SUSTAINABLE INTENSIFICATION OF SMALLHOLDER FARMING SYSTEMS USING PUSH-PULL TECHNOLOGY AS A TEMPLATE

SYLVIA IMBUHILA BULETI

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Sustainable Intensification of Smallholder Farming Systems Using Push-Pull Technology as a Template

Sylvia Imbuhila Buleti

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other University.

Signature.. Date..

Sylvia Imbuhila Buleti

This thesis has been submitted for examination with our approval as the University Supervisors:

Signature.. Date..

Dr. Shem Kuyah, PhD

JKUAT, Kenya

Signature.. Date..

Dr. Samuel Were, PhD

JKUAT, Kenya

Signature.. Date..

Dr. Moses Gichua, PhD

JKUAT, Kenya

DEDICATION

This thesis is dedicated to my parents, Mr. and Mrs. Buleti and Mr. and Mrs. Aloo, my lovely husband Eng. James Ogutu, and our babies Bethel, Minchah, Lulu, Faith and Amara. Thank you to my parents for always believing in me, encouraging me, and praying for me. Thank you, James, for encouraging me to take up this challenge and being the greatest support system. It is because you constantly believed in me that I was encouraged to keep moving on.

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ABBREVIATIONS AND ACRONYMS

ANOVA	Analysis of Variance
CAN	Calcium Ammonium Nitrate
DAP	Di-ammonium Phosphate
EC	Electrical Conductivity
FGD	Focus Group Discussion
HSD	Honestly Significantly Difference
ICIPE	International Centre for Insect Physiology and Ecology
KALRO	Kenya Agricultural and Livestock Research Organization
KII	Key Informant Interviews
LER	Land Equivalent Ratio
LR	Long Rain Season
MD	Push-pull (Maize + Desmodium)
MDP	Push-pull + Pigeon pea
MM	Maize Monocrop
MP	Maize + Pigeon pea
NGO	Non-Governmental Organisation
NPK	Nitrogen Phosphorus Potassium
SOC	Soil Organic Carbon
SR	Short Rain Season

ABSTRACT

Sustainable intensification is essential for increasing food production on shrinking smallholder farms while reducing environmental risks. In western Kenya, farmers use practices such as intercropping, crop rotation, agroforestry, crop-livestock integration, and push-pull technology to address constraints such as low soil fertility, pests, diseases, and limited land for production. Push-pull technology, which combines cereal crops with repellent and trap companion crops, is effective in managing striga weed, stem borer, and fall armyworm, but its adoption remains limited because it is mainly cereal-based and its companion crops are not edible. This study aimed to identify farmers' preferred sustainable intensification options for integration into push-pull systems and to assess the effects of the selected option on soil fertility, pests, natural enemies, and maize productivity in Kisumu, Siaya, and Vihiga counties. Farmers' preferred intensification practices were identified through participatory research involving focus group discussions, key informant interviews, and validation with farmers. Integration of *Cajanus cajan* (pigeon pea) into push-pull technology was selected as a priority option because pigeon pea provides additional benefits, including food, feed, and fuelwood. Field trials were then established on farmers' plots during the long and short rainy seasons of 2021, 2022, and 2023 using four treatments: push-pull, push-pull with pigeon pea, maize with pigeon pea, and maize monocrop. Subplots were used to monitor crop growth, striga weed density, fall armyworm, stem borer, and natural enemies. Equally, soil physical and chemical properties, maize grain and stover yield, pigeon pea productivity, Brachiaria biomass, and desmodium biomass were measured in the same plot. Data were analyzed using analysis of variance, and treatment means were separated using Tukey's Honestly Significant Difference test. Farmers identified several sustainable intensification options for integration into push-pull systems, with intercropping, crop rotation, crop-livestock integration, and agroforestry ranked as the most preferred. Their main motivations were food diversification, fuelwood and fodder provision, soil improvement, and pest management. Soil fertility varied across counties, ranging from low in Vihiga to moderate in Kisumu and Siaya. Major nutrients, particularly nitrogen, phosphorus, and potassium, were generally below critical levels, while micronutrients such as zinc and manganese were sufficient. Integrating pigeon pea improved nitrogen, phosphorus, and potassium levels in the tested soils, indicating its potential to support soil fertility improvement in maize-based systems. Maize monocrop recorded the highest striga density and the greatest infestation by fall armyworm and stem borer, whereas maize with pigeon pea had significantly lower striga density. Maize grain yield did not differ significantly for treatments across sites and seasons, indicating that intensified systems-maintained productivity. However, maize monocrop produced the highest stover yield, followed by push-pull, maize + pigeon pea, and push-pull + pigeon pea. Pigeon pea also contributed additional benefits, including food, fodder, and fuelwood, while supporting striga suppression and maintaining maize productivity. The findings show that integrating pigeon pea into push-pull and other maize-based farming systems can diversify farm benefits without compromising crop productivity. The study recommends the integration of pigeon pea into push-pull and maize-based systems in Kisumu, Siaya, and Vihiga counties as one of the practical strategies for improving soil fertility, suppressing striga weed, maintaining crop production, and providing additional farm products such as food, fodder, and fuelwood.

CHAPTER ONE

INTRODUCTION

1.1 Background of Study

There is increasing evidence that sustainable intensification is needed to boost production in order to meet the rising demand for food supply due to a rapidly increasing population. Intensifying farms sustainably refers to increasing productivity over the same size of land while conserving resources and minimizing negative impact. Some of the key elements of sustainable intensification include alternative practices and systems that aim to reduce negative externalities while addressing challenges of pests and diseases, moisture stress, low soil fertility and climate change (Smith et al., 2017). Sustainable intensification pathways commonly applied in sub-Saharan Africa include; conservation agriculture, crop rotation, intercropping, agroforestry, push-pull technology, integrated soil management practices, integrated pest management practices, organic farming and water conservation methods (Snapp et al., 2021). Some of the benefits associated with the application of sustainable intensification include resilience and maximum utilization of farms, reduced yield gap, increased crop productivity, increased livestock productivity, improved soil fertility, ecological system balance, environmental conservation and pests management (Jabbar et al., 2020). However, there is little evidence about synergies in different intensification pathways for example integration of other sustainable intensification in push-pull system.

Push-pull cropping system is an agroecological practice widely promoted in East Africa, after crop improvement (Midega et al., 2017). The push-pull system involves the use of trap plants and push plants. The trap plants include; *Pennisetum purpureum* (Napier) or Brachiaria cv *Mulato* (Brachiaria grass). The pull crop attracts pests (stem borer (*Busseola fusca)*, fall armyworm (*Spodoptera frugiperda* (J E Smith)). The repellants (*Desmodium* species) on the other hand repel the stem borer and cause suicidal germination of parasitic weeds of the genus Striga (e.g. *Striga hermonthica*) germination (Midega et al., 2017). Additionally, push-pull technology increases parasitism by enhancing predator presence such as spiders, earwigs and ants which predate on the larvae of stem borers (Da Silva et al., 2022).

Farmers in Kenya, Ethiopia and Tanzania have demonstrated willingness to adopt pull-pull technology (Murage et al., 2015). Farmers who have adopted push-pull technology have encountered positive impacts on their livelihoods (Murage et al., 2015). Improved livelihoods are derived from increased yields of maize, balanced ecosystem (where push-pull technology crops provide fodder and livestock provide manure), improved soil fertility, diversified sources of income and controlled pests (Midega et al., 2018a; Murage et al., 2015). Push-pull technology has been widely promoted and successfully implemented at plot level. However, push-pull technology has never been tried with other crops to diversify its functionality mainly because of lack of technical know-how, restrictions to cereal crops, and lack of proper integration into farming systems. It is also not known whether the efficacy of push-pull technology will change when further intensified.

Several options exist for further intensification of push-pull systems, including crop-livestock integration, intercropping, crop rotation, use of organic manure and fertilizers, conservation agriculture, and improved maize varieties. Among these options, intercropping offers strong potential for diversifying push-pull system through the inclusion of African leafy vegetables, kales, high-value crops, and legumes whose benefits may outweigh their costs (Kermah et al., 2017). Previous studies show that integrating edible beans into push-pull system can provide food, diversify diets, and maintain economic benefits without compromising the system's effectiveness in managing weeds and pests, although adoption remains low (Khan et al., 2008). However, limited information is available on how push-pull technology performs under when combined with other sustainable intensification practices common in East Africa.

Evidence from previous meta-analyses indicates that farmers in East Africa commonly integrate trees into farming systems, intercrop with high-value legumes, practice organic farming, and use improved crop varieties (Pumariño et al., 2015). These practices can manage pests and diseases, improve soil fertility, increase productivity, and enhance resilience in farming system (Snapp et al., 2021). Because push-pull technology can improve household food security, integrating it into farmers' broader livelihood options could support successful upscaling, especially in western Kenya where livelihoods are strongly linked to farming and livestock keeping. This study therefore aimed to identify sustainable intensification practices that farmers would prefer to integrate into push-pull system and to test the effectiveness of the selected practice on pest and striga weed management, natural enemy enhancement, soil fertility, and crop productivity through experimental trials.

1.2 Problem Statement

Farmers in western Kenya continue to experience declining maize yields due to biotic stress (Njeru et al., 2023) and soil degradation (Droppelmann et al., 2017). Push-pull system can mitigate these effects although it is applied on a limited scale. Push-pull system as currently implemented in East Africa, has been restricted to cereal based farming system particularly maize, sorghum and millet (Midega et al., 2017). This is because the system has not been tried with other sustainable intensification practices, limiting the farmers' options for its utilization. A typical small-scale farm entails growing crops for food and fodder and keeping of livestock and poultry for food and manure.

The maximum utility of the available arable land in smallholder systems calls for interventions that enable the integration of multiple sustainable practices. Sustainable intensification practices that farmers would prefer to integrate into push-pull farms are not documented. Furthermore, the effects of integrating these other sustainable intensification practices into push-pull farming system are also unknown. Even though push-pull has been in existence for some decades, the adoption rate has been low (Murage et al., 2015). Gaps on comprehensive information on push-pull productivity were reported by Ndayisaba et al., (2020) and consequently recommended further landscape studies to fully assess system productivity under push-pull and common maize-based cropping systems in western Kenya. Such landscape studies need to be implemented through priority setting with farmers and field experiments to determine the options available for expanding the utility of the push-pull system.

1.3 Justification

Push-pull technology as currently implemented has untapped potential for further sustainable intensification. It is mainly practiced at a limited scale in maize- and sorghum-based systems (Midega et al., 2017), yet its wider adoption requires expansion beyond its scope of pest control to address broader smallholder farmer needs. Further, intensification of push-pull system can enhance its relevance by providing diverse food options, income, fuelwood, fodder, and improved soil fertility. Integrating agroforestry components such as pigeon pea offers potential benefits, including fuelwood supply, soil fertility improvement, and pest control. Similarly, linking push-pull with livestock-based farming systems can support a circular bioeconomy, where crops provide food and fodder while livestock supply manure, milk, and income. Desmodium further contributes to soil fertility through nitrogen fixation and control of soil erosion. However, identifying farmers' preferences for further intensification options is not enough for recommendation unless supported by experimental trials.

The current changes in climate, along with their effects on soil fertility and crop yields, have necessitated and increased demand for sustainable intensification using locally available solutions which improve soil health and provide fodder (Droppelmann et al., 2017). Push-pull as an intensification practice can be applied to mitigate these effects of climate change. The potential to enhance food security is embedded in such sustainable intensification pathways, given the current pressure on diminishing land production area (Gassner et al., 2019). There is evidence of an increasing willingness to adopt pull-pull technology among sampled farmers in Tanzania (92.1%), Ethiopia (88.6%), and Kenya (84.3%) (Murage et al., 2015). There is need for a participatory process to identify context-specific sustainable intensification practice before experimentally validating the most promising option.

