil colloids were replaced by H^+, the more the H^+ held by the exchange complex of soil in relation to basic cations held, the greater the acidity of the soil (Shaheen *et al*., 2013).

5.3.3 Total nitrogen, phosphorus and soil organic carbon (macro-nutrients)

Total nitrogen, phosphorus and organic carbon levels were higher in the TSFS cropping system than in no TSFS system. This could be due to the decomposition of incorporated residue thereby yielding high organic matter in the soil. The soil organic matter released served as a reservoir for nutrients for plant use. These results are consistent with the findings of Uzoh *et al*. (2019), who reported that crop residue incorporation and nitrogen fertilizer application significantly improved soil nitrogen and maize grain yield over non-residue incorporation. Ghimire *et al*. (2012), reported that an increase in the amount of residue returned in the soil significantly increased soil organic carbon and nitrogen in the system. Murphy *et al*. (2016), also reported that the retention of crop residues resulted in 110% increase in the recovery of fertilizer-derived N in vegetative biomass and a significant increase in 41% for total N in the soil-crop system.

The forage strata in the TSFS acted as hedge-rows in the cultivated plots thereby creating a barrier preventing soil loss either through run-offs or wind. The practices involved in conservation agriculture like crop residue retention holds the potential of enhancing phosphorus availability by altering the activities of enzymes and microbial diversity in the soil which in turn increases soil phosphorus availability (Bezerra *et al*., 2015; Bhan & Behera, 2014).

The residues incorporated decomposed thereby increasing soil organic carbon into the soil. Zhang *et al*. (2016), found out that the incorporation of straw significantly increased the levels of organic carbon and storage levels as compared to control. According to Malhi *et al*. (2011), the amount of soil organic carbon is directly associated with the amount of crop residues incorporated. Previous research by Chalise *et al*. (2019) reports increased soil organic carbon and decreased soil bulk density with crop residue incorporation. The high levels of soil organic carbon in TSFS cropping system was expected as it is closely related to soil nitrogen. Soil nitrogen dynamics has also been observed to be directly related to that of soil organic carbon (Moges & Holden, 2008).

5.3.4 Potassium, Calcium and Magnesium levels

There was no significant difference in K levels in both cropping systems. This finding is not in agreement with Madar *et al*. (2020), who found that crop residue retention at 6.0 t/ha significantly improved grain yield of maize and wheat by (10.17% and 9.87%, respectively), dry matter accumulation and K uptake and redistribution in K pools compared to control. The availability of K in the soil depends on geochemical conditions, the addition of K fertilizers, crop residue and tillage practices (Britzke *et al*., 2012; Singh *et al*., 2018). The levels of potassium in both cropping systems could have been attributed by soil temperatures. Low soil temperatures affect the levels of potassium in soil.

Calcium is a secondary macro-nutrient and is essential in the formation of new cells needed for plant roots, stems and leaves to grow (Dong *et al*., 2021). In this study, the levels of calcium had no significant differences in both cropping systems. This results are not in agreement with the previous studies that showed, calcium ions in soil are easily affected by changes in soil pH, cation exchange capacity and soil moisture (Khaledian *et al*., 2017). In this study, the levels of calcium could have been affected by the presence of other competing ions like Mg^{+} ions thereby reducing their availability in the soil.

Magnesium is an essential element for crops and its deficiency could affect plant processes like photosynthesis and carbohydrate partitioning (Farhat *et al*., 2016). In this study, Mg levels in soil were found to be higher in the TSFS cropping system than in no TSFS. This variation could be due to different agricultural practices in the two cropping systems. The availability of Mg in the soil could depend on climatic conditions and agronomic management practices as observed by Mikkelsen (2010). In the TSFS, the residues incorporated reduced nutrient losses through leaching and thus high Mg^{2+} ions levels. Mg^{2+} ions are highly mobile in nature and this makes it susceptible to leaching from the root zone by heavy rainfall (Gransee & Fuhrs, 2013; Grzebisz, 2011).

Iron is an essential micronutrient that plays a significant role in plant metabolic processes like respiration, DNA synthesis and photosynthesis (Rout & Sahoo, 2015). Its availability in soil highly depends on soil pH level. The results obtained from soil analysis indicated that Fe levels were higher in the TSFS cropping system than in no TSFS. The residues incorporated decomposed thereby releasing organic matter in the TSFS system. During organic matter decomposition, Fe previously tied up in the organic compounds is released in the soil in forms available for plant use (Mimmo *et al*., 2014).

5.3.5 Manganese, Iron and zinc levels

Manganese is an essential micronutrient for plant growth and development and also sustains metabolic roles within plant cells (Alejandro *et al*., 2020). In this study, Mn showed no significant difference in both TSFS and in no TSFS cropping systems. This result is not in agreement with previous research on Mn levels in the soil. Most available Mn in soil occurs as exchangeable Mn and this is associated with organic matter (OM) content in the soil. Soils high in OM are likely to be deficient in Mn due to the increased formation of OM and Mn complexes (Li *et al*., 2021). Soil micro-organisms also appear to reduce the availability of Mn by oxidizing Mn to less available forms (Zobiole *et al*., 2011). In this study, the constant levels of manganese in both cropping systems could have been due to soil temperature and seasonal variations.

Zinc is an essential micronutrient and is involved in activating enzymes responsible for protein synthesis (Hafeez *et al*., 2013). In this study, there was no difference in the levels of Zn^{2+} ions in the two cropping systems. This was contrary to previous research on Zn levels in soil and factors affecting its availability. Generally, in sandy and leached soils the levels of

Zn^{2+} ions are usually low (Swietlik, 2010). Soils with low organic matter have also been reported to exhibit Zn deficiency (Dhaliwal *et al*., 2019). The results could have been due to high concentrations of magnesium in the soil that led to constant zinc levels in both cropping systems.

Copper is an essential mineral for plants, it is involved in photosynthetic and respiratory electron transport chains and cell wall metabolism (Rehman *et al*., 2019). Higher levels of Cu were observed in no TSFS than in TSFS cropping system. This was expected due to the differences in soil pH and soil organic matter. The results obtained are consistent with those reported by (Bravo *et al*., 2017), who found that Cu levels are higher in more acidic soils than alkaline soils. Organic matter levels in the soil also dictate the level of copper in the soil. In the TSFS cropping system, the organic matter from decomposed crop residues formed complexes with copper thereby reducing its availability. Copper is strongly bound to organic matter, an increase in the organic matter further increases the probability of copper deficiency (Usman *et al*., 2012).

CHAPTER SIX
CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This study is an effort to determine an alternative cropping system that can provide food, feed and restore the fertility of the soil. Based on the results, the conclusion is as follows:

i. The crops yielded higher in TSFS than in no TSFS system, TSFS could be alternative cropping system that can provide food and feed within the same plot of land.
ii. The TSFS system is environmentally friendly as production is not pegged on fertilizer application and can easily be adopted by most farmers.
iii. Crop management practices like residue incorporation influences soil chemical properties like nitrogen, phosphorus and soil organic carbon.

6.2 Recommendations

The following recommendations were derived from this study

i. Three-strata forage cropping system should be adopted by farmers to provide livestock feeds thereby reducing chances of using crop residues as animal feeds.
ii. A few crops should be included in the three-strata forage cropping system as multiple crops could be quite challenging for small holder farmers.

REFERENCES

Abdissa Y, Tekalign T., & Pant, L. M. (2011). Growth, bulb yield and quality of onion (*Allium cepa* L.) as influenced by nitrogen and phosphorus fertilization on vertisols, growth attributes, biomass production and bulb yield. *African Journal of Agricultural Research*, *6*(14), 3252-3258. https://doi.org/10.5897/AJAR10.1024

Abebe, Z., Tadesse, S., & Tola, M. (2016). Multiple advantages of pigeon pea (*Cajanus cajan*) in maize based cropping systems: Used as live stake for climbing bean with phosphorus rates maize productivity enhancement in mono cropping areas. *Journal of Natural Sciences Research 6* (19), 58-69.

Abu-Hafsa, S. H., Hassan, A. A., Elghandour, M. M., Barbabosa-Pliego, A., Mellado, M., & Salem, A. Z. (2022). Dietary Anti-Nutritional Factors and Their Roles in Livestock Nutrition. In: Yata, V.K., Mohanty, A.K., Lichtfouse, E. (Eds) *Sustainable Agriculture Reviews 57: Animal Biotechnology for Livestock Production 2*, 131-174.

Abu-Salem, F. M., & Abou-Arab, E. A. (2011). Physico-chemical properties of tempeh produced from chickpea (*Cicer arietinum* L.) seeds. *Journal of American Science*, *7*(7), 107-118.

Akinola, R., Pereira, L. M., Mabhaudhi, T., De Bruin, F. M., & Rusch, L. (2020). A review of indigenous food crops in Africa and the implications for more sustainable and healthy food systems. *Sustainability*, *12*(8), 1-30.

Alejandro, S., Höller, S., Meier, B., & Peiter, E. (2020). Manganese in plants: from acquisition to subcellular allocation. *Frontiers in Plant Science*, *11*, 300-314.

Alemayehu, A., Tamado, T., Nigussie, D., Yigzaw, D., Kinde, T., & Wortmann, C. S. (2017). Maize–common bean intercropping to optimize maize-based crop production. *The Journal of Agricultural Science*, *155*(7), 1124-1136.