Participatory research is critical for community-based research. Stakeholder input is very important for priority setting because participants understand intrinsic factors influencing their choice of individual sustainable intensification practices and integration of indigenous knowledge systems. The use of focus group discussion (FGD) and key informant interviews (KII) as a way of collecting data provided a platform for interaction between researchers and farmers to improve research outputs. Such an initiative to amalgamate scientific research and farmers' opinions, skills and knowledge can ease implementation of sustainable intensification integration in push-pull system; since farmers' autonomous choices are embraced thus stimulating ownership (Jambo et al., 2019). Even though involving farmers in research through participatory approach is critical, no study reports priority setting with farmers for integrating sustainable intensification in the push-pull system, hence creating a need for the current study.

Mixed method approach is crucial in research as it completements participatory approaches. This was particularly relevant for this study because smallholder farming systems in western Kenya face multiple interacting constraints, relating to soil fertility, climate variability, pest infestation, and land availability (Droppelmann et al., 2017). The performance of intensification practices depends on local ecological and management conditions. Therefore, participatory methods alone are not sufficient to recommend further intensification of push-pull technology and other farming systems. Field experimentation was required to provide empirical evidence on the functionality and compatibility of the intensified push-pull system, thereby supporting context-specific recommendations for scaling in Kisumu, Siaya, and Vihiga counties.

1.4 Objective

1.4.1 Overall Objective

The overall objective of this study was to identify and evaluate sustainable intensification pathways for the push-pull system in Kisumu, Siaya and Vihiga

1.4.2 Specific Objectives

1. To identify sustainable intensification practices that farmers prefer to be integrated into push-pull system
2. To determine effect of integrating pigeon pea into push-pull system on soil health in Kisumu, Siaya and Vihiga counties
3. To determine the effect integrating pigeon pea into push-pull system on pests (stem borer, striga weed, and fall armyworm) and natural enemies in Kisumu, Siaya and Vihiga counties
4. To determine the effect of integrating pigeon pea into push-pull system on productivity in Kisumu, Siaya and Vihiga counties

1.5 Research Questions

1. What sustainable intensification practices do farmers want to integrate into the push-pull system?
2. How does pigeon pea integration in push-pull system affect soil health, pests, natural enemies and productivity?

1.6 Hypotheses

1. Further intensification of the push-pull system with pigeon pea has no effect on soil health in Kisumu, Siaya and Vihiga counties
2. Further intensification of the push-pull system with pigeon pea has no effect on pests (stem borer, striga weed, and fall armyworm) and natural enemies in Kisumu, Siaya and Vihiga counties
3. Further intensification of the push-pull system with pigeon pea has no effect on productivity in Kisumu, Siaya and Vihiga counties

1.7 Scope of the Study

The study was carried out in Kisumu, Siaya, and Vihiga counties in western Kenya on farmers' fields. These counties have a history of using push-pull system to control striga and stem borer and to improve soil health. The region is also characterized by low soil fertility and small land sizes. Through KII and FGD, the study identified sustainable intensification practices that farmers would want to integrate into the push-pull system in Kisumu, Siaya and Vihiga. The impact of the selected sustainable intensification pathway was tested for four seasons (two short rain seasons and two long rain seasons).

CHAPTER TWO

LITERATURE REVIEW

2.1 Smallholder Agriculture in Sub Saharan Africa

Cereals, particularly maize (*Zea mays*) and sorghum (*Sorghum bicolor*), are among major staples grown by millions of smallholder farmers throughout Sub Saharan Africa (SSA). Other staples include rice, wheat and millets such as pearl millet (*Penissetum galucum*) or finger millet (*Eleusine coracana*). Production of cereals is constrained by several factors including pests and diseases (Ankrah et al., 2023), climate variabilities (Bedeke et al., 2019), infertile soils (Ogada et al., 2015). Climate-related effects lead to changes in rainfall and temperature patterns which negatively impact yields. Infertile soils lead to a scanty supply of plant nutrients which has a positive correlation with susceptibility to pests and disease pathogen infestation. These triple effects lower maize production particularly in Kenya, yield was significantly declined by approximately 6.5% in the year 2022 compared to the year 2021 (Njeru et al., 2022). As a result, Kenya was not able to meet the demands for maize by the rising population (Njeru et al., 2023).

Integrated and complementary strategies are commonly applied in managing climate variabilities, soils fertility problems and pests. Crop diversification and use of improved and adaptable varieties are examples of integrated pathway for managing these problems (Bedeke et al., 2019). In addition, timely planting and application of modern technologies, such as irrigation contribute to managing climate variabilities (Ankrah et al., 2023). To address soil infertility, maize is the most fertilized crop in Kenya's grain basket because it is a staple food. Occasionally, integrated soil management systems such as soil liming, fertilizer use, and compost manure are applied (Mucheru-Muna et al., 2014). Maize-legume rotation and residue retention have been instrumental in improving maize yield by improving soil fertility when the soils are responsive (Roobroeck et al., 2021). A combination of low soil fertility and pest and disease incidence further reduce maize grain yield.

Stem borer, fall armyworm and striga, are among the major pests causing damage to the maize crop and consequently cause grain yield reduction in SSA (Da Silva et al., 2022; Silberg et al., 2020; Tambo et al., 2020). Different types of stem borer exist including *B. fusca* (African maize stalk borer), *Chilo partellus* (swinhoe), *Sesamia calamistis* (African pink stem borer) and *Chilo orichalcociliellus* (coastal stalk borer*).* The *B. fusca* is the most common species; it causes 20- 40 % crop damage during cultivation and 30-90% yield losses post-harvest and during storage in SSA (Midingoyi et al., 2016). Yield losses depend on the plant's age, the rate of infestation, and environmental conditions. To manage maize stem borer, chemical, biological, and cultural management practices are used. Application of chemical pesticides and herbicides is discouraged because of their toxic nature and high cost. As a result of the toxic nature of chemical pesticides and herbicides, biological control of stem borer is on the rise. The most important parasitoids for *C. partellus* and *B. fusca* are *Cotesia flavipes* and *Cotesia sesamiae.* The use of biocontrol accounts for an estimated net present value over twenty years to be US$ 142 million in Kenya for sorghum and maize with potentially improved lives for 57,400 people (Midingoyi et al., 2016).

Fall armyworm (*Spodoptera frugiperda* (J E Smith) is another destructive pest to maize productivity in SSA. They are widely distributed depending on species they prey on, host species, and climatic conditions. The fall armyworm is polyphagous in nature and has insatiable feeding habits (Tambo et al., 2020). The fall armyworm can easily lay 1000-3000 eggs, and its life cycle is shortened in the SSA. It can have several generations per season and bearing in mind that it lacks diapause and management strategies are equally limited, it poses a threat to food security (De Groote et al., 2020; Prasanna et al., 2022). It is currently declared a national major pest in Kenya with an estimated maize yield loss of 1 million tons per year (De Groote et al., 2020).

Several strategies have been applied to manage fall armyworms including crop rotation, intercropping, use of improved varieties, and timing of planting. Even after farmers have applied their current control strategies, a loss of 11.5% is observed, implying that current control strategies are not effective. There is a great need for

SSA to customize these control strategies for effective management of the fall armyworm pest. Integrated pest management remains the most important control strategy for management of fall armyworm in Africa (Matova et al., 2020). Natural enemies are important components of the integrated strategy for pest management. Use of natural enemies can replace the application of chemical pesticides which are toxic to humans, animals, and the environment (Kaiser et al., 2017). Though the associated costs are expensive for smallholder farmers they are a sustainable alternative (Soujanya et al., 2024). This makes push-pull technology a fitting alternative for the management of fall armyworm.

Striga is a parasitic weed that also affects maize productivity. *S. hermonthica* Benth is the most common species of striga in East Africa. It causes 100% yield losses in maize production when not managed (Midega et al., 2017). Striga competes with the host plant for nutrients and releases toxins that cause stunted growth and low grain yield. Effects of striga on crops grown vary depending on striga count, host crop species and genotype, current farming systems, soil nutritional status, and rainfall patterns. The severity of striga infestation increases with low soil fertility. Several approaches are applied in coping with striga because no single management strategy has achieved complete striga elimination. These include; intercropping of cereals with legumes, crop rotation, the use of resistant crop varieties, application of manure and nitrogen fertilizer and push-pull system (Kanampiu et al., 2018).

Crop rotation is a strategy applied to manage striga while improving soil fertility. It is however constrained by the small nature of land sizes, common in western Kenya. Resistant varieties are also useful, but they are often too expensive for resource-poor farmers. Push-pull system offer a practical alternative, because desmodium species intercropped with maize can reduce striga effect, tolerate drought and support increased maize grain yield over time (Midega et al., 2017). Soil physical, chemical, and biological properties are negatively associated with striga infestation (Tariq et al., 2019). This is especially important in western Kenya, where soils are generally low in major nutrients such as nitrogen and carbon and often have high acidity due to improper application of nitrogen-based fertilizers (Buleti et al., 2023). Striga infestation increases under low soil fertility and varies across regions (Roobroeck et al., 2023) thus improving soil health is central to its effective management.

2.2 Sustainable Intensification of Smallholder Farming Systems in East Africa

To manage the triple problem of climate variability, soil infertility and pests and diseases. African farming systems are increasingly being intensified (Gassner et al., 2019). This is compelled by an increased population which demands more food thus necessitating the urgency to address food shortage crises (Droppelmann et al., 2017; Teklewold et al., 2013). The goal of sustainable intensification is economic viability, high productivity, improved nutrition, social stability, reduced poverty and hunger, and safeguarding the natural resource base (Pretty et al., 2011; Thomson et al., 2019). Practices commonly used to intensify farming systems in SSA include: use of improved varieties, crop diversification, organic manure, crop rotation, intercropping, and agroforestry (Kuyah et al., 2021).

The benefits associated with sustainable intensification practices include: increased crop production, improved pest management, changes in soil organic carbon and total nitrogen, food and nutrition security, mitigation and adaptation to climate change (Jain et al., 2020; Thomson et al., 2019). The adoption rate of these practices is determined by education level of implementors, availability of land for cultivation, access to information and extension service, social participation, and climate variabilities. Ultimately, the desired productivity and environmental protection can be achieved by co-adopting several sustainable intensification practices (Jabbar et al., 2020).

Sustainable intensification practices such as soil and water conservation, crop-livestock and tree integration, intercropping, improved varieties, and legume-based crop rotation can improve soil health and increase maize yield (Kanampiu et al., 2018). Deep-rooted crops, particularly trees, can improve short-term phosphorus availability and also contribute to pest control. For example, integrating *Tephrosia vogelli* into maize systems can effectively manage African armyworms (Choongo et al., 2018). Intercropping with high-value legumes is becoming increasingly common in SSA, and maize–pigeon pea systems have been shown to manage striga and fall armyworm in Mozambique (Soujanya et al., 2024). These suggest that cereal-legume intercropping has strong potential for integration into Kenyan farming systems, especially when farmers are actively involved in technology selection and adoption.

Sustainable intensification remains the most resilient and reliable pathway for improving soil health, managing pests and achieving yield stability even on small portions of land. This is because East Africa is characterized by reduced land areas of production, increasing population, increased urbanization and encroachment into forest lands. The benefits of sustainable intensification might be long-term but are more profitable in the end especially when environmental conservation is a priority. The tradeoffs in a sustainable intensified farm outweigh the immediate short-term benefits of practices such as the use of fertilizers which are expensive and inorganic. Fertilizers lead to increased acidity in the soil and eventually contribute to soil degradation (Droppelmann et al., 2017; Njoroge et al., 2017; Teklewold et al., 2013).

2.3 Push-Pull System as a Template for Sustainable Intensification

Push-pull technology is a widely promoted agroecological practice in East Africa because it supports stemborer management, striga weed suppression, and soil fertility improvement. The system works by intercropping cereals with a repellant "push" crop, usually desmodium, while planting an attractive "pull" crop, such as Napier or Brachiaria grass, around the field border (Midega et al., 2017; Murage et al., 2015). Over time, push-pull has evolved from conventional systems based on silver leaf desmodium and Napier grass to climate-smart system that use green leaf desmodium and Brachiaria grass, and more recently to third-generation system that include more climate-resilient species such as *D. incanum* and Xaraes grass (Cheruiyot et al., 2020; Murage et al., 2015). Climate-smart push-pull is particularly preferred because green leaf desmodium and Brachiaria grass are more drought-tolerant than silver leaf desmodium and Napier grass, while Brachiaria grass is also locally available in Kenya. The evolution of push-pull technology shows its potential as a flexible template for sustainable intensification, especially where farmers need climate-resilient systems that manage pests, suppress weeds, improve soil fertility, and provide fodder.

A typical push-pull farm is less than 50 m by 50 m, with maize spaced at 75 by 30 cm inter- and intra-row, respectively. Maize and desmodium are spaced at 75cm, and Napier or Brachiaria grass is usually planted at 75 by 50 cm spacing on the border, with seed or using stem cuttings (Eigenbrode et al., 2016). Specifically, desmodium produces repellant volatiles of the stem borer parasitoid, enhancing parasitism of the target pests. On the other hand Napier/Brachiaria grass produces toxic sticky exudates which attracts stem borer moths to lay eggs and hatch on it, but prevent larvae from developing (Khan et al., 2008). In addition, the push-pull crops attract diverse population of natural enemies which prey on stemborer including ants, earwigs and spiders (Kebede et al., 2018). Cheruiyot et al., (2020) reported new Xaraes and Mulato II as the most preferred alternative genotype to Napier grass, as they hold promise for better push-pull effectiveness. The effectiveness of push-pull system is influenced by agroecological zones, landscapes (Kebede et al., 2018), season of planting and cropping systems (Midega et al., 2018a). In the process striga weed is also managed.

Push-pull technology as a sustainably intensified system suppresses striga weed while improving soil fertility and farm productivity. Striga is one of the most damaging parasitic weeds because it produces many seeds, disperses easily, and forms a persistent seedbank that makes control difficult (Uzoh et al., 2019). In push-pull system, desmodium roots release chemicals that suppress striga through mechanisms such as abortive germination of striga seeds (Midega et al., 2017). Secondly, the system improves soil health by recycling nutrients through biomass accumulation, with the potential to return more than 150 kg nitrogen, 13 kg phosphorus, and 370 kg potassium, which is higher than other cereal-legume intercrops and maize monocrops (Ndayisaba et al., 2020). Desmodium and Brachiaria grass further function as cover crops by conserving soil moisture, reducing erosion, improving soil structure through reduced tillage, and protecting maize from strong winds when border grasses are used (Khan et al., 2010). Weed suppression, nutrient cycling, and ecological pest management are pathways through which push-pull system improves income, livelihoods, and household food security in smallholder farming systems (Chepchirchir et al., 2018; Cheruiyot et al., 2020; Ndayisaba et al., 2021).

2.4 Effect of Sustainable Intensification on Soil Fertility, Agricultural Pests and Natural Enemies and Productivity

2.4. 1 Effect of Sustainable Intensification on Soil Fertility

Soil infertility is one of the leading causes of low maize productivity in SSA. Sustainable intensification such as crop diversification do influence soil fertility (Rusinamhodzi, 2015). The soil fertility is evaluated based on the following chemical indicators; changes in soil organic carbon, pH, cation exchange capacity, micro and macro nutrients. Soils in western Kenya are deficient majorly in nitrogen, and phosphorus. This situation is aggravated by poor responsive nature of soils to fertigation (Roobroeck et al., 2021). Sustainable intensification pathways for mitigating soil fertility related challenges include intercropping, crop rotation, agroforestry and application of organic manure. Collectively these practices influence soil fertility, insect pest population and weed density, natural enemies' distribution and crop yields. The health of the soil determines the rate of pest and disease infestation. Crops grown in healthy soils are less susceptible to pests and weeds infestation including striga weed (Kamara et al., 2020).

Intercropping as a strategy for intensification is a soil fertility management widely practiced in SSA. Soil fertility is enhanced via intercropping cereals with legumes, cover crops, tubers and vegetables. The nitrogen fixing legumes enhance nutrients such as N and soil organic carbon, cover crops reduce soil erosion, and jointly they enhance soil microorganisms (Cotrufo et al., 2019). Additionally, cereal legume intercrops can reduce soil-borne diseases (Huber et al., 2012) and increases plant root function. This is achieved when deep-rooted legume such as pigeon pea are used to enhance soil microbial diversity which is critical for a balanced ecosystem (Drinkwater et al., 2021). Pigeon pea has advantages over other legumes due to its compatibility with a wide range of cereals and other tree crops. Incorporation of pigeon pea in cropping systems leads to fixing higher amounts of nitrogen. This deep-rooted nature of pigeon pea enhances nutrient mobility and increases soil organic matter through litter fall and root senescence (Renwick et al., 2020; Rusinamhodzi et al., 2012).

Crop rotation as an intensification practice improves soil fertility by allowing the rotation crop to utilize leached nutrients hence leading to optimal nutrient utilization. It also enables symbiosis between plant and soil biota to occur which results in improved nutrient balance from both organic and mineral sources. Rotation with deep-rooted crops such as pigeon pea improves water and nutrient distribution in the soil. Crop rotation can also be applied as a soil conservation strategy when a cover crop, such as sweet potato, is used. Such crops act as mulch, help maintain moisture of the soil and prevent soil erosion hence conserving the soil moisture (De Groote et al., 2010; Rusinamhodzi, 2015).

Agroforestry is another sustainable intensification pathway with multiple benefits to soil fertility enhancement. In agroforestry trees are integrated on boundaries of farm and compound, scattered within cropland or compound, and in woodlots depending on tree species and purpose (Franzel et al., 2014). Demand for agroforestry in western Kenya is driven by both primary benefits such as fuelwood, income, food, fodder and secondary benefits such as improving soil fertility and maintaining ecosystem services (Kuyah et al., 2021). Agroforestry can improve soil nutrients and ensure moisture retention within the cropping area (Apuri et al., 2018). Implementation of agroforestry has positive outcome when applied by small and large scale farmers because it has multiple benefits (Kuyah et al., 2021).

Agroforestry also contributes to enhancement of total soil nitrogen, soil organic carbon, and available phosphorus in the soil. In addition, agroforestry reduces runoff and soil loss while improving infiltration rates and soil moisture content. Potential carbon sequestration due to agroforestry is estimated at 12-228 Mg ha^{-1} , with a median of 95 Mg ha^{-1} (Brown et al., 2020; Njoroge et al., 2017). Fertilizer trees help in tapping nutrients from deeper soil depth and availing them for long-term use and allowing spatial distribution of soil water. They also maintain soil moisture and prevent strong wind which can cause damage to maize hence reducing the yield (Pumariño et al., 2015; Wamugunda et al., 2019).

Use of organic manure as a sustainable intensification pathway is slowly gaining popularity in farming systems in Kenya. This is because combinations of organic manure and green manure has proven to be better soil management practices (Achieng et al., 2010). Application of organic manure improves soil fertility, enhances nutrient cycling, and supports resilience of farming systems (Snapp et al., 2021). The shift from use of mineral fertilizers to organic manure has also been largely motivated by the inability to afford mineral fertilizers and the potential of crop-livestock farming system as sources of organic manure (Peterson et al., 2020). The main source of green manure in smallholder farming systems is foliage from trees and crop remains. Application of organic manure improves organic matter and builds the structure of the soil thus enhancing. water and nutrient retention. Besides, organic manure is environmentally safe and cheaper for the owner but expensive for those purchasing. The main challenge facing organic manure users is the labor intensity, bulkiness and nutrient levels being lower than mineral fertilizers. (Ademba et al., 2015).

2.4.2 Effect of Sustainable Intensification on Pests (Insects and Weeds) and Natural Enemies

Sustainable intensification practices are critical in insect pest and weed management. For example, pest occurrence is low on intercrops compared to monocrops of the same components (Da Silva et al., 2022). Intercrops achieve this insect pest management and enhancement of natural enemies in different ways, depending on crop diversity and agroecological zones (Mwalusepo et al., 2015). Some intercrops are unsuitable hosts of the pest, others interfere with the life cycle of the pests while others create a favorable environment for the natural enemies which predate on the insect (Pretty et al., 2011). Intercropping allows greater light penetration in cereal-legume intercrops than in pure stands of maize. This is essential in managing weeds. Some of the intercrops such as desmodium and Tephrosia act as deterrents for pests and weeds (Choongo et al., 2018; Midega et al., 2015). Intercropping can result in increased occurrence of natural enemies (such as ants and earwigs), reduced effects of pesticide resistance and maintaining the natural enemies' population which can are endangered by non-targeted pesticides (Da Silva et al., 2022).

Crop rotation as an intensification intervention targets insect pest and weed management and controlling soil-borne diseases (Rodríguez et al., 2020); other benefits include residue production, controlled nutrient uptake and biological activity. Management of soil pathogens and weeds results in better quality soil which consequently increases the crop yield (Mupangwa et al., 2021; Tariq et al., 2019). Successful rotation of crops follows a sequence of crops from different families for example legumes and cereals and reduces pests, weeds and diseases (Rodríguez et al., 2020). This is achieved by breaking the life cycle of pests and diseases, thus keeping their population low; compared to monocropping which allows buildup of pests and diseases. Differences in yield and monetary value realized during crop rotation when pest pressure is reduced cannot be replaced by pesticides or fertilizers (Tariq et al., 2019).

Crop rotation maintains natural enemies by creating a balanced ecosystem; indirectly one minimizes use of pesticides which in most cases are harmful to non-target organisms (Rodríguez et al., 2020). Rotation with trees is not common but a study reports reduced infestation by termites and weeds in pure stands of Sesbania, Sesbania + pigeon pea, Sesbania + Tephrosia and Tephrosia + pigeon pea rotations (Sileshi & Mafongoya, 2003). Sustainable practices such as crop rotation which enhance physical, chemical and biological properties of the soil have a positive correlation with crop plant ability to resist or tolerate insect pests and diseases (Rodríguez et al., 2020). The highest resistance to diseases is observed in plants with optimal nutritional status and susceptibility increases as nutritional status deviates from the optimum (Huber et al., 2012).

Agroforestry is another sustainable intensification practice that contributes to reduction in insect pest and weed pressure in farming systems. Trees provide shading and enhance effectiveness of natural enemies within the farming systems. The temperature effect caused by the shading affects development, survival, range, and abundance of pests (Pumariño et al., 2015). Sesbania and Tephrosia have negative impact on weeds and termites infestation but when intercropped with cereals (Sileshi & Mafongoya, 2003). Agroforestry serves as a refuge for beneficial insects thereby sustaining parasitoid diversity, which potentially affects parasitism in cropping systems. The presence and absence of parasitoids is dependent on the interaction of rainfall and altitude (Mailafiya et al., 2010). Positive and negative correlations have been observed between parasitism and temperature in cultivated and natural habitats, respectively (Mailafiya et al., 2010). Productivity of maize is improved when natural enemies hosted by trees reduce incidences of pest and disease pathogen (Apuri et al., 2018).

2.4.3 Effect of Sustainable Intensification on Productivity in Smallholder Farming Systems

The main motivation for sustainable intensification is to diversify productivity however; different intensification practices have different effects on yield and land productivity. Common cereal-legume intercrops for example, comprise maize, sorghum, millet (finger and pearl), and common bean, cowpea, soybean, pigeon pea and occasionally crotalaria (Ndayisaba et al., 2020). Yield productivity in intercrops may increase or decrease depending on crop arrangement. Intercropping cereals and legumes such as maize and high-value legumes such as soybean (Kamara et al., 2020) and pigeon pea can achieve more than 1 land equivalent ratio. This is an indication that it is profitable on land utilization while improving maize quality by increasing height, 1000 seed weight and total grain yield (Kermah et al., 2017). Podding of legumes may be reduced or delayed in some cases because of maize shading in intercrops compared to legume monocrops. In most cases, though, farmers use legumes as companion crops in intercropping, and their main aim is to diversify food, mitigate effects of climate change and manage pest for better farm productivity (Midega et al., 2014).

Crop rotation as a sustainable practice allows the production of a wide range of crops seasonally which results in diet diversification. Crop rotation is carried out to improve soil health, manage weeds and insect pests, and for caution against climate shocks, to allow continuous production on farm (Mupangwa et al., 2021). These factors work together to enhance productivity and yield increase. Productivity in a crop-rotated field increases by a factor of 5 over a monocrop due to weed control (De Groote et al., 2010). Generally, crop rotation is practical and most beneficial when land is sufficient for production of alternate food crops within a season.