Ali, A., Ghani, M. I., Haiyan, D., Iqbal, M., Cheng, Z., & Cai, Z. (2020). Garlic substrate induces cucumber growth development and decreases Fusarium wilt through regulation of soil microbial community structure and diversity in replanted disturbed soil. *International Journal of Molecular Sciences*, *21*(17), 6008-6017.

Ali-Olubandwa, A. M., Kathuri, N. J., Odero-Wanga, D., & Shivoga, W. (2011). Challenges facing small scale maize farmers in western province of Kenya in the agricultural reform era. *American Journal of Experimental Agriculture*, *1*(4), 466-476.

Aminifard, M.H., Aroiee, H., Nemati, H., Azizi, M., & Khayyat, M. (2012). Effect of nitrogen fertilizer on vegetative and reproductive growth of pepper plants under field conditions. *Journal of Plant Nutrition*, *35*(2), 235-242.

Aruani, M. C., Reeb, P. D., & Barnes, N. E. (2014). Influence of soil properties on yield and fruit maturity at harvest of 'Williams' pear. *Chilean Journal of Agricultural Research, 74*(4), 460-467. https://dx.doi.org/10.4067/S0718-58392014000400013.

Assefa, G. (2012). Retrospect and prospects of forage and pasture crops research in Ethiopia. In: Getnet, A., Mesfin, D., Jean, H., Getachew, A., Solomon, M., & Alemayehu, M. (Eds) *Forage Seed Research and Development in Ethiopia. Ethiopian Institute of Agricultural Research, Addis Ababa, Ethiopia*, 7-14.

Aziz, S., & Islam, M. S. (2023). Erosion and runoff reduction potential of vetiver grass for hill slopes: A physical model study. *International Journal of Sediment Research, 38*(1), 49-65.

Balasubramanian, P., Mariappan, V. E., Lourdusamy, D. K., Chinnamuthu, C. R., & Swetha, S. (2020). Peanut as a smart food and their nutrients aspects in planet: A review. *Agricultural Reviews*, *41*(4), 403-407.

Baldissera, T. C., da Silveira Pontes, L., Giostri, A. F., Barro, R. S., Lustosa, S. B. C., de Moraes, A., & de Faccio Carvalho, P. C. (2016). Sward structure and relationship between canopy height and light interception for tropical C4 grasses growing under trees. *Crop and Pasture Science*, *67*(11), 1199-1207.

Bar-El Dadon, S., Abbo, S., & Reifen, R. (2017). Leveraging traditional crops for better nutrition and health-The case of chickpea. *Trends in Food Science and Technology*, *64*, 39-47.

Bedoussac, L., Journet, E. P., Hauggaard-Nielsen, H., Naudin, C., Corre-Hellou, G., Jensen, E. S., & Justes, E. (2015). Ecological principles underlying the increase of productivity achieved by cereal-grain legume intercrops in organic farming. A review. *Agronomy for Sustainable Development*, *35*(3), 911-935.

Bento, C. B., Filoso, S., Pitombo, L. M., Cantarella, H., Rossetto, R., Martinelli, L. A., & Do Carmo, J. B. (2018). Impacts of sugarcane agriculture expansion over low-intensity cattle ranch pasture in Brazil on greenhouse gases. *Journal of Environmental Management*, *206*, 980-988.

Bezerra, R. P. M., Loss, A., Pereira, M. G., & Perin, A. (2015). Phosphorus fractions and correlation with soil attributes under no-tillage and crop-livestock integration systems in Cerrado of Goias. *Semina: Ciências Agrárias*, *36*(3), 1287-1306.

Bhan, S., & Behera U. K. (2014). Conservation agriculture in India – Problems, prospects and policy issues. *International Soil and Water Conservation Research 2*(4), 1–12

Bhatt, R., Kukal, S. S., Busari, M. A., Arora, S., & Yavad, M. (2016). Sustainability issues on rice–wheat cropping system. *International Soil and Water Conservation Research*, *4*(1), 64-74.

Boissele, T. (2017). The potential of synergy developing a tool to design ecosystems for sustainable soil management. *European Journal of Sustainable Development*, *6*(4), 517-530.

Bravo, S., Amorós, J. A., Pérez-De-Los-Reyes, C., García, F. J., Moreno, M. M., Sánchez-Ormeño, M., & Higueras, P. (2017). Influence of the soil pH in the uptake and bioaccumulation of heavy metals (Fe, Zn, Cu, Pb and Mn) and other elements (Ca, K, Al, Sr and Ba) in vine leaves, Castilla-La Mancha (Spain). *Journal of Geochemical Exploration*, *174*, 79-83.

Bremner, J. M. (1960). Determination of nitrogen in soil by the Kjeldahl method. *The Journal of Agricultural Science, 55*(1), 11-33.

Britzke, D., Da Silva, L. S., Moterle, D. F., dos Santos Rheinheimer, D., & Bortoluzzi, E. C. (2012). A study of potassium dynamics and mineralogy in soils from subtropical Brazilian lowlands. *Journal of Soils and Sediments*, *12*(2), 185-197.

Brooker, R. W., Bennett, A. E., Cong, W. F., Daniell, T. J., George, T. S., Hallett, P. D., & Li, L. (2015). Improving intercropping: a synthesis of research in agronomy, plant physiology and ecology. *New Phytologist Foundation*, *206*(1), 107-117.

Butterly, C. R., Baldock, J. A., & Tang, C. (2013). The contribution of crop residues to changes in soil pH under field conditions. *Plant and Soil*, *366*(1), 185-198.

Carr, P. M., Gramig, G. G., & Liebig, M. A. (2013). Impacts of organic zero tillage systems on crops, weeds, and soil quality. *Sustainability*, *5*(7), 3172-3201.

Chalise, K. S., Singh, S., Wegner, B., Kumar, S., Pérez-Gutiérrez, J. D., Osborne, S., Nleya, T., Guzman, J., & Rohila, J. S. (2019). Cover crops and returning residue impact on soil organic carbon, bulk density, penetration resistance, water retention, infiltration, and soybean yield. *Agronomy Journal*, *111*(1), 99–108. https://doi.org/10.2134/agronj2018.03.0213

Chaudhari, S. K., Arshad, M., Amjad, M. S., & Fatima, S. (2013). Taxonomic inventory of grasses on the basis of morphological attributes from Thal desert, Pakistan. *International Journal of Scientific & Engineering Research*, *4*(11), 509-517.

Chen, B., Liu, E., Tian, Q., Yan, C., & Zhang, Y. (2014). Soil nitrogen dynamics and crop residues. A review. *Agronomy for Sustainable Development*, *34*, 429-442.

Chen, S., Xu, C., Yan, J., Zhang, X., Zhang, X., & Wang, D. (2016). The influence of the type of crop residue on soil organic carbon fractions: An 11-year field study of rice-based cropping systems in southeast China. *Agriculture, Ecosystems and Environment*, *223*, 261-269.

Chepkoech, C. (2015). *Effect of Legume Integration and Application of Organic Fertilizers on Soil Nutrient Status and Kale Yield in Kabete, Kenya* (Doctoral Dissertation in Land Resource Management and Agricultural Technology. University of Nairobi)

Cheruiyot, D. (2018). *Understanding agronomic and phytochemical properties of Brachiaria for management of cereal stemborers in East Africa* (Doctoral Dissertation, in Environmental Science. North-West University).

Cheruiyot, D., Midega, C. A., Pittchar, J. O., Pickett, J. A., & Khan, Z. R. (2020). Farmers' perception and evaluation of Brachiaria grass (Brachiaria spp.) genotypes for smallholder cereal-livestock production in East Africa. *Agriculture*, *10*(7), 268.

Chibesa, C. (2020). *An Investigation of Whether Small Scale Farmers Consider Crop Diversification as an Alternative to Sustainable Familyhood Income Generation. A Case Study of Choma District* (Doctoral dissertation, in Development Studies. Cavendish University).

Choudhary, V. K., Dixit, A., Kumar, P. S., & Chauhan, B. S. (2014). Productivity, weed dynamics, nutrient mining, and monetary advantage of maize-legume intercropping in the Eastern Himalayan Region of India. *Plant Production Science*, *17*(4), 342-352.

Cong, W. F., Hoffland, E., Li, L., Six, J., Sun, J. H., Bao, X. G., & Van Der Werf, W. (2015b). Intercropping enhances soil carbon and nitrogen. *Global Change Biology*, *21*(4), 1715-1726.

Corriher, V. A., Hill, G. M., Bernard, J. K., Jenkins, T. C., West, J. W., & MullinixJr, B. G. (2010). Pigeon peas as a supplement for lactating dairy cows fed corn silage-based diets. *Journal of Dairy Science*, *93*(11), 5309-5317.

Cotrufo, M. F., Wallenstein, M. D., Boot, C. M., Denef, K., & Paul, E. (2013). The Microbial Efficiency-Matrix Stabilization (MEMS) framework integrates plant litter decomposition with soil organic matter stabilization: Do labile plant inputs form stable soil organic matter? *Global Change Biology*, *19*(4), 988-995.

Da Silva Dias, J. C. (2015). Biodiversity and plant breeding as tools for harmony between modern agriculture production and the environment. *Molecular Approaches to Genetic Diversity*, 1-44.

Danga, B. O., Wakindiki, I. I., & Ouma, J. P. (2013). Chickpea residue properties controlling decomposition dynamics and nitrogen availability in some tropical acid soils. *South African Journal of Plant and Soil*, *30*(4), 203-212.