The effect of agroforestry on crop yield can be both positive and negative, depending on how the intercrop tree is managed. Trees can have three impacts on farm; they can compete for nutrients, complement the system or balance off the systems (Kuyah et al., 2019). Competitive tree types include eucalyptus which are highly discouraged on farm. Fertilizer trees such as *Markhamia lutea*, *Sesbania sesban* and *Grevillea robusta* do complement in most cases and occasionally balance off the system (Diallo et al., 2019). Having these complementary trees on farm leads to increased yield of crops such as maize. Conversely, having eucalyptus on farm drastically reduces yield of other crops planted nearby (Kuyah et al., 2019; Pumariño et al., 2015). Two studies reported increased plant biomass, soil moisture, and crop yield (Wamugunda et al., 2019) as a result of agroforestry involving *Grevillea robusta*, *Cordia africana*, *Vachellia xanthophloea*, *Vachellia seyal* and *Faidherbia albida*) (Diallo et al., 2019).

The use of improved varieties is considered as one of the fastest ways to increase yield, which is the greatest motivation of every farmer (Sibhatu, 2016). This is possible because some of the improved varieties may have early maturing and pests and disease resistance properties, resilience to the effects of climate change, and thus high yielding (Jaleta et al., 2018; Pretty & Bharucha, 2015). Several challenges are, however, faced when using improved varieties such as high cost and poor germination caused by the occurrence of uncertified seed by agro-dealers. Another challenge is the need to use intensive fertilizers and herbicides or pesticides for those which are not resistant to weeds and pests (Roobroeck et al., 2023). Proper application of fertilizers results in a 40% increase in yield productivity because N, which is a component of most mineral fertilizers is positively correlated to the yield of major crops including maize (Achieng et al., 2010; Ademba et al., 2015). Environment friendly fertilizers are highly encouraged for this case.

2.5 Participatory Approaches to Selection of Sustainable Intensification Practices

Selection and implementation of sustainable intensification require inclusion of implementors. This has been undermined for a long time and considered adjunct to experimental research but this is changing and gaining popularity as it leads to inclusivity (Elder & Odoyo, 2018). The lack of involvement of key players has led to many cases of research amiss and less adaptive, for example when farmers are not engaged through FGD and or KII, the reverse is true. Research experts within the participatory research field have reported that including relevant key stakeholders in research guarantees the adoption of and increased ownership of the new technologies, which is useful for the continuation of the project post the stipulated project years (Jabbar et al., 2020). Through participatory research one can achieve culturally suitable research outcome, enhance capacity and expertise among key stakeholders, escalate output and outcome quality and enhance project sustainability while creating a platform for future projects and interventions to existing problems (Jagosh et al., 2012).

Implementation of participatory research has several limitations. During participatory research, one has to care for the power play between the participants and the research process, as this could be a potential source of problems leading to the unsuccessful implementation of projects and partnerships if not well taken care of (De Oliveira, 2023). In addition to this, the heterogenous nature of communities makes it very difficult to replicate or use the voices of one community in another, also participation is void of proof to cause empowerment and sustainability and usually works best in small projects (Kanyamuna & Zulu, 2021). Despite its shortcomings, participatory research is still highly recommended as the precedent of any project involving other stakeholders and this includes emerging interventions such as sustainable intensification.

Diverse approaches have been applied in the identification of sustainable intensification practices. These include reviews, FGD and KII (Jambo et al., 2019; Kuyah et al., 2021; Pretty & Bharucha, 2015). A systematic review identified the following as critical sustainable intensification practices; crop rotation, intercropping, minimum tillage, and use of improved seed. In addition level of exposure, information and extension service access, and social participation increase significantly predict the adoption of sustainable intensification practices (Jabbar et al., 2020). It was noted that the implementation of sustainable intensification practices requires the assessment of both intrinsic and extrinsic factors assessment through interviews (Jambo et al., 2019).

Implementation of sustainable intensification needs to be context specific to meet targeted needs. Rudel, (2020) proposes the consideration and inclusion of sustainable intensification strategies that are customized to different social and economic contexts and agroecological suitability. This requires keen notice of socio-ecological contexts, to include the participation of local communities and other consumers of the sustainable intensification pathways. Previous research has mainly focused on the functionality of push-pull system on pest management and soil fertility improvement. To the best of knowledge available no other participatory research has been carried out to determine the sustainable intensification practices that farmers in western Kenya would like to integrate in the push-pull system and the effects of such an integration.

CHAPTER THREE

DETERMINATION OF SUSTAINABLE INTENSIFICATION PRACTICES THAT FARMERS WANT TO BE INTEGRATED IN PUSH-PULL SYSTEM

3.1 Introduction

Smallholder agriculture is the mainstay of agricultural production and food security for millions of rural populations across the world (Poole, 2017). In SSA, almost 80% of farms are under 2 hectares (Lowder et al., 2016). Of these, about 12.85 million household farms are classified in the subsistence production domain (*ibid*). However, smallholder agriculture is gradually being transformed into more productive and profitable enterprises that can increase food security and household income (Gassner et al., 2019). Much effort has been invested in increasing agricultural productivity in SSA, for example, through the implementation of innovative sustainable agronomic practices (Kuyah et al., 2021). Despite decades of these efforts, yield gaps persist in the region. Thus, most smallholder farmers remain poor and food insecure (Droppelmann et al., 2017). Even then, sustainable agriculture is expected to provide food, fodder, fiber, fuel, and feedstock, and assist people in escaping poverty (Gassner et al., 2019).

Agriculture in Africa is expected to meet the dual objectives of providing food and helping people to escape poverty. African agriculture is dominated by smallholdings and donors generally target their agricultural support at the smallholder sector. The expectation is that if the gap between actual and potential yields can be closed, smallholders will grow sufficient crops to feed their families, with a surplus to sell, thus meeting food security needs and generating income to move them out of poverty. Technologies already exist that can improve smallholder farmers' yields 3 or 4 times, even under rainfed conditions (Kuyah et al., 2021). However, the small size of land available to them limits how much can be grown, and the per capita income from agriculture is insufficient to allow people to move above the current World Bank-defined poverty line of US$1.90 per day. This study is linked with farmer typologies to further explain that there are large differences between individual farming households in terms of their investment incentives and capability to benefit from field-level technologies that are aimed at increasing farm productivity.

Cereals such as maize and sorghum form essential components of diets for many smallholder farmers in Africa; their efficient production in the region is constrained by pests and diseases, parasitic weeds, soil infertility and effects of climate change. Stemborers and the invasive fall armyworm are the most damaging maize insect pests; they cause yield losses of 8.3-20.6 million tons annually in SSA and 1 million tons in Kenya (De Groote et al., 2020). Parasitic weeds in the genus Striga also constrain cereal production in the region, causing total maize yield losses. The severity of these constraints is aggravated by low soil fertility and the effects of climate change (De Groote et al., 2020; Midega et al., 2018a). Management practices applied to mitigate these constraints include; application of biological control methods like the push-pull system (Hooper et al., 2015) and use of insect and herbicide-resistant maize for the management of pre- and post-harvest pests (De Groote et al., 2010). Additionally fertilizers and manures are applied to improve soil fertility (Tambo et al., 2020; Tefera et al., 2016).

Improvement of soil fertility and pest management interventions applied have the potential to increase crop productivity, some are limited by yield trade-offs and environmental regulations. For example, many chemical pesticides are discouraged as they are harmful to human health and other beneficial organisms such as pollinators (Biondi et al., 2012). Another limitation relates to the prevalent application of inorganic fertilizers, which are known to boost crop yields in the short term, but lose their effect over time (Njoroge et al., 2017). Hence, improving crop production while reversing environmental degradation and restoring ecosystem services is becoming the focus of poverty alleviation efforts in SSA (Droppelmann et al., 2017). The development of pest control strategies, including integrated pest management, that provide additional ecosystem services, represents an important component of efforts to sustainably improve food security in SSA (Snapp et al., 2021). In such instances push-pull has been identified as a strategic intervention with limited to no environmental effects.

Push-pull system manages the constraints of cereal production in eastern Africa by companion crops; desmodium emits volatile compounds that 'push' away gravid moths, while the grass border emits compounds that 'pull' the moths but offers an oviposition substrate that does not support stemborers and fall armyworms larval development (Chidawanyika et al., 2014; Erdei et al., 2022; Midega et al., 2018b). Desmodium suppresses the parasitic striga weed through allelopathy; root exudates contain novel isoflavanones, that induce abortive germination or inhibit radicle growth of striga seeds (Hooper et al., 2015). Desmodium also improves soil health (Drinkwater et al., 2021). Other benefits of push-pull technology include improved abundance and activity of arthropods for biological pest control which breakdown plant materials into humus. These benefits boost grain yields, while grasses and desmodium provide fodder, enabling crop-livestock integration.

Push-pull system has been shown to significantly increase smallholder farmers' income and food security (Kassie *et al*., 2018; Khan *et al*., 2008). Its uptake by farmers, however, falls short of these demonstrated benefits. This is likely due in part to the lack of options for integrating the technology with other crops, such as vegetables, and to its limited compatibility with other sustainable farming practices, such as crop rotation (Chidawanyika et al., 2023). In addition, pressures on land available for other food and cash crops constrain the adoption and expansion of push-pull technology (Niassy et al., 2022).

Further intensification of push-pull systems may enable synergistic benefits that would improve farmers' livelihoods, food security, and the environmental sustainability and resilience of the farming system. However, to date, no published information exists on what practices and crops farmers would prefer to integrate into push-pull systems. A participatory needs assessment is required to identify potential practices and crops that could expand the scope of push-pull beyond cereal production and fodder components on small plots. This study aims to fill this gap by conducting a participatory exploration of farmers' perspectives on the push-pull system and its compatibility with other smallholder sustainable intensification practices, and to identify farmers' needs and preferences for further intensification of the push-pull system.

3.2 Materials and Methods

3.2.1 Study Site

The study was carried out in three counties (Kisumu, Siaya, and Vihiga) in western Kenya. Kisumu sites are located in lower midland agro-ecological zone characterized by lake sediments, commonly with sand and clay soils and red-loamy soils. Siaya site is located in the low-midland zones which are sub-humid and humid zones characterized by dry spells, flooding, and heat stress. Crop and livestock production, fishing, and trading are elements of production in the region. Vihiga site is located in the lower midland zone and has mainly red loamy sand soils, derived from sedimentary and basalt rocks. Soil fertility in the study region ranges from low in Vihiga to moderate in Siaya and Kisumu. The sites vary in the level of major nutrients such as nitrogen, potassium and phosphorus, which generally fall below critical levels. The Kisumu site is located at latitude 0°20' - 0°50'S, longitude 33°20'- 35°20'E, with an elevation range of 1134 - 400 m; the Siaya site is located at latitude 0°00 - 0°06'S, longitude 34°16'- 34°23'E, with an elevation range of 1200 – 1500 m; Vihiga is located at latitude 0°00' - 0°30'N, longitude 34°40'E - 34°43'E, with an elevation range of 1300 - 1900 m (Awiti et al., 2022; Kimathi et al., 2023).

Rainfall in the study region ranges between 1200 and 2763 mm per annum in Vihiga, 1000 and 1800 mm in Kisumu, and is variable in Siaya: the northern part of Siaya receives 1750 mm or above while the Southern area receives a range of 1000 - 1250 mm. The long-term and short-term average annual rainfall and temperature across the three counties was 2530.8 mm in the year 2020 before experiments were established, 1754.5 mm in 2021 and 735 mm in 2022. Seasonal temperature varies between 17.9ºC - 27.3ºC in Siaya, 18ºC - 28ºC in Kisumu and 14ºC - 32ºC in Vihiga (Table 3.1).

Table 3.1: Periodic (1982 - 2016) and Annual (2017 - 2022) Mean Annual Rainfall and Temperature in Western Kenya. Rainfall for 2022 was estimated over four Months (January - April).