Dhaliwal, S. S., Naresh, R. K., Mandal, A., Singh, R., & Dhaliwal, M. K. (2019). Dynamics and transformations of micronutrients in agricultural soils as influenced by organic matter build-up: A review. *Environmental and Sustainability Indicators*, *1*, 100007.

Diacono, M., & Montemurro, F. (2011). Long-term effects of organic amendments on soil fertility. In: Lichtfouse, E., Hamelin, M., Navarrete, M., Debaeke, P. (Eds) *Sustainable agriculture volume 2*, 761-786.

Dolijanović, Ž., Momirović, N., Simić, M., Kovačević, D., Oljača, S., & Mikić, A. (2013). Fall and spring sown legume-cereal cover crops for sweet maize production. In Proceedings of *2nd International Scientific Conference, Soil and Crop Management: Adaptation and Mitigation of Climate Change, 26-28 September, 2013, Osijek, Croatia*. Croatian Soil Tillage Research Organization (CROSTRO), 128-135.

Dong, Q., Bai, B., Almutairi, B. O., & Kudla, J. (2021). Emerging roles of the CBL-CIPK calcium signaling network as key regulatory hub in plant nutrition. *Journal of Plant Physiology*, *257*, 153335.

Drost, S. M., Rutgers, M., Wouterse, M., De Boer, W., & Bodelier, P. L. (2020). Decomposition of mixtures of cover crop residues increases microbial functional diversity. *Geoderma*, *361*, 114060-114076.

Dumlao, M. R., Darehshouri, A., Cohu, C. M., Muller, O., Mathias, J., Adams, W. W., & Demmig-Adams, B. (2012). Low temperature acclimation of photosynthetic capacity and leaf morphology in the context of phloem loading type. *Photosynthesis Research*, *113*(1-3), 181-189.

Emefiene, M. E., Joshua, V. I., Nwadike, C., Yaroson, A. Y., & Zwalnan, N. D. E. (2014). Profitability analysis of pigean pea (*Cajanus cajan*) production in Riyom LGA of Plateau State. *International Letters of Natural Sciences*, *13*(2), 73-88

FAOSTAT. (2011). http:www.fao.org/faostat/en/#data/_Accessed on 27th December, 2022.

FAOSTAT. (2013). http://www.fao.org/faostat/en/#data/ Accessed on 4th April, 2021.

FAOSTAT. (2017). http://www.fao.org/faostat/en/#data/ Accessed on 20th August, 2019.

Farhat, N., Elkhouni, A., Zorrig, W., Smaoui, A., Abdelly, C., & Rabhi, M. (2016). Effects of magnesium deficiency on photosynthesis and carbohydrate partitioning. *Acta physiologiae plantarum, 38*(6), 1-10.

Fikre, A., Desmae, H., & Ahmed, S. (2020). Tapping the economic potential of chickpea in sub-Saharan Africa. *Agronomy*, *10*(11), 1707.

Fu, B., Chen, L., Huang, H., Qu, P., & Wei, Z. (2021). Impacts of crop residues on soil health: A review. *Environmental Pollutants and Bioavailability*, *33*(1), 164-173.

Gachene, C. K., Nyawade, S. O., & Karanja, N. N. (2019). Soil and water conservation: An overview. In: Leal F. W., Azul, A. M., Brandli, L., Özuyar, P.G., Wall, T. (Eds) *Zero Hunger. Encyclopedia of the UN Sustainable Development Goals.*

Garbach, K., Milder, J. C., DeClerck, F. A., Montenegro, M., Driscoll, L., & Gemmill-Herren, B. (2017). Examining multi-functionality for crop yield and ecosystem services in five systems of agroecological intensification. *International Journal of Agricultural Sustainability*, *15*(1), 11-28.

García, E., Siles, P., Eash, L., Van Der Hoek, R. E. I. N., Kearney, S. P., Smukler, S. M., & Fonte, S. J. (2019). Participatory evaluation of improved grasses and forage legumes for smallholder livestock production in Central America. *Experimental Agriculture, 55*(5), 776-792.

Gellings, C. W., & Parmenter, K. E. (2016). Energy efficiency in fertilizer production and use. In: Clark, W. G. (Ed) *Efficient Use and Conservation of Energy*. *Encyclopedia of Life Support Systems*, 123-136.

Gemede, H. F., & Ratta, N. (2014). Anti-nutritional factors in plant foods: potential health benefits and adverse effects. *International Journal of Nutrition and Food Sciences*, *3*(4), 284-289.

Ghimire, R., Adhikari, K. R., Chen, Z. S., Shah, S. C., & Dahal, K. R. (2012). Soil organic carbon sequestration as affected by tillage, crop residue, and nitrogen application in rice–wheat rotation system. *Paddy and Water Environment*, *10*(2), 95-102.

Gonsalvez, J. (2016). Integrated Community Food Production. *A Compendium of Climate-resilient Agriculture Options. Copenhagen, Denmark: CGIAR Research Program on Climate Change, Agriculture and Food Security* (CCAFS). https://hdl.handle.net/10568/75968.

Government of Kenya, (2013a). Busia County Integrated Development Plan

Gransee, A., & Führs, H. (2013). Magnesium mobility in soils as a challenge for soil and plant analysis, magnesium fertilization and root uptake under adverse growth conditions. *Plant and Soil*, *368*(1), 5-21.

Grzebisz, W. (2011). Magnesium–food and human health. *Journal of Elementology*, *16*(2). https://www.jelem. 10.5601/jelem.2011.16.2.13.

Guo, Y., Fan, R., Zhang, X., Zhang, Y., Wu, D., McLaughlin, N., & Liang, A. (2020). Tillage-induced effects on SOC through changes in aggregate stability and soil pore structure. *Science of the Total Environment*, *703*, 134617.

Hafeez, B. M., Khanif, Y. M., & Saleem, M. (2013). Role of zinc in plant nutrition-a review. *American Journal of Experimental Agriculture*, *3*(2), 374-385.

Hailu, G., Niassy, S., Zeyaur, K. R., Ochatum, N., & Subramanian, S. (2018). Maize–legume intercropping and push–pull for management of fall armyworm, stemborers, and Striga in Uganda. *Agronomy Journal*, *110*(6), 2513-2522. http://hdl.handle.net/123456789/954.

Hansen, J. H., Hamelin, L., Taghizadeh-Toosi, A., Olesen, J. E., & Wenzel, H. (2020). Agricultural residues bioenergy potential that sustain soil carbon depends on energy conversion pathways. *GCB Bioenergy*, *12*(11), 1002-1013.

HCDA (2013). National Horticulture Validated Report 2013. Horticultural Crops Development Authority (HCDA), Nairobi.

Heuzé, V., Tran, G., Eugène, M., & Bastianelli, D., (2015). Silver-leaf desmodium (*Desmodium uncinatum* L.). In: Heuzé, V., Tran, G., Thiollet, H., (Eds) *Feedepedia: Animal Feed Resources Information system 1-8*.

Hijbeek, R., van Ittersum, M. K., Berge, H. F., Gort, G., Spiegel, H., & Whitmore, A. P. (2017). Do Organic Inputs Matter: A Meta-Analysis of Additional Yield Effects for Arable Crops in Europe. *Plant and Soil*, *411*, 293–303. https://doi.org/10.1007/s11104-016-3031-x

Hombegowda, H. C., Adhikary, P. P., Jakhar, P., Madhu, M., & Barman, D. (2020). Hedge row intercropping impact on run-off, soil erosion, carbon sequestration and millet yield. *Nutrient Cycling in Agroecosystems*, *116*, 103-116.

Hufnagel, J., Reckling, M., & Ewert, F. (2020). Diverse approaches to crop diversification in agricultural research. A review. *Agronomy for Sustainable Development*, *40*(2), 1-17.

Huluka, S. G., Wogi, D., & Argaw, M. (2018). *Nutrient flows and balances under crop-livestock farming system of yabala, bedele district, southwesteren oromia, Ethiopia* (Doctoral Dissertation, Haramaya University).

Hussain, W. S., & Abbas, M. M. (2021). Application of allelopathy in crop production. *Agricultural Development in Asia-Potential Use of Nano-Materials and Nano-Technology*.

Ibrahim, A., Abaidoo, R. C., Iliasso, A. D., & Fatondji, D. (2018). Nutrient release dynamics from decomposing organic materials and their mulching-effect on pearl millet yields in a low-input Sahelian cropping system. *Nutrient Cycling in Agroecosystems*, *112*(1), 45-59.

Jaetzold, R., Hornetz, B., Shisanya, C. A., & Schmidt, H. (2012). Farm management handbook of Kenya Vol I-IV (Western Central Eastern Nyanza Southern Rift Valley Northern Rift Valley Coast). *Nairobi: Government Printers*.

Jain, M., Misra, G., Patel, R. K., Priya, P., Jhanwar, S., Khan, A. W., & Yadav, M. (2013). A draft genome sequence of the pulse crop chickpea (*Cicer arietinum* L.). *The Plant Journal*, *74*(5), 715-729.

Jela, N. P. (2016). *Prevalence of Childhood Malnutrition and Associated Factors Among Children Aged 6-59 Months in Busia District* (Doctoral dissertation, in Food and Nutrition. University of Nairobi).

Jin, Z. Q., Shah, T. R., & Zhang, L. (2020). Effect of straw returning on soil organic carbon in rice–wheat rotation system: a review. *Food and Energy Security*, *9*(2), 13-17.

Juárez-Hernández, S., & Sheinbaum Pardo, C. (2020). Assessing the potential of alternative farming practices for sustainable energy and water use and GHG mitigation in conventional maize systems. *Environment, Development and Sustainability*, *22*, 8029-8059.

Kagabo, M. D. (2013). *Participatory Integrated Watershed Management in the North-Western Highlands of Rwanda* (Doctoral Dissertation, in Soil Physics and land Use, Wageningen University).

Kar, G., & Singh, A. K. (2023, January). Jute and Allied Fibres for Environmental Sustainability. In *National Conference on Natural Fibre for Sustainable Societal Development 1*, 1-8.

Karanja, J. K., Mugendi, B. J., Khamis, F. M., & Muchugi, A. N. (2013). Nutritional composition of the pumpkin (*Cucurbita spp*.) seed cultivated from selected regions in Kenya. *Journal of Horticulture Letters*, *3* (1), 17-22.

KARI (2011). Annual Report 2011. Kenya Agricultural Research Institute (KARI), Nairobi

Karri, V. R., & Nalluri, N. (2017). Pigeon pea (*Cajanus cajan* L.) by-products as potent natural resource to produce protein rich edible food products. *International Journal of Current Agricultural Sciences 7*(7), 229-236.

Katungi, E., Farrow, A., Chianu, J., Sperling, L., & Beebe, S. (2009). Common bean in Eastern and Southern Africa: a situation and outlook analysis. *International Centre for Tropical Agriculture*, *61*, 1-44.

Katungi, E., Farrow, A., Mutuoki, T., Gebeyehu, S., Karanja, D., Alamayehu, F., Sperling, L., Beebe, S., Rubyogo, J. C., & Buruchara, R. (2010). Improving common bean productivity, an analysis of socioeconomic factors in Ethiopia and Eastern Kenya. *Baseline Report Tropical Legumes II*. CIAT, Cali, Colombia.

Kauer, K., Pärnpuu, S., Talgre, L., Eremeev, V., & Luik, A (2021). Soil Particulate and Mineral-Associated Organic Matter Increases in Organic Farming under Cover Cropping and Manure Addition. *Agriculture*, *11*, 903-911.

Kaur, M., & Sharma, S. (2018). Development and nutritional evaluation of cake supplemented with pumpkin seed flour. *Asian Journal of Dairy and Food Research*, *37*(3), 232-236.

Khaledian, Y., Brevik, E. C., Pereira, P., Cerdà, A., Fattah, M. A., & Tazikeh, H. (2017). Modeling soil cation exchange capacity in multiple countries. *Catena*, *158*, 194-200.

Khan, Z. R., Pickett, J. A., Hassanali, A., Hooper, A. M., & Midega, C. A. O. (2008). Desmodium species and associated biochemical traits for controlling Striga species: present and future prospects. *Weed Research*, *48*(4), 302-306.

Khan, Z., Midega, C., Pittchar, J., Pickett, J., & Bruce, T. (2011). Push—pull technology: a conservation agriculture approach for integrated management of insect pests, weeds and soil health in Africa. *UK government's Foresight Food and Farming Futures project. International Journal of Agricultural Sustainability*, *9*(1), 162-170.

Kimurto, P. K., Towett, B., Mulwa, R. S., Njogu, N., Kosgei, A., Songok, S., & Macharia, J. K. (2014). An overview of chickpea breeding programs in Kenya. *Legume Perspectives*, (3), 55-57.

Kinyua, M. K. (2019). Report on the forage and feed product flow in Kenya (Busia, Bungoma, Kakamega and Siaya Counties). *International Center for Tropical Agriculture 44*, Nairobi, Kenya

Kinyua, M., Cao Diogo, R. V., Sibomana, J., Bolo, P. O., Gbedjissokpa, G., Mukiri, J., & Kihara, J. M. (2019). Green manure cover crops in Benin and Western Kenya-A review. *CIAT Publication*.

Kremen, C., Iles, A., & Bacon, C. (2012). Diversified farming systems: an agro-ecological, systems-based alternative to modern industrial agriculture. *Ecology and Society*, *17*(4), 288-306.

Kumawat, A., Bamboriya, S. D., Meena, R. S., Yadav, D., Kumar, A., Kumar, S., & Pradhan, G. (2022). Legume-based inter-cropping to achieve the crop, soil, and environmental health security. In: Ram, S. M., & Sandeep, Kumar., (Eds) *Advances in Legumes for Sustainable Intensification 16,* 307-328. Academic Press.

Li, H., Santos, F., Butler, K., & Herndon, E. (2021). A critical review on the multiple roles of manganese in stabilizing and destabilizing soil organic matter. *Environmental Science & Technology*, *55*(18), 12136-12152.

Li, T., Li, Y., Wang, S., Wang, Z., Liu, Y., Wen, X., & Liao, Y. (2022). Assessing synergistic effects of crop rotation pattern, tillage practice, and rhizosphere effect on soil bacterial community structure and assembly in China's Loess Plateau farmlands. *Applied Soil Ecology*, *174*, 104411-104426.

Liao, Y., Wu, W. L., Meng, F. Q., Smith, P., & Lal, R. (2015). Increase in soil organic carbon by agricultural intensification in northern China. *Bio-geosciences*, *12*(5), 1403-1413.

Lissu, C. S. (2016). *The influence of desmodium and manure on the agronomic performance of fodder plants in Lushoto District, Tanzania.* (Doctoral Dissertation, in Management of Natural Resources for Sustainable Agriculture. Sokoine University of Agriculture).

Lithourgidis, A. S., Dordas, C. A., Damalas, C. A., & Vlachostergios, D. (2011). Annual intercrops: an alternative pathway for sustainable agriculture. *Australian Journal of Crop Science*, *5*(4), 396-410.

Liu, G., & Hanlon, E. (2012). Soil pH range for optimum commercial vegetable production. *EDIS*, *2012*(11).

Madar, R., Singh, Y. V., Meena, M. C., Das, T. K., Paramesh, V., Al-Mana, F. A., & Elansary, H. (2020). Residue and potassium management strategies to improve crop productivity, potassium mobilization, and assimilation under zero-till maize–wheat cropping system. *Journal of Agriculture*, *10*(9), 401-407.

Maggio, G., Sitko, N. J., & Ignaciuk, A. (2018). *Cropping system diversification in Eastern and Southern Africa: Identifying policy options to enhance productivity and build resilience.* Food and Agriculture Organization of the united nations, Agricultural Development, Economics Division.

Makate, C., Wang, R., Makate, M., & Mango, N. (2016). Crop diversification and livelihoods of smallholder farmers in Zimbabwe: adaptive management for environmental change. *Springer Plus*, *5*(1), 1-18.

Malhi, S. S., Nyborg, M., Goddard, T., & Puurveen, D. (2011). Long-term tillage, straw management and N fertilization effects on quantity and quality of organic C and N in a Black Chernozem soil. *Nutrient Cycling in Agroecosystems*, *90*(2), 227-241.

Matui, M. S., Gonzalez, Y. S., Gema, J., & Koomen, I. (2016). *From aid to sustainable trade, driving competitive horticulture sector development: A quick scan of the horticulture sector* (No. 16-03/CDI-16-045). Wageningen Centre for Development Innovation.

Matus, F. J., Escudey, M., Förster, J. E., Gutiérrez, M., & Chang, A. C. (2009). Is the Walkley–Black method suitable for organic carbon determination in chilean volcanic soils? *Communications in Soil Science and Plant Analysis*, *40*(11-12), 1862-1872.

Mbaeyi-Nwaoha, I. E., & Obetta, F. C. (2016). Production and evaluation of nutrient-dense complementary food from millet (*Pennisetum glaucum*), Pigeon pea (*Cajanus cajan*) and seedless breadfruit (*Artocarpus altillis*) leaf powder blends. *African Journal of Food Science*, *10*(9), 143-156.

McCarty, L. B., Rodriguez, I. R., Bunnell, B. T., & Waltz, F. C. (2003). Fundamentals of turfgrass and agricultural chemistry. In: Berry, J. E. C., Edwards, M., & Liu, H. (Eds) *Fundamentals of Turfgrass and Agricultural Chemistry*.

McDaniel, M. D., Tiemann, L. K., & Grandy, A. S. (2014). Does agricultural crop diversity enhance soil microbial biomass and organic matter dynamics? A meta-analysis. *Ecology Applications*, *24*(3), 560–570.

McLean, E. O. (1965). Aluminum. *Methods of Soil Analysis: Part 2 Chemical and Microbiological Properties*, *9*, 978-998.

Mehlich, A. (1984). Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. *Communications in Soil Science and Plant Analysis*, *15*(12), 1409-1416.

Mertz, O., Mbow, C., Reenberg, A., & Diouf, A. (2009). Farmers' perceptions of climate change and agricultural adaptation strategies in rural Sahel. *Environmental Management*, *43*(5), 804-816.

Michler, J. D., & Josephson, A. L. (2017). To specialize or diversify: agricultural diversity and poverty dynamics in Ethiopia. *World Development, 89,* 214-226. DOI: https://doi.org/10.1016/j.worlddev.2016.08.011.

Midega, C. A., Bruce, T. J., Pickett, J. A., Pittchar, J. O., Murage, A., & Khan, Z. R. (2015). Climate-adapted companion cropping increases agricultural productivity in East Africa. *Field Crops Research*, *180*, 118-125.

Midega, C. A., Pittchar, J., Salifu, D., Pickett, J. A., & Khan, Z. R. (2013). Effects of mulching, N-fertilization and intercropping with *Desmodium uncinatum* on *Striga hermonthica* infestation in maize. *Crop Protection*, *44*, 44-49.