Year	1982-2016	2017	2018	2019	2020	2021	2022
Rainfall (mm)	1765.8	1961.8	2216.2	2530.8	2763.4	1754.5	735.2
Temperature (°C)	23.1	23.4	22.6	23.0	22.5	23.0	23.2

Cropping seasons in the region correspond to rainfall patterns either short or long rain season received between April to July and September to December respectively, the onset of the rainfall is however variable. Households rely on crop and livestock farming, fishing, tourism, engagement in agro-based industries and small-scale trade for livelihoods. Soils in the study sites are variable, with cambisols dominating Kisumu, black cotton and ferrosols in Siaya, while well drained loamy sand in Vihiga (Njoroge et al., 2017).

Nine village-level meetings were held between May and August 2021 in Kisumu, Siaya and Vihiga; a 10th meeting with field technicians was conducted in Kisumu. These counties represent areas of contrasting socio-ecological conditions. The average size of farm per person is 1 ha, 1.5 ha and 0.41 ha in Kisumu, Siaya and Vihiga respectively. The populations in these study counties vary with approximately 1,150,000 people in Kisumu, 993,000 in Siaya, and 590,000 in Vihiga. Figure 3.1 shows the location of the villages where FGD were conducted in Kisumu, Siaya, and Vihiga.

Figure 3.1: Location of Villages (Venues) where Focus Group Discussions were conducted in Kisumu, Siaya, and Vihiga Counties in Western Kenya

3.2.2 Determination of Sustainable Intensification Practices by Farmers for Push-Pull Integration

Two participatory approach assessment methodologies were used to identify the sustainable intensification practices that farmers would prefer to integrate into push-pull technology. These entailed FGD, and KII. A total of 90 farmers were selected and invited from Kisumu, Siaya and Vihiga counties to participate in FGD. Of these, 85 farmers attended the FGD. Key informants comprised of 25 experts chosen to identify alternative sustainable intensification practices available for integration into the push-pull system. Collectively information on crops and farming systems, tree production, push-push technology, livestock production and extension services information were obtained.

3.2.3 Selection of Focus Group Discussion and Key Informant Interview Participants

A sampling frame consisting of a list of all farmers known to practice push-pull technology in each of the three counties was obtained from the International Centre of Insect Physiology and Ecology (ICIPE), Thomas Odhiambo campus. From the sampling frame, 15 farmers currently practising, or who previously practised the push-pull system were randomly selected in each county (Kisumu, Siaya, Vihiga). An additional 15 farmers who were not practising (and had never practised) the push-pull system were randomly selected from names provided by lead farmers, community leaders, and field assistants in each county. Care was taken to maintain a minimum distance of at least 500 m (or at least five households) between farmers to allow diversity while selecting participants.

Ten FGD were conducted comprising nine groups of farmers in nine villages (summing up to 85 participants) and one group of field technicians (summing up to seven participants) as indicated in Figure 3.1. Each FGD comprised 7 to 12 participants, ensuring approximately 50% gender representation, except for the field technician group, which comprised only men. Field technicians were selected based on their role in the implementing push-pull system or other sustainable intensification practices (e.g. agroforestry, organic farming) and their involvement in agriculture in the region. Meetings with farmers took place at the homesteads of lead farmers in nine groups, each in a village: Ebusatsi, Emakunda, and Mwikusi villages in Vihiga County; Kosio, Marera, and Yenga villages in Kisumu County; and Ng'ayo, Komonge, and Ndira B villages in Siaya County (Figure 3.1).

Participants selected for KII comprised women and men, commodity traders (input suppliers), lead farmers, local leaders (e.g., Assistant Chiefs or Chiefs), agricultural extension officers, advisory providers (i.e. NGOs involved in technology transfer) and researchers. Key informants were purposively selected for the specific information they possessed based on their expertise and involvement in agriculture or agribusiness in the region. Fifteen of the twenty five key informants participated in person and ten participated virtually based on the convenience and adherence to the

COVID-19 protocol of the Ministry of Health, Kenya. In a second stage of data gathering, validation and ranking of the FGD data were carried out within the same region. Ninety-nine participant farmers were selected to rank crops, highlighting their suitability for sustainable intensification in push-pull system. The number of participants for the validation exercise was inclusive of the 85 (FGD participants) and an additional 14 new interested farmers.

3.2.4 Data Collection and Analysis

A questionnaire was used to guide FGD and KII (Appendix III). Detailed information was captured on crops and cropping systems, available sustainable intensification practices, preferred sustainable intensification practices, motivation for particular crops or cropping systems, farmer knowledge and aspirations, and support systems. The interview sessions were facilitated by a team of trained research assistants (comprising a moderator and note or record keeper) and a supervisor. During the FGD, the objectives of the exercise were presented, the role of various stakeholders explained, and the procedures highlighted for communication. Participants were encouraged to use a language with which they were most familiar and comfortable. Where a participant used the local/ native language, a local interpreter was used to translate. To ensure free, prior and informed consent, to the interview and recording of the sessions, a verbal and written consent form were sought and signed respectively after proper explanation (Appendix II).

A similar approach was used for the KII. Each FGD session and KII lasted approximately 1 hour or until no new information was forthcoming. Later follow up meetings, targeting validation of FGD data was carried out with 99 farmers (41 in Vihiga, 30 in Kisumu and 28 in Siaya). The validation tool was a matrix developed from data collected through FGD and KII. Farmers were asked to rank food crops, tree crops, intensification practices and benefits from the crops. All responses per question across the counties were combined for each group. The data were organized into structured data sheets and cleaned. The responses were categorized as belonging to four major themes and patterns were established based on the responses to the questions per group or key informant. Anonymity was maintained for individual responses. The number of times various themes were mentioned in a group or by key informants was used as a frequency measure. The data were analysed in Microsoft Office Excel. The results are discussed based on the emerging themes from the guiding questions.

3.3 Results

3.3.1 Crops and Cropping Systems

The study revealed that farmers in Kisumu, Siaya and Vihiga cultivate a variety of crops, including cereals, legumes, tubers, fodder crops, exotic and indigenous vegetables, fruits trees and shrubs, cash crops and oil crops (Table 3.2). According to the farmers and field technicians, maize and common bean (*Phaseolus vulgaris*) are the main crops cultivated in the region, though a respondent in Vihiga reported a shift from maize cultivation to banana (*Musa* spp.) production because the latter is more profitable. Field technicians reported groundnut *(Arachis hypogaea)*, sweet potato (*Ipomoea batatas*) and banana as common across the three counties; tea (*Camellia sinensis*) and coffee (*Coffea arabica*) as common in Vihiga; soybean (*Glycine max*), rice (*Oryza sativa*) and tomato (*Solanum lycopersicum*) are common in Kisumu; while sorghum (*Sorghum bicolor*) and cassava (*Manihot esculenta*) were common in Siaya.

Key informants noted similarities and diversity in crop production. They reported maize (25/25), common bean (20/25) and groundnut (15/25) as the most common crops in the region. Farmers reported a slight variation in crop production per county for sweet potato in Kisumu, sorghum in Siaya and banana in Vihiga. These crops are grown in six identified "cropping systems", which is defined here as specific combinations of crops or practices used on a farm. Different cropping systems are sometimes nested on the same farm, either within the same field or across different parcels. The cropping systems highlighted in FGD and KII included intercropping, crop rotation, crop-livestock farming, agroforestry, monocropping, and push-pull system.

Table 3.2: Crops Grown and Livestock Kept by Farming Households in Kisumu, Siaya and Vihiga Counties in Western Kenya

Crop/Animal classification	Crops/Animals
Cereals	Maize (10), sorghum (5), millet (4)
Grain legumes	Common bean (10), cowpea (*Vigna unguiculata*) (8), soybean (7), green gram (*Vigna radiata*) (2), pigeon pea (*Cajanas cajan*)
Tubers	Sweet potato (10), cassava (10), arrowroot (*Colocasia esculenta)* (2)
Fruits	Avocado *(Persea americana*) (5), mango (*Mangifera indica*) (6), pawpaw (*Carica papaya*) (4), watermelon (*Citrullus lanatus)* (2), banana (8), citrus spp.
Indigenous vegetables	Amaranth (3), African nightshade (*Solanum* spp.) (7), cowpea (8), spider plant *(Cleome gynandra) (5)*, crotalaria (*Crotalaria* spp.) (1), jute mallow (*Corchorus olitorius*) (3), Ethiopian Kale (*Brassica carinata) (1)*
Exotic vegetables	Collards (*Brassica oleracea*) (7), spinach (*Spinacia oleracea*) (2), spring onion (*Allium fistulosum*) (1), bulb onion (*Allium cepa),* tomato (*Solanum lycopersicum*) *(4)*, carrot (*Daucas carota*), coriander *(Coriandrum sativum)*, spices
Fodder crops	Napier grass (*Pennisetum purpureum*) (5), Brachiaria (5), Desmodium (5), Lucerne
Oil crop	Sunflower (*Helianthus annus*), groundnut *(10),* Bambara nut (*Vigna subterranean*) (1), sesame (*Sesamum indicum*) (1)
Cash crops	Tea (1), coffee (1), cotton (*Gossypium herbaceum*), sugarcane (*Saccharum officinarum*) (1), rice (1), sisal (*Agave* spp.), cassava and hibiscus (1)
Trees and shrubs	*Grevillea robusta (5)*, *Calliandra var calothyrsus (5)*, *Markhamia lutea (3)*, *Leucaena leucocephala (2)*, *Sesbania sesban (4)*, *Eucalyptus* spp. (3), *Tithonia diversifolia (1)*, *Moringa oleifera (1), Casuarina equisetifolia*, *Hesperocyparis lusitanica* (1), *Croton megalocarpus*, and *Maesopsis eminii*
Livestock and poultry	Cattle, goats, sheep, donkeys, chicken, quails, turkey, guinea fowls and rabbits

The list represents all the crops grown and livestock mentioned during the ten focus group discussions. The type of crop or livestock differ between farmers and counties. The numbers in brackets indicate how many discussion groups mentioned the crop or animal. Those crops or animals without numbers were mentioned only by key informant.

Crops and cropping systems are usually selected based on land availability and farmer preferences. Most farmers reported that crop and cropping system selection was primarily influenced by land availability and their personal preferences. Farmers with relatively large farms, for example, 3 to 10 acres in Siaya (reported by technicians) tend to practice monocropping and crop rotation, while those with small farms (less than 1 acre) prefer intercropping. Maize and sorghum were intercropped or rotated with common bean, groundnut or cowpea and occasionally with tubers such as sweet potato or cassava. Here, monocropping involved pure stands of maize, vegetables, sorghum, common bean, soybean or groundnut. This practice was popular among farmers who desired to mechanize production, those involved in agricultural projects with specific requirements, commercial farms, or among farmers who simply wanted to minimize crop competition. Crop rotation also occurred at the plot-level (e.g. in kitchen gardens) where maize was alternated with indigenous vegetables. There is a shift from the production of vegetables in kitchen gardens to commercial scales, especially for indigenous African vegetables. All cropping systems mentioned by the farmers except intercropping were also cited as sustainable intensification practices that they used to increase the productivity of their farms in an environmentally friendly way.

Respondent farmers cultivated specific crops for income, fodder, firewood and fruits. Cash and oil crops (Table 3.2) were considered important sources of income and also for provision of raw materials utilized in neighbouring industries. Fodder crops were grown for household livestock use and for sale. Fodder crops were grown in monocrops or as intercrops for particular purposes; for example, desmodium, Napier and Brachiaria grass were grown as components of the push-pull system. Most farmers had diverse tree species on farm. Trees and shrubs are mainly cultivated for income, firewood and fruits. Some trees were included in crop fields (e.g. *G. robusta*) while others were planted in woodlots (e.g. *Eucalyptus* spp. in Vihiga) or along boundaries (e.g. *M. lutea*) depending on farmers' needs and knowledge. Cattle, goats, pigs, sheep and chicken were reported as the most common livestock and poultry in the region (Figure 3.2). All groups reported owning cattle; however, dairy cattle and dairy goats were specifically mentioned only by two groups in Siaya and by the field technician. "Overall" as a category, represents the field technician group who mentioned the livestock that were common in the region.