Mikkelsen, R. (2010). Soil and fertilizer magnesium. *Better Crops, 94*(2), 26-28. DOI: http://www.researchgate.net/publication/308795926.

Mimmo, T., Del Buono, D., Terzano, R., Tomasi, N., Vigani, G., Crecchio, C., & Cesco, S. (2014). Rhizospheric organic compounds in the soil–microorganism–plant system: their role in iron availability. *European Journal of Soil Science*, *65*(5), 629-642.

Miriko, M. C., Korir, N. K., & Gweyi-Onyango, J. P. (2018). Benefits of Rhizobial Inoculation and Phosphorus Application on Growth of Lucerne (*Medicago-sativa*) in Kenya. *International Journal of Plant and Soil Science*, *21*(6), 1-7.

Mkonda, M. (2014). Rainfall variability and its association to the trends of crop production in Mvomero District, Tanzania. *European Scientific Journal 10*(20), 263-273. https://doi.org/10.19044/esj.2014.v10n20p

Mligo, J. K., & Craufurd, P. Q. (2005). Adaptation and yield of pigeon pea in different environments in Tanzania. *Field Crops Research*, *94*(1), 43-53.

Mndzebele, B., Ncube, B., Fessehazion, M., Mabhaudhi, T., Amoo, S., du Plooy, C., & Modi, A. (2020). Effects of cowpea-amaranth intercropping and fertiliser application on soil phosphatase activities, available soil phosphorus, and crop growth response. *Agronomy*, *10*(1), 1-20.

Moa, S., & Jica, N. (2000). Local and Export Vegetables Growing Manual. *Ministry of agriculture and Japan international co-operation agency, Agricultural Information Centre*, Nairobi, 1-21.

Moges, A., & Holden, N. M. (2008). Soil fertility in relation to slope position and agricultural land use: A case study of Umbulo catchment in southern Ethiopia. *Environmental Management*, *42*(5), 753-763.

Mohammadi, K., Sohrabi, Y., Heidari, G., Khalesro, S., & Majidi, M. (2012). Effective factors on biological nitrogen fixation: Review. *African Journal of Agricultural Research*, *7*(12), 1782-1788.

Mudryj, A. N., Yu, N., & Aukema, H. M. (2014). Nutritional and health benefits of pulses. *Applied Physiology, Nutrition, and Metabolism*, *39*(11), 1197-1204.

Muperi, S. (2016). *Effects of intercropping maize (Zea mays) with butternuts (Cucurbita moschata) at varying butternut population levels on maize growth, yield and weed suppression* (Bachelors Dissertation in Natural Resource Management and Agriculture. Midlands State University)

Muraoka, R., Matsumoto, T., Jin, S., & Otsuka, K. (2016). On the possibility of a maize green revolution in the highlands of Kenya: An assessment of emerging intensive farming systems. In: Otsuka, K., Larson, D. (Eds) *Pursuit of an African Green Revolution 48*, 145-164. Springer, Tokyo.

Murphy, R. P., Montes-Molina, J. A., Govaerts, B., Six, J., Kessel, C., & Fonte, S. J. (2016). Crop residue retention enhances soil properties and nitrogen cycling in smallholder maize systems of Chiapas, Mexico. *Applied Soil Ecology*, *103*, 110-116.

Mwakha, F. A., Gichimu, B. M., Neondo, J. O., Kamau, P. K., Odari, E. O., Muli, J. K., & Budambula, N. L. (2020). Agro-morphological characterization of Kenyan Slender Leaf (*Crotalaria brevidens* and *C. ochroleuca*) Accessions. *International Journal of Agronomy*,*2020*, 1-10.

Nakaziba, R., Anyolitho, M. K., Amanya, S. B., Sesaazi, C. D., Byarugaba, F., Ogwal-Okeng, J., & Alele, P. E. (2021). Traditional medicinal vegetables in northern uganda: An ethnobotanical survey. *International Journal of Food Science*. Naresh, R. K., Jat, P. C., Kumar, V., Singh, S. P., & Kumar, Y. (2018). Carbon and nitrogen dynamics, carbon sequestration and energy saving in soils under different tillage, stubble mulching and fertilizer management in rice–wheat cropping system. *Journal of Pharmacognosy and Phytochemistry*, *7*(6), 723-740.

Ndung'u, N., Thugge, K., & Otieno, O. (2011). Unlocking the future potential for Kenya. The Vision 2030. *Office of the Prime Minister, Ministry of State for Planning, National Development and Vision, 2030*.

Nelson, G. C., Rosegrant, M. W., Palazzo, A., Gray, I., Ingersoll, C., Robertson, R., & You, L. (2010). *Food security, farming, and climate change to 2050, scenarios, results, policy options*. International Food Policy Research Institute, 172

Nene, Y. L., Reddy, M. V., Haware, M. P., Ghanekar, A. M., Amin, K. S., Pande, S., & Sharma, M. (2012). *Field Diagnosis of Chickpea Diseases and their Control. Information Bulletin No. 28 (revised)*. International Crops Research Institute for the Semi-Arid Tropics.

Neumann, K., Verburg, P. H., Stehfest, E., & Müller, C. (2010). The yield gap of global grain production. A spatial analysis. *Agricultural Systems*, *103*(5), 316-326.

Ngalamu, T., Odra, J., & Tongun, N. (2015). Cowpea production handbook. *IFS/AGRA.*

Ngugi, I. K., Gitau, R., & Nyoro, J. (2007). Access to high value markets by smallholder farmers of African indigenous vegetables in Kenya. *Re-governing markets Innovation Practice series,* International Institute for Environment and Development, London.

Nguku, S. A., Donald, M. G., Musimba, N. K., Amwata, D., & Kaindi, E. M. (2016). Primary production variables of brachiaria grass cultivars in Kenya dry lands. *Tropical and Subtropical Agro-ecosystems*, *19*(1), 29-39.

Nie, S. A., Lei, X., Zhao, L., Wang, Y., Wang, F., Li, H., & Xing, S. (2018). Response of activity, abundance, and composition of anammox bacterial community to different fertilization in a paddy soil. *Biology and Fertility of Soils*, *54*, 977-984.

Nitis, I. M., Lana, K., Sukanten, W., Putra, S., & Suarna, M. (1993). Increasing the forage supply and cattle production through a three-strata forage system. In *Proceedings of the XVII International Grassland Congress, Palmerston North* (pp. 498-499).

Nolipher, K. (2014). *Evaluation of Malawi pigeon pea (cajanus cajan l) accessions for tolerance to moisture stress and superior agronomic traits in Uganda* (Doctoral Dissertation, Makerere University).

Ntawuruhunga, D., Assefa, F. A., Mambo, W., Momanyi, H. M., & Omeli, M. R. (2016). *Farmers' Knowledge, Attitude and Practice towards African Indigenous Vegetables in Kenya* (Doctoral Dissertation, Jomo Kenyatta University of science and Technology).

Nwaogu, L. A., & Emejulu, A. A. (2010). Evaluation of the toxicity of cyanogens in a commonly consumed Nigeria legume pigeon pea (*Cajanus cajan*) seed and its biochemical effects in rabbits. *International Journal of Biological and Chemical Sciences*, *4*(5), 1435-1441

Odokonyero, K., Acuña, T. B., Cardoso, J. A., De la Cruz Jimenez, J., & Rao, I. M. (2016). Fungal endophyte association with Brachiaria grasses and its influence on plant water status, total non-structural carbohydrates and biomass production under drought stress. *Plant and Soil*, *409* (1/2), 273-282.

Okalebo, J. R., Gathua, K. W., & Woomer, P. L. (2002). Laboratory methods of soil and plant analysis: a working manual second edition. *Sacred Africa, Nairobi*, *21*, 25-26.

Ondabu, N., Maina, S., Kimani, W., Njarui, D. M. G., Djikeng, A., & Ghimire, S. R. (2016). Genetic diversity of Brachiaria grass ecotypes in Kenya. In *proceedings of workshop on Climate Smart Brachiaria Grasses for Improving Livestock Production in East Africa–Kenya Experience*, 14-16 September 2016, Naivasha, Kenya.

Paciullo, D. S., Castro, C. R., Gomide, C. A., Fernandes, P. B., Rocha, W. S., Müller, M. D., & Rossiello, R.O. (2010). Soil bulk density and biomass partitioning of *Brachiaria decumbens* in a silvo-pastoral system. *Scientia Agricola*, *67*(5), 598-603.

Pahalvi, H. N., Rafiya, L., Rashid, S., Nisar, B., & Kamili, A. N. (2021). Chemical fertilizers and their impact on soil health. Microbiota and Biofertilizers. In: Dar, G. H., Bhat, R. A., Mehmood, M. A., Hakeem, K. R. (Eds) *Microbiota and Biofertilizers 2,*1-20. https://doi.org/10.1007/978-3-030-61010-4_1

Pal. S., Chattopadhyay, B., & Mukhopadhyay, S. K. (2016) Importance of agriculture and crop residues in carbon sequestration and nutrient enrichment at agricultural farms of East Kolkata Wetland area, a Ramsar site. *Current Science 110*(7),1330-1337. https://www.jstor.org/stable/24908022

Pande, S., Sharma, M., & Guvvala, G. (2013). An updated review of biology, pathogenicity, epidemiology and management of wilt disease of pigeon pea (*Cajanus cajan* (L.) Millsp.). *Journal of Food Legumes*, *26*(1/2), 1-14.

Pandey, D. (2020). Agricultural sustainability and climate change nexus. In: Singh, P., Singh, R., & Srivastava, V. (Eds) *Contemporary environmental Issues and Challenges in Era of climate change,* pp 77-97.

Pardo, M. T., Ristori, G., D'acqui, L. P., & Almendros, G. (2003). An assessment of soil fertility and agronomic constraints in southern African savannas: A case study of the Panbamatenga area, Botswana. *South African Geographical Journal, 85*(1), 35-41. https://doi.org/10.1080/03736245.2003.9713782

Piccoli, I., Sartori, F., Polese, R., & Berti, A. (2020). Crop Yield After 5 Decades of Contrasting Residue Management. *Nutrient Cycle Agroecosystem*, *117*, 231–241. Springer.com/article/10.1007/s10705-020-10067-9

Pickett, J. A., Hooper, A. M., Midega, C. A., & Khan, Z. R. (2013). Allelopathy. In: Joel, D., Gressel, J., Muselman, L. (Eds) *Parasitic Orobanchaceae* (pp. 459-467). Springer, Berlin, Heidelberg.

Pitman, W. D., & Sotomayor-Rios, A. (2000). In: Antonio, S. (Ed) *Tropical Forage Plants Development and Use*. CRC Press.

Pleasant, J. (2016). Food yields and nutrient analyses of the Three Sisters: A Haudenosaunee cropping system. *Ethnobiology Letters*, *7*(1), 87-98.

Postma, J. A., & Lynch, J. P. (2012). Complementarity in root architecture for nutrient uptake in ancient maize/bean and maize/bean/squash polycultures. *Annals of botany*, *110*(2), 521-534.

Rao I. M., Srinivas C., & Brian, K. (2009). "Capabilities of four novel warm-season legumes in the southern Great Plains, grain production and quality." *Crop Science 49*(3), 1103-1108.

Rao, I. M., Miles, J. W., Beebe, S. E., & Horst, W. J. (2016). Root adaptations to soils with low fertility and aluminium toxicity. *Annals of Botany*,*118*(4), 593-605.

Rebello, C. J., Greenway, F. L., & Finley, J. W. (2014). A review of the nutritional value of legumes and their effects on obesity and its related co-morbidities. *Obesity Reviews*, *15*(5), 392-407.

Reckling, M., Hecker, J. M., Bergkvist, G., Watson, C. A., Zander, P., Schläfke, N., & Bachinger, J. (2016). A cropping system assessment framework; evaluating effects of introducing legumes into crop rotations. *European Journal of Agronomy*, *76*, 186-197.

Rehman, M., Liu, L., Wang, Q., Saleem, M. H., Bashir, S., Ullah, S., & Peng, D. (2019). Copper environmental toxicology, recent advances, and future outlook: a review. *Environmental Science and Pollution Research*, *26*(18), 18003-18016.

Renard, D., & Tilman, D. (2020). Reply to: Crop asynchrony stabilizes food production. *Nature*, *588*(7837), 13.

Rout, G. R., & Sahoo, S. (2015). Role of iron in plant growth and metabolism. *Reviews in Agricultural Science, 3*, 1-24.

Sahoo, U., Maitra, S., Dey, S., Vishnupriya, K. K., Sairam, M., & Sagar, L. (2023). Unveiling the potential of maize-legume intercropping system for agricultural sustainability: A review. *Farming and Management*, *8*(1), 1-13.

Sarkar, S., Panda, S., Yadav, K. K., & Kandasamy, P. (2020). Pigeon pea (*Cajanus cajan*) an important food legume in Indian scenario-A review. *Legume Research*, *43*(5), 601-610.

Saxena, K. B., Kumar, R. V., & Gowda, C. L. L. (2010). Vegetable pigeon pea a review. *Journal of Food Legumes*, *23*(2), 91-98.

Sekaran, U., Lai, L., Ussiri, D. A., Kumar, S., & Clay, S. (2021). Role of integrated crop-livestock systems in improving agriculture production and addressing food security–A review. *Journal of Agriculture and Food Research*, *5*, 100190.

Shah, K. K., Modi, B., Pandey, H. P., Subedi, A., Aryal, G., Pandey, M., & Shrestha, J. (2021). Diversified crop rotation: an approach for sustainable agriculture production. *Advances in Agriculture*, *2021*, 1-9. https://doi.org/10.1155/2021/8924087

Shaheen, S. M., Tsadilas, C. D., & Rinklebe, J. (2013). A review of the distribution coefficients of trace elements in soils: Influence of sorption system, element characteristics, and soil colloidal properties. *Advances in Colloid and Interface Science*, *201*, 43-56.

Sharma, N., Kumar, A., & Chaudhary, R. (2022). Pigeon pea (Cajanus cajan)-Recent biotechnological advances to enhance salt tolerant traits. *Progressive Agriculture*, *22*(2), 195-201.

Shava, S., Donoghue, R., Krasny, M. E., & Zazu, C. (2009). Traditional food crops as a source of community resilience in Zimbabwe. *International Journal of African Renaissance Studies*, *4* (1), 31-48.

Shinde, R., Shahi, D. K., Mahapatra, P., Singh, C. S., Naik, S. K., Thombare, N., & Singh, A. K. (2022). Management of crop residues with special reference to the on-farm utilization methods: A review. *Industrial Crops and Products*, *181*, 114772.

Shrestha, N. (2020). Detecting multicollinearity in regression analysis. *American Journal of Applied Mathematics and Statistics*, *8*(2), 39-42.

Shurtleff, W., & Aoyagi, A. (2013). *Early named soybean varieties in the United States and Canada: Extensively annotated bibliography and sourcebook*. Soy info Center.

Sikuku, P. A., Kimani, J. M., Kamau, J. W., & Njinju, S. (2016). Influence of nitrogen supply on photosynthesis, chlorophyll content and yield of improved rice varieties under upland conditions in Western Kenya. *American Journal of Experimental Agriculture 13*(2), 1-14. https://doi.org/10.9734/AJEA/2016/13859.

Silva, J. S. D., Oliveira, D. P., Rufini, M., Silva Junior, C. L. D., Baptista, M. V. B. D. G., Aragão, O. O. D. S., & Moreira, F. M. D. S. (2021). New strains of Bradyrhizobium enrich plant biomass nitrogen content in Crotalaria for use as a green manure. *Bragantia*, *80*, e4021.

Simon, P. L., Dieckow, J., Zanatta, J. A., Ramalho, B., Ribeiro, R. H., van der Weerden, T., & de Klein, C. A. (2020). Does Brachiaria humidicola and dicyandiamide reduce nitrous oxide and ammonia emissions from cattle urine patches in the subtropics. *Science of the Total Environment*, *720*, 137692.

Singh, K. M., Meena, M. S., & Kumar, A. (2012). An economic view to forage and fodder production in Eastern India. *Available at SSRN 2030697*.

Singh, V. K., Dwivedi, B. S., Singh, S. K., Mishra, R. P., Shukla, A. K., Rathore, S. S., & Jat, M. L. (2018). Effect of tillage and crop establishment, residue management and K fertilization on yield, K use efficiency and apparent K balance under rice-maize system in north-western India. *Field Crops Research*, *224*, 1-12.

Sodaeizadeh, H., & Hosseini, Z. (2012, September). Allelopathy an environmentally friendly method for weed control. In: Farhad, N. (Ed) *International Conference on Applied Life Sciences*.

Soetan, K. O., Olaiya, C. O., & Oyewole, O. E. (2010). The importance of mineral elements for humans, domestic animals and plants-A review. *African Journal of Food Science*, *4*(5), 200-222.

Sofi, S. A., Muzaffar, K., Ashraf, S., Gupta, I., & Mir, S. A. (2020). Chickpea. In: Manickavasagan, A., & Thirunathan, P. (Eds) Pulses. *Processing and Product Development*, 55-76.

Soree, A. M. (2017). Effects of climate change on rural livelihoods in Busia County, Kenya. *International Journal of Agriculture and Earth Science*, *3*(8), 75-89.

Sparrow, L. A., & Uren, N. C. (2014). Manganese oxidation and reduction in soils: effects of temperature, water potential, pH and their interactions. *Soil Research*, *52*(5), 483-494.

Stegarescu, G., Escuer-Gatius, J., Soosaar, K., Kauer, K., Tõnutare, T., Astover, A., & Reintam, E. (2020). Effect of Crop Residue Decomposition on Soil Aggregate Stability. *Agriculture 10*, 527-534.

Su, Y., Lv, J. L., Yu, M., Ma, Z. H., Xi, H., Kou, C. L., & Shen, A. L. (2020). Long-term decomposed straw return positively affects the soil microbial community. *Journal of Applied Microbiology*, *128*(1), 138-150.

Sui, N., Zhou, Z., Yu, C., Liu, R., Yang, C., Zhang, F., Song, G., & Meng, Y. (2014). Yield and potassium use efficiency of cotton with wheat straw incorporation and potassium fertilization on soils with various conditions in the wheat-cotton rotation system. *Field Crop Research*, *172*, 132-144.

Swietlik, D. (2010). Zinc nutrition in horticultural crops. In: Jules, J. (Ed) *Horticultural Reviews*, *23*, 109-180.

Talgre, L., Lauringson, E., Roostalu, H., Astover, A., & Makke, A. (2012). Green manure as a nutrient source for succeeding crops. *Plant, Soil and Environment*, *58*(6), 275-281.