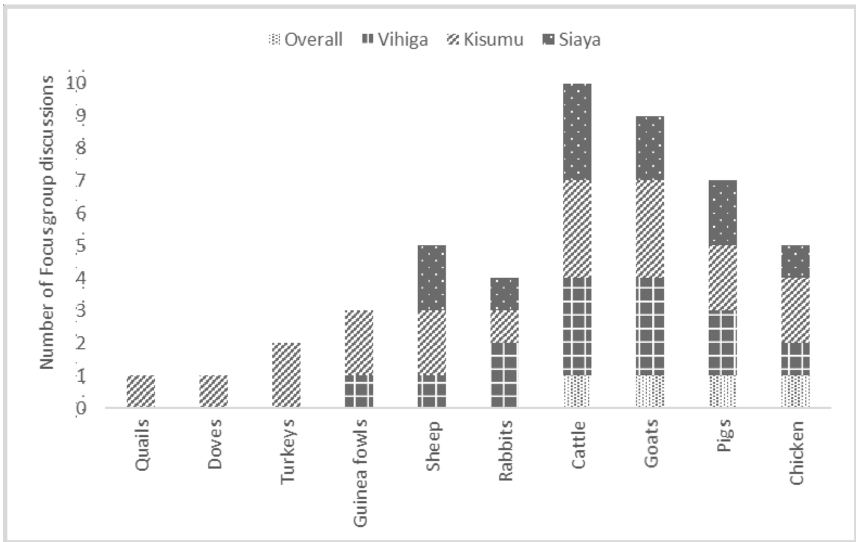

Figure 3.2: Livestock and Poultry mentioned during Focus Group Discussions in Western Kenya.

Farmers in the region occasionally practiced fallowing for periods ranging from a few months to several cropping seasons. They utilized the fallow land for grazing while allowing soil fertility to recover. Respondent farmers were aware of climate variabilities and embraced a variety of adaptation strategies. They cultivated maize during the long rain season and common bean or cowpea during the short rain season to mitigate the effect of heavy rains on legumes, increase income and diversify diets. Farmers used both local and improved varieties. The majority perceived local varieties to be tolerant to pests and resilient to drought; those who use improved varieties cited uniform maturity and high yield as the main motivation. Key informants highlighted that the adoption of improved varieties was higher in Vihiga than Kisumu and Siaya.

3.3.2 Sustainable Intensification Practices in the Region

Respondents mentioned low soil fertility, pests (Stemborer, fall armyworm and termites), and high cost of inputs as major constraints to crop production. They were also aware of and mentioned several practices they use to address these challenges and increase crop yield without increasing the area of cultivation. There are some intensification practices, which were seen by the farmers as sustainable while others were not (Appendix 1). Intercropping, crop rotation, use of organic manure and use of inorganic fertilizer were mentioned as common intensification practices by 9 out of 10 groups.

Seven out of 10 FGD reported using improved varieties and monocropping, whereas 6 out of 10 FGD reported crop-livestock farming (Figure 3.3). Conservation agriculture, agroforestry and fallowing were rarely reported in FGD as commonly practiced intensification practices. In contrast, key informants mentioned push-pull (15/25), use of improved varieties (9/25) and agroforestry (8/25) as commonly reported intensification practices. According to key informants, practices are considered sustainable if they conserve the soil, address fertilizer and seed resource needs, and improve soil nutrients. Based on this perception, 9 out of 12 practices and cropping systems were considered as sustainable by key informants. However, practices not considered sustainable by key informants could be considered so by farmer respondents (Figure 3.5). It was thus noted that the concept of sustainable intensification was not always well understood or agreed upon among the respondents. The “Overall” category in the figure represents the field technicians' assessment of practices commonly implemented across the study region. Practices marked with an asterisk (*) were identified by farmers as intensification practices but were considered sustainable by only a subset of participants.

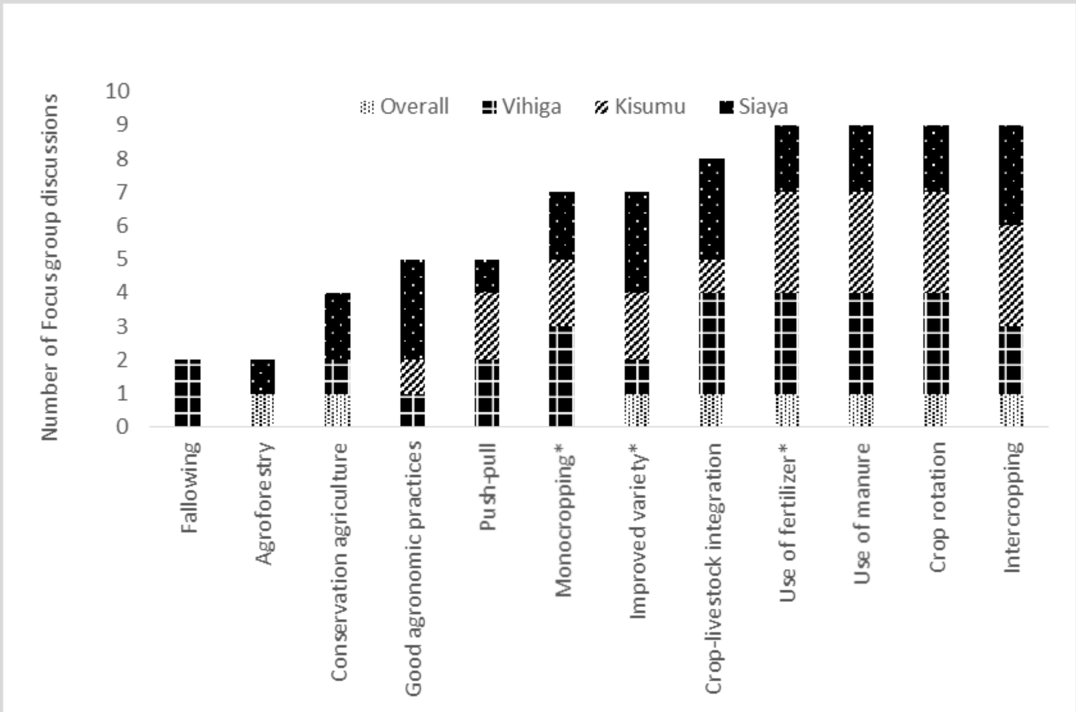

Figure 3.3: Sustainable Intensification Practices Identified during the Focus Group Discussions in Western Kenya.

3.3.3 Farmers' Motivation for Sustainable Intensification

Most participants indicated that subsistence (food) and income generation were the main reasons for intensification of farming systems in Kisumu, Siaya and Vihiga counties. Other motivations included improved soil health, management of pests, higher crop yield and food security, and fodder provision (Appendix I). The respondents mentioned intercropping and crop rotation as the main strategies for improving crop yield, increasing the number of harvestable products, and ensuring food security. They intercrop common bean and/ or vegetables with maize as a means of ensuring food security. The former matures before maize, providing food when cereal stocks are depleted; the latter (e.g., kales) is harvested across seasons for food or income. Intercropping was also used to reduce the chances of total crop failure. Respondents reported use of crops such as cassava and sweet potato as a safety net during hunger as they could be stored *in situ*. Other crops such as sorghum and millets were preferred for their nutrition and perceived medicinal value. Farmers were aware of the role of legume-based intercropping (e.g. cowpea, common bean, groundnut, and soybean) for nitrogen fixation. Intercropping with tuber crops, such as sweet potato, was mainly aimed at soil conservation. Inorganic fertilizers were used alone by farmers who did not have livestock and were not able to purchase manure.

The incorporation of green manure from shrubs (*T. diversifolia* and *T. vogelii*) and residues from intercrops or rotated crops was also practiced. Motivations that were specifically reported by key informants included income from the sale of seeds, food security and mitigation of effects of climate change. Livestock, poultry and bee keeping enterprises were employed to diversify farm productivity and nutrient cycling. These enterprises provided manure, meat, milk, and honey for subsistence and sale. Sale of livestock and poultry (both local and improved breeds) was perceived as an easy source of income; to cater for emergencies such as school fees or buy other items that are not produced on farm.

Agroforestry is another sustainable practice reported and observed to be common in the region. Fruit trees such as *M. indica* were identified as common components of agroforestry beneficial for food and income through the sale of fruits, firewood and timber. On the other hand, *C. calothyrsus, L. leucocephala, S. sesban* and *T. diversifolia* were identified as the most common trees for meeting the dual need for fodder and firewood. Other benefits of trees and shrubs mentioned include: medicinal purposes (*M. oleifera* and *T. diversifolia*), windbreaks, shade, erosion control, soil moisture conservation, source of green manure and also as a youth and women empowerment tool. One key informant (in Siaya) reported having trees to provide nectar for bees. Several ecological benefits of trees were reported by key informants viz. soil fertility improvement, nutrient cycling, protection of riverbanks, and cultural ecosystem services such as aesthetic (ornamental) and boundary demarcation. Among the sustainable intensification practices mentioned, intercropping, agroforestry, crop-livestock integration and use of manure were some of the preferred intensification practices for environmental friendliness.

3.3.4 Factors Limiting the Adoption of Sustainable Intensification Practices

The application of sustainable intensification is not void of challenges; farmers still face several challenges that hinder adoption and sustained use of these practices (Appendix I). Limited knowledge and skills about emerging technologies, land tenure and ownership, high initial cost, and poor targeting of technologies were the main challenges associated with the adoption of such practices. Farmers cited lack of the requisite skills and training in sustainable intensification and particularly for agroforestry, conservation agriculture, and the management of push-pull systems.

Competing needs for food, fodder and firewood were mentioned alongside the shortage of land; this would favor intensification such as intercropping as opposed to crop rotation. Furthermore, land is traditionally owned by men and inherited by children, often sons. Land issues were enumerated along with socio-cultural norms about gender, ownership and especially on decision making about the use of land. Often, women are the ones who work on the farms, but men make the decision on what is grown. Land ownership problems were also cited, for example, regarding leased parcels, where the owner restricts how the land was being used and may not allow growing of perennial crops. In other cases, the landowner calls off a leasing agreement when a project has been implemented but they are not interested in the posterity of the project.

Regarding the targeting of technologies, respondents were reluctant to adopt technology that did not meet their immediate needs, particularly food production, income generation and firewood supply. As a result, farmers often elect to implement technologies with a clear benefit in the short term (such as additional food from intercropping) rather than a long-term benefit with potential implementation costs (e.g. agroforestry, push-pull system). The high cost and low availability of farm inputs restrict farmers from integrated soil fertility and pest management through the inclusion of fertilizers, manure, and pesticides. Application of fertilizers was perceived as the quickest way to improve soil fertility in the medium term, but the yields tend to decline over time. Although preferred, the use of manures as a sustainable intensification practice was limited by a lack of knowledge and materials for composting, and by the high labor intensity of this practice.

3.3.5 Push-Pull System: Awareness, Benefits, and Limitations

On average, 95% of respondents were aware that the push-pull system was introduced to control maize stalk borer, eliminate striga weed and improve soil fertility, although only a few currently practiced it on their farms. Some respondents started practising and had stopped after some seasons when support (e.g. free inputs) ceased or a project ended; a few (5%) others had never heard about or practised push-pull system. Respondents who practiced push-pull system emphasized the positive impacts on crop production and provision of fodder (Appendix 1). In addition to the products and services from push-pull systems, farmer teachers and opinion leaders noted that sharing their experiences with push-pull system through radio, farmer field schools, and exchange programmes contributed to building their social capital.

The respondents identified several weaknesses that limit the application of the push-pull system (Appendix 1). They consider push-pull to be a labour-intensive technology. It takes longer to maintain a push-pull plot (carefully remove other weeds without damaging desmodium) compared to non-push-pull plots, although the effort could be leveraged elsewhere if the weeding is used to get fodder for livestock. Because of the perennial nature of the companion plants, deep ploughing on the whole plot is not practicable, and this leads to soil compaction and couch grass establishment in the push-pull system plots. Lack of knowledge about management of push-pull system plots has greatly contributed to the perception in our study area that push-pull system plots are ‘specially dedicated plots for research’ and that local livestock breeds cannot feed on desmodium, even though desmodium represents a prime fodder rich in protein.