Tesfai, M., Njarui, D. M. G., & Ghimire, S. R. (2019). Sustainable intensifications of African agriculture through legume-based cropping and Brachiaria forage systems. *African Journal of Agricultural Research 14*(27), 1138-1148.

Thavarajah, P. (2012). Evaluation of chickpea (*Cicer arietinum* L.) micronutrient composition: Biofortification opportunities to combat global micronutrient malnutrition. *Food Research International*, *49*(1), 99-104.

Toniutti, M. A., Fornasero, L. V., Albicoro, F. J., Martini, M. C., Draghi, W., Alvarez, F., & Del Papa, M. F. (2017). Nitrogen-fixing rhizobial strains isolated from *Desmodium incanum* DC in Argentina: Phylogeny, biodiversity and symbiotic ability. *Systematic and Applied Microbiology*, *40*(5), 297-307.

Torres González, A. M., & Morton, C. M. (2005). "Molecular and morphological phylogenetic analysis of *Brachiaria* and *Urochloa* (Poaceae)". *Molecular Phylogenetics and Evolution*, *37* (1), 36–44. https://doi.org/10.1016/j.ympev.2005.06.003

Turmel, M. S., Speratti, A., Baudron, F., Verhulst, N., & Govaerts, B. (2015). Crop residue management and soil health: A systems analysis. *Agricultural Systems*, *134*, 6-16. https://doi.org/10.1016/j.agsy.2014.05

Urruty, N., Tailliez-Lefebvre, D., & Huyghe, C. (2016). Stability, robustness, vulnerability and resilience of agricultural systems. A review. *Agronomy for Sustainable Development*, *36*(1), 1-15.

USAID. (2014). *Household and community experiences and perceptions on climate change impacts due to floods, and expectations on policy in Bunyala Sub-County, Western Kenya*. United States Agency for International Development.

Usman, K., Khan, S., Ghulam, S., Khan, M. U., Khan, N., Khan, M. A., & Khalil, S. K. (2012). Sewage sludge: An important biological resource for sustainable agriculture and its environmental implications. *American Journal of Plant Sciences 3*(12), 1708-1721.

Uzoh, I. M., Igwe, C. A., Okebalama, C. B., & Babalola, O. (2019). Legume-maize rotation effect on maize productivity and soil fertility parameters under selected agronomic practices in a sandy loam soil. *Scientific Reports*, *9*(1), 1-9.

Valenzuela, H. (2011). Pigeon peas: A multi-purpose crop for Hawaii. *Hanai'Ai/The Food Provider, March-April-May edition*, 1-8.

Van der Lans, C. J. M., Snoek, H. M., De Boer, F. A., & Elings, A. (2012). *Vegetable chains in Kenya: Production and consumption of vegetables in the Nairobi metropolis* (No. 1130). Wageningen UR Greenhouse Horticulture.

Verhulst, N., Govaerts, B., Verachtert, E., Castellanos-Navarrete, A., Mezzalama, M., Wall, P., & Sayre, K. D. (2010). Conservation agriculture, improving soil quality for sustainable production systems. In: Lal, R., & Stewart, B. A. (Eds) *Advances in soil science: food security and soil quality*, *1799267585*, 137-208.

Wafula, J. K., Njoka, F. M., Nthakanio, P. N., Mosioma, J. O., Mukono, S. T., & Onyari, C. A. (2021). Nodulation and protein content of selected chickpea varieties as impacted by spacing and n-fertiliser rates in Eastern Kenya. *African Journal of Agricultural Research*, *17*(6), 882-895.

Wafula, J. S. (2021). *Genotypic Variation of Bambara Groundnut (Vigna subterranea* L. *Verdc) For Tolerance to Low Phosphorus in Acidic Soils* (Doctoral dissertation, University of Eldoret).

Waiman, C. V., Avena, M. J., Garrido, M., Band, B. F., & Zanini, G. P. (2012). A simple and rapid spectrophotometric method to quantify the herbicide glyphosate in aqueous media. Application to adsorption isotherms on soils and goethite. *Geoderma*, *170*, 154-158.

Wang, L., Sun, X., Li, S., Zhang, T., Zhang, W., & Zhai, P. (2014). Application of organic amendments to a coastal saline soil in North China: Effects on soil physical and chemical properties and tree growth. *PLoS one*, *9*(2), e8915.

Wang, X., Butterly, C. R., Baldock, J. A., & Tang, C. (2017). Long-term stabilization of crop residues and soil organic carbon affected by residue quality and initial soil pH. *Science of the Total Environment*, *587*, 502-509.

Wei, X., Liu, S., Müller, K., Song, Z., Guan, G., Luo, J., & Wang, H. (2019). Urbanization-induced acid rain causes leaching loss of calcium from limestone-derived soil in South China. *Journal of Soils and Sediments*, *19*, 3797-3804.

Wekesa, B. M., Ayuya, O. I., & Lagat, J. K. (2018). Effect of climate-smart agricultural practices on household food security in smallholder production systems: micro-level evidence from Kenya. *Agriculture & Food Security*, *7*(1), 1-14.

West, P. C., Gerber, J. S., Engstrom, P. M., Mueller, N. D., Brauman, K. A., Carlson, K. M., & Siebert, S. (2014). Leverage points for improving global food security and the environment. *Science*, *345*(6194), 325-328.

Wezel, A., Casagrande, M., Celette, F., Vian, J. F., Ferrer, A., & Peigné, J. (2014). Agroecological practices for sustainable agriculture. A review. *Agronomy for Sustainable Development*, *34*(1), 1-20.

White, P. J., George, T. S., Dupuy, L. X., Karley, A. J., Valentine, T. A., Wiesel, L., & Wishart, J. (2013a). Root traits for infertile soils. *Frontiers in Plant Science*, *4*, 193-199. https://doi.org/10.3389 /fpls.2013.00193.

White, P. J., George, T. S., Gregory, P. J., Bengough, A. G., Hallett, P. D., & McKenzie, B. M. (2013b). Matching roots to their environment. *Anatomy and Botany 112*(2), 207–222. https://doi.org/10.1093/aob/mct123.

Williams, L. J., & Abdi, H. (2010). Fisher's least significant difference (LSD) test. *Encyclopedia of Research Design*, *218*, 840-853.

Xiao, K., Xu, J., Tang, C., Zhang, J., & Brookes, P. C. (2013). Differences in carbon and nitrogen mineralization in soils of differing initial pH induced by electrokinesis and receiving crop residue amendments. *Soil Biology and Biochemistry*, *67*, 70-84.

Yadav, M., Jain, S., Tomar, R., Prasad, G. B., & Yadav, H. (2010). Medicinal and biological potential of pumpkin: an updated review. *Nutrition Research Reviews*, *23*(2), 184-190.

Yadvinder, S., Bijay, S., Ladha, J. K., Khind, C. S., Khera, T. S., & Bueno, C. S. (2004). Effects of Residue Decomposition on Productivity and Soil Fertility in Rice-Wheat Rotation. *Journal of Soil Science*, *68*(3), 854-864.

Yamaguchi, M. (2012). World vegetables. In: Yamaguchi, M. (Ed) *principles, production and nutritive values*. Springer Science & Business Media.

Yeboah, S., Ennin, S. A., Ibrahim, A., Oteng-Darko, P., Mutyambai, D., Khan, Z. R., & Niassy, S. (2021). Effect of spatial arrangement of push-pull companion plants on fall armyworm control and agronomic performance of two maize varieties in Ghana. *Crop Protection*, 145, 105-112. https://hdl.handle.net/12345/1573.

Zhang, C., Lin, Z., Que, Y., Fallah, N., Tayyab, M., Li, S., & Zhang, H. (2021). Straw retention efficiently improves fungal communities and functions in the fallow ecosystem. *BMC Microbiology*, *21*(1), 1-13.

Zhang, P., Chen, X., Wei, T., Yang, Z., Jia, Z., Yang, B., & Ren, X. (2016). Effects of straw incorporation on the soil nutrient contents, enzyme activities, and crop yield in a semi-arid region of China. *Soil and Tillage Research, 160,* 65-72.

Zhao, J., Dong, Y., Xie, X., Li, X., Zhang, X., & Shen, X. (2011). Effect of annual variation in soil pH on available soil nutrients in pear orchards. *Acta Ecologica Sinica*, *31*(4), 212-216.

Zingore, S., Mutegi, J., Agesa, B., Tamene, L., & Kihara, J. (2015). Soil degradation in sub-Saharan Africa and crop production options for soil rehabilitation. *Better Crops with Plant Food*, *99*(1), 24-26.

Zobiole, L. H. S., Kremer, R. J., Oliveira Jr, R. S., & Constantin, J. (2011). Glyphosate affects micro-organisms in rhizospheres of glyphosate-resistant soybeans. *Journal of Applied Microbiology*, *110*(1), 118-127.