Farmers noted trade-offs between food crops and fodder. This is despite the benefit the total productivity of an average push-pull field being high. By their submission, the fodder component occupies a large fraction of the push-pull plot, which may not be appealing to farmers without livestock. Besides, some farmers lack market for fodder; a component which they think can be incorporated into the system for better results. Push-pull fields were reported to be commonly re-established every season, for example, in areas where livestock freely graze in cropland after harvest (e.g., Alego Usonga in Siaya and Seme in Kisumu), thereby compromising the original perennial design. This limits the ecological functions of push-pull system and increases the costs of establishment and maintenance.

3.3.6 Options for Adaptation and Further Intensification of Push-Pull System

Figure 3.4 shows sustainable intensification practices that farmers considered to be of interest for further intensification of the push-pull system. Agroforestry, intercropping with legumes, crop rotation and crop-livestock integration ranked high among potential intensification options across the three counties. The use of fertilizer alone was reported as a key intensification practice in the region by field technicians, though it is not sustainable. Explanation on what sustainable intensification practices entail was then provided to farmers to improve their understanding of the concept.

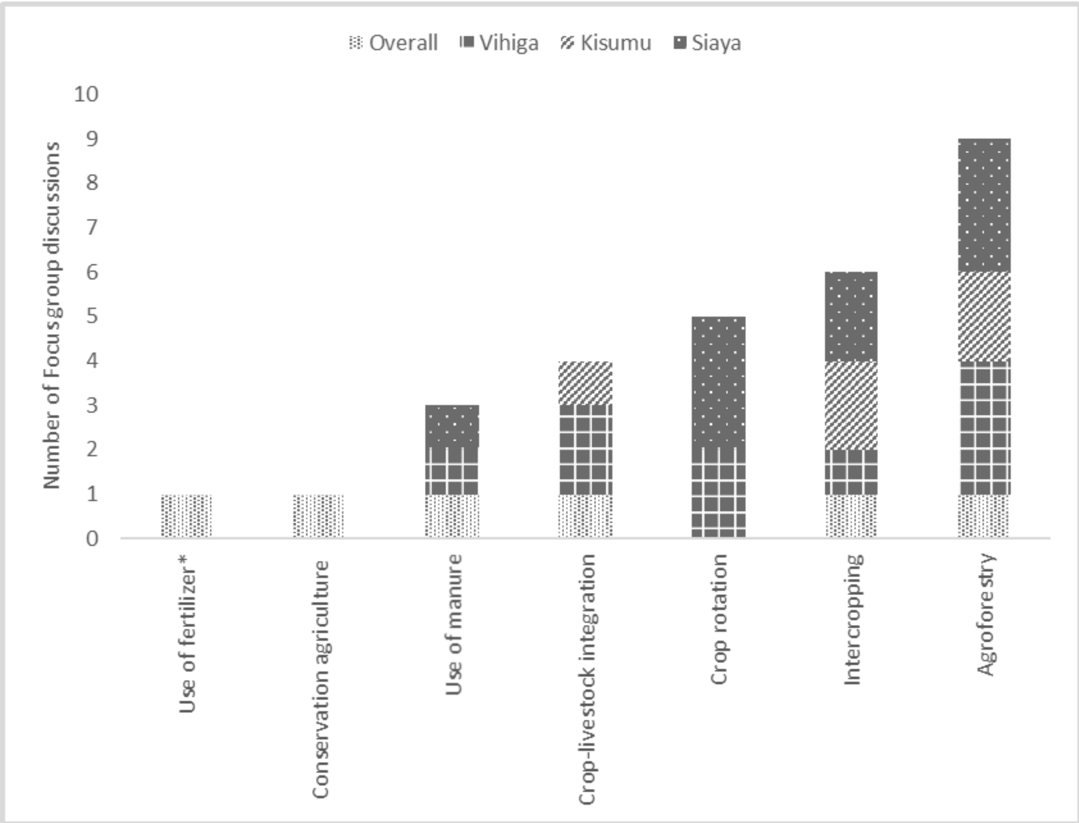

Figure 3.4: Sustainable Intensification Practices Suggested by Focus Group Discussion for Further Intensification of Push-Pull in Western Kenya

Respondents reported integration with agroforestry for food, firewood and fodder, to create resilient systems and diversify income. In this regard trees that improve soil fertility, provide fodder and firewood simultaneously were proposed. While some farmers mentioned that trees cannot fit into conventional push-pull plots (usually between 10m x 10m or 30m x 30m), the majority argued that trees could be integrated as long as suitable design and guidelines were provided and adhered to. Intercropping and crop rotation mostly with legumes, aimed to address food and nutritional security by providing edible products not offered by current push-pull companion crops. Crop-livestock integration was proposed to support fodder markets and ensure nutrient cycling. Key informants also identified agroforestry, crop-livestock integration and intercropping as key practices for push-pull intensification (Figure 3.5).

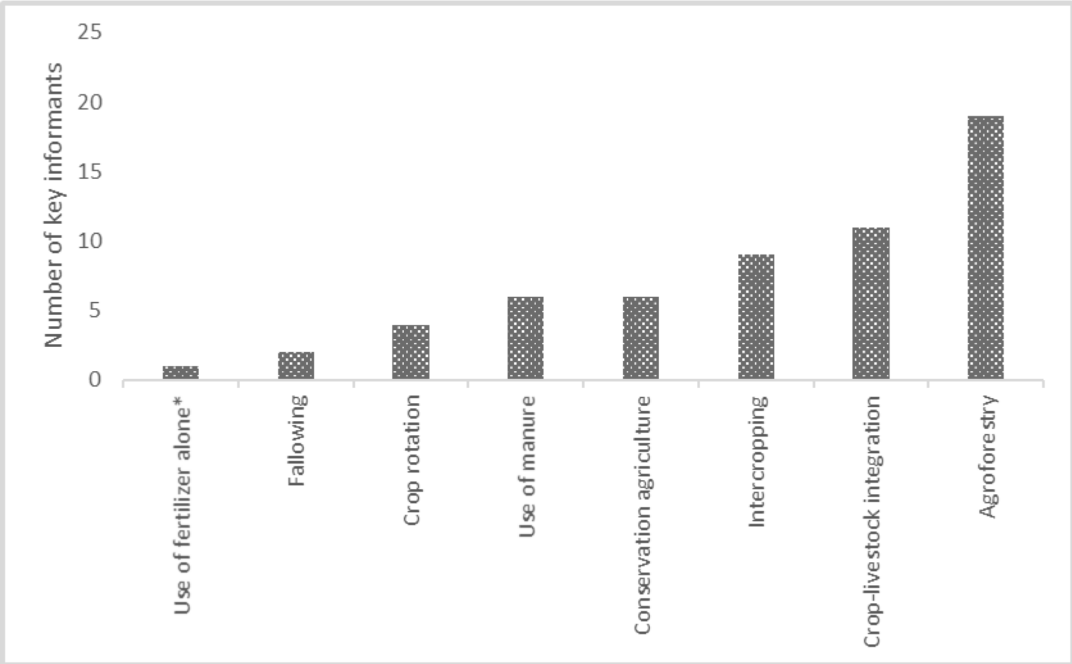

Figure 3.5: Sustainable Intensification Practices Preferred for Further Intensification of Push-Pull System, Based on Key Informants (n=25)

Farmers identified 18 priority crops to meet their needs through ranking (Table 3.3). Among these, maize (90%), common bean (49%) and banana (37%) were mentioned as the top priority crops in Vihiga. Maize (97%), common bean (70%) and sweet potato (33%) were prioritized in Kisumu and maize (96%), common bean (79%) and sorghum (36%) in Siaya. Seven priority trees were mentioned: Grevillea, Eucalyptus, Markhamia, Calliandra, Moringa, Sesbania and Tithonia (Table 3.3). Further, farmers' aspirations regarding further intensification of push-pull were explored. Similarities were observed for some of the preferred/ proposed sustainable intensification practices between FGD and KII.

Table 3.3: Ranking of Priority Crops and Sustainable Intensification Practices in Vihiga, Kisumu and Siaya County (in Decreasing Order of Preference)

	Vihiga (41 farmers)	Kisumu (30 farmers)	Siaya (28 farmers)
Sustainable intensification practices	Crop-livestock integration, intercropping, crop rotation	Intercropping, Crop-livestock integration or crop rotation	Crop-livestock integration or intercropping, crop rotation
Priority crops produced	Maize, common bean, banana	Maize, common bean, sweet potato	Maize, common bean, sorghum
Crop benefits	Maize: food, income, fodder Common bean: food, income, fodder Bananas: food, fodder, income	Maize: food, income, fodder Common bean: food, income, improved fertility Sweet potato: food, income, improved soil fertility	Maize: food, income, fodder Beans: food, income, manure or composting Sorghum: food, income fodder
Overall priority benefits (%)	Food 75 Income 66 Fodder 40	Food 95 Income 73 Fodder 22	Food 98 Income 88 Fodder 18
Priority trees	Eucalyptus, Grevillea, Markhamia	Grevillea, Eucalyptus, Markhamia	Grevillea, Markhamia, Mango
Tree benefits	Eucalyptus: income, firewood, construction material Grevillea: firewood, income, construction material Markhamia: firewood, construction material, income	Grevillea: construction material, income, firewood Eucalyptus: income, timber Markhamia: construction material, firewood, income	Grevillea: timber, income construction material Markhamia: income construction material/ timber, firewood Mango: food, income, firewood

Data based on the validation matrix by 99 farmers based on initial FGD and KII data

Using the validation matrix, farmers identified crop-livestock integration, use of fertilizers, use of manure, and intercropping as the foremost practices for expanding the utility of push-pull in the region (Table 3.3). Individual respondents identified *G. robusta* and *M. lutea* as trees that could be considered for inclusion in crop fields without compromising crop yields. Eucalyptus was preferred in woodlots for its timber and commercial value. The woodlots were also considered suitable for cultivating desmodium. Crop rotation was applicable in areas with large sizes of land (e.g., Siaya). Maize was considered a "must have crop" to be included in the rotation plan and could be rotated with common beans, vegetables (collards, cowpea, and nightshades), ground nut, green grams, or sorghum (Figure 3.6).

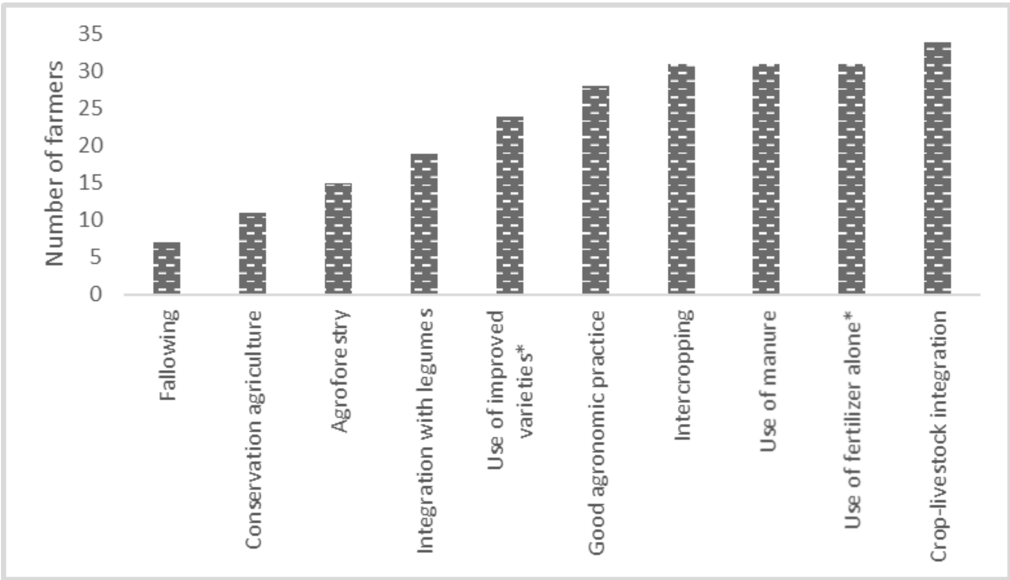

Figure 3.6: Sustainable Intensification Practices Preferred for Further Intensification of Push-Pull System, Based on a Validation Questionnaire of Individual Farmer Respondents (n=99).