APPENDICES

Appendix A. ANOVA table for growth, yield and yield components of maize crop in two locations across three seasons

Source of variation	Df	Plant vigor	Chlorophyll content (µmol m^{-2})	Stomatal conductance (mmol m^{-2} s^{-1})	Plant Height (cm)	Biomass (g)	Grains per cob	100 seed weight (g)	Yield (tons/ha)
TSFS	1	8.82*	26.67***	28.55***	824.55***	5421.13***	7701.52	5476.74***	8.22***
Location	1	121.80***	9.15	0.14	21628.11***	61301.63***	42972.59***	24128.96***	40.81***
TSFS*location	1	2.01	18.10*	0.03	299.11*	164.22	40.59	34.75	0.05
Season	2	99.17***	46.94***	438.72***	279.33**	1128.42***	1146.93	24456.54***	7.25***
Location *season	2	26.63*	42.77***	1.57	433.84***	2361.29***	3609.10	1397.91	0.13
TSFS * L* S	4	6.68	4.66	0.11	299.19***	215.24***	360.85	290.25	0.17
Error	24	7.43	2.69	1.72	48.91	41.89	2117.45	379.65	0.87
CV		5.30	3.23	5.35	6.03	3.13	10.97	5.82	14.39
R^2		0.69	0.79	0.95	0.95	0.98	0.54	0.90	0.75

*, **, *** Significant at ($P \leq 0.05$), ($P \leq 0.01$) and ($P \leq 0.001$) respectively, TSFS-three strata forage system, L-location, S-season

Appendix B. ANOVA table for growth, yield and yield components of beans in two locations across three seasons

Source of variation	df	Plant vigor	Chlorophyll content (µmol m^{-2})	Stomatal conductance (mmol m^{-2} s^{-1})	Plant Height (cm)	Biomass (g)	Pods per plant	Yield (tons/ha)
Cropping system	1	19.71	4.92*	11.46*	749.84***	1483.91***	55.80***	0.79*
Location	1	84.51***	99.63	4.39	328.57**	1209.30	11.53*	0.16
Cropping system*location	1	8.80	49.91	0.02	0.14	17.48	1.27	0.01
Season	2	260.63***	5.19*	368.49***	893.16***	4529.16***	28.68***	2.98***
Location *season	2	85.22***	5.55	0.33	577.51***	3878.63***	8.15	0.10
Cropping system * Location* Season	4	1.85	19.13	0.93	21.87	51.76	0.23	0.03
Error	24	6.23	18.17	2.55	37.27	84.59	1.98	0.12
CV		9.38	20.05	6.59	7.78	7.18	12.39	24.52
R^2		0.84	0.81	0.92	0.82	0.90	0.75	0.71

*,**, *** Significant at (P≤0.05),(P≤0.01) and (P≤0.001) respectively

Appendix C. ANOVA table for growth, yield and yield components of groundnuts crop in two locations across three seasons

Source of variation	df	Plant vigor	Chlorophyll content (μmol m^{-2})	Stomatal conductance (mmol m^{-2} s^{-1})	Plant Height (cm)	Biomass (g)	Pods per plant	100 seed weight (g)	Yield (tons/ha)
Cropping system	1	8.30^{*}	45.93^{***}	14.49^{*}	54.29	924.36^{***}	64.69^{***}	11675.16^{***}	2.14^{***}
Location	1	37.35^{***}	0.01	30.69^{**}	24.81	10.11	28.69	18339.02^{***}	6.36^{***}
CS*L	1	3.94	0.43	1.90	5.51	54.46	1.49	159.72	0.17
Season	2	26.31^{***}	324.60^{***}	16.66	27.88	1433.12^{***}	126.32^{***}	3943.09^{***}	0.17
Location *season	2	1.67	60.04^{***}	16.33	95.86^{***}	1468.15^{***}	49.05^{***}	5751.62^{***}	0.02
CS*L*S	4	2.87	0.95	3.33	4.49	19.05	6.53	483.08	0.03
Error	24	2.02	2.57	3.53	7.65	67.12	1.84	565.14	0.08
CV		7.56	6.24	9.34	5.61	8.91	8.67	6.87	14.92
R^2		0.71	0.92	0.69	0.66	0.81	0.91	0.79	0.83

*,**, *** Significant at (P≤0.05),(P≤0.01) and (P≤0.001) respectively, CS-Cropping system, L-location, S-season

Appendix D. Means for soil chemical properties in TSFS and no TSFS cropping systems in two sites

Source of Variation	df	Soil pH	EA	TN	SOC	P	K	Ca	Mg	Mn	Cu	Fe	Zn	Na
Location	1	1.09***	3.19***	0.03***	0.51***	35.44	0.01***	0.42***	0.02***	0.42***	0.02***	0.01***	0.56***	6461.66***
Replication	4	0.94	1.53	0.08	0.38	1478.72	0.19	0.65	0.22	0.65	0.22	0.51	0.38	6764.88
Cropping system	1	0.13*	0.94***	0.01***	0.14***	486.85***	0.01***	0.01***	0.03***	0.01***	0.03***	0.01***	0.17***	415.48***
Location*cropping system	1	0.38***	0.26	0.03***	0.25***	475.46	0.06***	0.01	0.35***	0.01	0.35***	0.06***	0.05***	22.44***
R^2	34	0.68	0.72	0.02	0.28	373.48	0.01	0.05	0.04	0.05	0.04	0.03	0.14	61.14
CV		3.36	20.28	15.92	6.5	10.96	3.33	9.79	3.39	9.79	3.39	12.76	3.47	2.13
R^2		0.83	0.91	0.91	0.92	0.87	0.99	0.96	0.95	0.96	0.95	0.98	0.97	0.99

*** Significant at ($P \leq 0.001$)

Appendix E. Mean monthly rainfall (mm) and temperature (0^0C) for the two locations during the three growing seasons in 2019, 2020 and 2021

Month	2019		2020		2021	
	Rainfall (mm)	Temperature (0^0C)	Rainfall (mm)	Temperature (0^0C)	Rainfall (mm)	Temperature (0^0C)
January	23.3	24.9	140.7	21.9	108.8	23.9
February	46.8	22.6	61.9	23.2	140.3	23.1
March	63.5	25.7	260.2	24.6	112.2	24.7
April	252.3	24.6	233.3	25.0	291.4	23.4
May	327.8	24.5	273.5	23.8	245.9	23.5
June	275.4	21.9	215.3	22.8	161.3	25.2
July	157.6	21.1	233.4	23.6	71.3	23.9
August	243.9	24.4	179.9	23.9	227.3	23.6
September	198.0	23.0	292.9	23.4	341.7	24.3
October	349.5	23.0	229.0	22.7	107.6	23.8
November	201.9	22.0	87.4	22.8	82.7	25.3
December	279.9	24.1	108.1	23.3	53.4	25.8

Source: Busia County metrological center

Appendix F. Published manuscript

Vol. 19(7), pp. 705-714, July, 2023
DOI: 10.5897/AJAR2023.16335
Article Number: 2892AE970971
ISSN: 1991-637X

http://www.academicjournals.org/AJAR

African Journal of Agricultural Research

Full Length Research Paper

Adopting a three-strata forage system for an integral food, feed outputs and agro-ecological sustenance

Dorine Oware[1]*, Erick Cheruiyot[1], Samuel Mwonga[1], Lydia Waswa[2], Sahrah Fischer[3] and Thomas Hilger[3]

[1]Department of Crops, Horticulture and Soils, Egerton University, P.O. Box 536-20115 Egerton, Kenya.
[2]Department of Human Nutrition, Egerton University, P.O. Box 536-20115 Egerton, Kenya.
[3]Institute of Agricultural Sciences in the Tropics, University of Hohenheim, P.O. Box 70599 Stuttgart, Germany.

Received 6 February, 2023; Accepted 31 March, 2023

The exploitation of diverse cropping practices alongside residue incorporation has remained low among small-holder rural farming households in Sub-Saharan Africa. Three-stratum forage system (TSFS) which integrates forages for animal feeds with food crops is a significant sustainable strategy for enhancing residue incorporation. This study was conducted in Busia County in Kenya to; (i) determine the effects of TSFS on yield of diversified food crops grown (ii) to determine the effect of TSFS on growth and physiological responses in food crops grown. In TSFS system, desmodium, brachiaria grass and pigeon peas were grown in the peripheral area of the farm as forages. The treatments were laid on a randomized complete block design at two locations for 3 years (2019, 2020 and 2021), yield in t ha^{-1}, growth and physiological responses in plants measured. The data collected were subjected to Analysis of variance (ANOVA) in SAS software and means separated using LSD at 5% level of significance. Plant growth vigor, physiological responses and yield in t ha^{-1} were significantly higher in TSFS system where residues were incorporated than in no TSFS system (P<0.001). The results revealed that TSFS cropping system could be a better solution to food security and agro-ecological sustenance.

Key words: Three-Strata forage cropping system (TSFS), crop residue incorporation, food security.

INTRODUCTION

Diversified cropping system improves productivity and resilience in agricultural systems. Research towards achieving food security through diversified farming system has received little attention despite its importance constrained by inappropriate farming practices like monocropping, burning of crop debris among others which have contributed to decline in soil fertility and low farm productivity. Most soils in the lowlands regions of

Appendix G. Research permit from NACOSTI

REPUBLIC OF KENYA

NATIONAL COMMISSION FOR SCIENCE, TECHNOLOGY & INNOVATION

Ref No: 846331

Date of Issue: 03/January/2022

RESEARCH LICENSE

This is to Certify that Ms.. DORINE ADONGO OWARE of Egerton University, has been licensed to conduct research in Busia on the topic: THREE-STRATA FORAGE CROPPING SYSTEM AS A DIVERSIFIED CROPPING SYSTEM AND ITS IMPACT ON SOIL CONDITIONS IN KENYA for the period ending : 03/January/2023.

License No: NACOSTI/P/22/14931

846331

Applicant Identification Number

Director General

NATIONAL COMMISSION FOR SCIENCE, TECHNOLOGY & INNOVATION

Verification QR Code

NOTE: This is a computer generated License. To verify the authenticity of this document, Scan the QR Code using QR scanner application.