All respondents reported receiving some training or technical information on agricultural intensification and general agricultural production. However, they highlighted that the information was mostly insufficient, often lagging in time based on the time of season. For example, information about fertilizer being delivered long after the planting season and being partly unreliable. Some of the respondents did not have practical knowledge on sustainable intensification. Actors such as non-governmental organizations (NGOs), research institutions such as ICIPE and the Kenya Agricultural and Livestock Research Organization (KALRO), and farmer groups were identified as critical in the adoption of technologies. They were identified as the main sources of information, along with mass media and institutions of higher learning. The extension officers were limited by support in terms of transport and generally the officer-to-farmer ratio was always low. The participants mentioned that the information they received was varied, and limited.

3.4 Discussion

The current study is one of the few that provide direct feedback from smallholder farmers, which is decisive to defining research priorities and actionable interventions. Understanding the context-specificity of farmers' needs and choice of farming practices within and across geographies is crucial for targeted technological dissemination to succeed. Hence, intensification technologies should adapt to farmers' needs across target areas. Since push-pull system is one intensification technology with multiple benefits, integrating it with compatible crops and farming systems can benefit many enterprises and improve farmers' livelihoods. There is need for researchers to be cognizant of the motivations, perceptions and challenges of farmers when seeking co-adoption of several sustainable intensification practices (Kanyenji et al., 2020). This can harness, but also promote indigenous knowledge, customized based on the diversity of cultural and socio-economic norms. Compared to conventional research, farmer-led research has self-reinforcing and long-lasting impacts on food and nutrition security among farmers (Waters-Bayer et al., 2015).

Farmers in Kisumu, Siaya and Vihiga counties reported integration of a variety of annual and perennial crops, vegetables, and trees for their livelihood, though maize and common bean dominate the landscape. This findings agree with a report that identified diverse crops and cropping systems on smallholder farms in western Kenya (Kansiime et al., 2021). The type of crop grown depends on farm size (Okeyo et al., 2020), farmer's educational level or expertise (Jambo et al., 2019), household needs (Valbuena et al., 2015), and access to information (Awiti et al., 2022). For example, sorghum is largely grown in Siaya, sweet potato in Kisumu, and banana in

Vihiga. These crops are primarily grown for food security and partly for income (Awiti et al., 2022; Ng'endo et al., 2018; Okeyo et al., 2020). The industrial use of sorghum and recent commercialization initiatives have increased their regional demand (Njinju et al., 2022). Sorghum (and sweet potato) are drought-tolerant (Motsa et al., 2015), and are widely promoted as alternative crops that buffer smallholder farmers against climate-induced shocks (Okeyo et al., 2020). The diversity of crops encountered underscores the importance of diversification for achieving food security among smallholder farmers, with intercropping being the most preferred practice among farmers with small parcels.

Farmers use different cropping strategies to address the region's low crop productivity associated with low soil fertility and pests. These practices were also mentioned as critical forms of sustainable intensification of push-pull. High value crops (e.g. legumes and vegetables) are candidate crops for integration with push-pull because of their contribution to food and nutritional security and high income relative to cereals (Gido et al., 2016). In addition they contribute to animal nutrition and food safety (Chidawanyika et al., 2023). Farming practices, including diversification with grain legumes, agroforestry, green manures, conservation agriculture, and integrated nutrient management with mineral and organic fertilizers are reported to improve the performance of maize-based systems in Africa (Droppelmann et al., 2017). For example, intensification of maize with long-duration pigeon pea increases food and biomass production (Droppelmann et al., 2017); and fast-growing, high leafy biomass trees with light crown are suitable for integration in croplands. However, farmers need training on the right approach to tree-crop integration. A review shows that integration of grain legumes and dryland cereals can enhance soil organic carbon (Kuyah et al., 2022); soils with high organic carbon are resilient to drought and floods and can also increase farm production (Iizumi & Wagai, 2019).

Smallholder farms in western Kenya intensify farming mainly for food security and income. Intercropping and crop rotation increase the variety of harvestable products, reduce chances of crop failure, and can increase crop yield when complementary (Mupangwa et al., 2021). Several studies show that intercropping maize and legumes increases crop yield, biomass (Kermah et al., 2017; Ndayisaba et al., 2021), fodder supply (Mupangwa et al., 2021), income diversification, and soil fertility (Drinkwater et al., 2021). Desmodium and Tephrosia intercrops with maize inhibit stemborers, African armyworm, and striga weed (Zhang et al., 2020). Furthermore, intercropping is gaining attention as a strategy for climate change mitigation and adaptation (Jambo et al., 2019; Mupangwa et al., 2021). Though maize-legume intercropping has multiple benefits, a careful targeting is necessary to maximize the returns (Ojiem et al., 2014). This is because some farmers are not aware of the right combinations and agronomic management that can reduce tradeoffs and maximize benefits.

Crop rotation was reported as a strategy for soil fertility enhancement. It is reported to consistently improve soil fertility, increase microbial diversity, and enhance resilience of the farming system (Rodríguez et al., 2020). These benefits from crop rotation can increase yield and lower production costs (Tariq et al., 2019). Agroforestry was highly recommended by farmers in FGD and by key informants, but individually farmers did not prefer it in push-pull system. This is mainly because farmers were not sure of the mechanisms of tree integration in push-pull system. The potential of priority practices identified for push-pull intensification to create resilience in farming systems, improve soil fertility, control pests and diseases, and increase productivity has been reported (Snapp et al., 2021).

Most respondents were aware of the pest control, soil improvement and socio-economic benefits of the push-pull system. However, multiple challenges that limit the adoption of push-pull system were also mentioned. These results correspond with (Midega et al., 2016; Niassy et al., 2022); as with other knowledge-intensive technologies, acquiring this requisite knowledge has remained a challenge, limiting the adoption of push-pull technology. Specifically, high costs of desmodium and Brachiaria seeds put the initial capital outlay beyond the reach of many smallholder farmers (De Groote et al., 2010). One respondent noted that push-pull technology faces competition from other pest management strategies such as the application of pesticides and biopesticides, and use of improved varieties. However, limited evidence compares push-pull and improved varieties. Even though, use of striga-resistant varieties is not considered to be economically viable for most farmers (De Groote et al., 2010).

Awareness and training on sustainable intensification were reported to be largely inadequate, sporadic, and unreliable. This limit most smallholder farmers who demonstrate willingness to adopt these practices but lack technical expertise. The problem of inadequate capacity and dearth of information is associated with limited agricultural extension (Midega et al., 2016). Many advisory services to smallholder farmers are provided by a research institution such as ICIPE, NGO, and input suppliers who in most cases have a target to meet and therefore their information is biased and specific to target groups. Integration of field days, farmer field schools, and farmer teachers in projects can bridge the knowledge gap and enhance adoption (Murage et al., 2011). This approach is however subject to the vagaries of competitive project funding. Project funding is inherently limited in time, and cannot address training needs at the scale necessary to have a country-wide and long-term impact on practices. Some of the intensification practices, e.g. the use of mineral fertilizers, are perceived by farmers as sustainable though they may not be considered as such by scientists.

Respondents reported financial constraints as a limitation to sustainable intensification adoption. Similarly, a study in Tanzania and Malawi identified the lack of financial resources as the leading setback for the adoption of intensification practices (Jambo et al., 2019). In western Kenya, farmers suggested use of fertilizer yet it has remained beyond their reach because of inadequate finances (Misiko et al., 2011), and outlays associated with the adoption of technologies tend to be high. Other limitations relate to cultural beliefs, whereby some respondents believe that local varieties were less costly and more climate resilient. These results call for a understanding the needs of farmers when designing sustainable intensification pathways, which often differ and could affect a targeted dissemination of the technology.

3.5 Conclusions

- The study identified intercropping, agroforestry, crop rotation (where land is available), and crop-livestock farming as desirable options for farmers to further intensify the push-pull system and improve its ecological and economic performance.
- Intercropping and crop rotation with vegetables and legumes was noted to potentially provide opportunities to diversify diets, incomes, and farming systems. Agroforestry offers a potential solution that is desirable for farmers to address problems of fodder supply, firewood, and the provision of fruits for dietary diversity.
- Limited diversification options, lack of knowledge, lack of a support system, and market access were identified as overarching challenges with sustainable intensification in the region.

3.6 Recommendations

- There is a need to strengthen farmer training and extension support on sustainable intensification practices in order to address existing knowledge gaps and improve adoption among respondents.
- The study highlighted the urgent need to integrate food legumes, particularly pigeon pea, into the push-pull system to diversify diets and income sources, improve resource-use efficiency, and enhance the delivery of additional ecosystem services.
- The study recommends further research needed to assess the suitability, performance, and effectiveness of the identified push-pull-based integrated systems across diverse agro-ecological and socio-cultural contexts.

CHAPTER FOUR

EFFECT OF PIGEON PEA INTEGRATION IN PUSH-PULL SYSTEM ON SOIL FERTILITY

4.1 Introduction

Low soil fertility is a major constraint to crop production limiting nutrient availability and driving yield declining yields in smallholder farming systems (Matichenkov & Bocharnikova, 2021). Globally, soil fertility decline is aggravated by soil erosion, continuous cultivation, and inappropriate fertilizer use (Lenka et al., 2012). Although inorganic fertilizers are commonly used to address nutrient deficiencies, their rising cost, limited farmer awareness, and application without soil testing often reduce their effectiveness (Sibusisiwe, 2013). In addition, the frequent use of nitrogen-based fertilizers without adequate soil diagnosis can increase soil acidity and further compromise soil health (Buleti et al., 2023). Therefore, long-term soil fertility improvement requires integrated and sustainable soil management practices that restore soil health.

Soil regeneration is one of the pathways to increasing food security among small scale farmers Some of the currently promoted soil regenerative strategies include sustainable practices such as zai pits, incorporation of organic manure, conservation agriculture, push-pull system, and soil amendments (biochar) (Kätterer et al., 2019; Kimaru-Muchai et al., 2020). Integrated soil fertility management is a promising sustainable strategy in the improvement of soils health as well (Kuyah et al., 2019; Vanlauwe et al., 2019). Sustainable practices such as integration of legumes are known to enhance farm diversification in smallholder farming system. This enhancement has the potential to increase nitrogen accumulation in leaves, especially within 6 months to 2 years (Ojiem et al., 2014). Agroforestry is one of the main interventions for rebuilding soil health and diversifying farming systems by enhancing nitrogen fixation, provision of services such as bioenergy and provision of fodder as in the case of pigeon pea.

Push-pull technology is one of the sustainable practices promoted for soil fertility. Desmodium in the push-pull system contributes to soil fertility enhancement by acting as a cover crop thus controlling soil erosion and fixing nitrogen. Farmers have, in past study, declared their aspirations for diversifying the push-pull systems with a need for the provision of fodder, fuelwood and food. They also mentioned soil fertility enhancement as one of the motivations for practicing sustainable intensification involving intercropping and crop rotation (Buleti et al., 2023). The limitation with push-pull technology such as difficult to manage desmodium can be explored when other crops are introduced into the system such as pigeon pea as an alternative or complementary to desmodium for the management of insect pests and weeds and for improvement of soil fertility.

Changes in land use are driven by population growth, and production systems have undergone a forced transformation to meet the increasing demands. Crops that were once considered poor man's food are now gaining popularity due to their adaptive nature to effects of climate change (Matichenkov & Bocharnikova, 2021). Pigeon pea is one such crop that has been identified as a dryland yet diverse crop with numerous benefits. The associated benefits include food diversification, carbon sequestration, nitrogen fixation, provision of fodder and firewood, resilience of the systems, and enhancing productivity (Diallo et al., 2019). Despite the proposal by farmers to further intensify push-pull system with edible legumes, no study has been carried out to see how soil fertility is affected in the system. Hence this study was carried out to determine the effect of integrating pigeon pea into push-pull technology on soil fertility.

4.2 Materials and Methods

4.2.1 Selection of Farms

Twenty-four farms were selected in Kisumu, Siaya and Vihiga counties of western Kenya. The farms were selected after a reconnaissance to ascertain conformity with selection criteria based on location, access suitability, cereal cultivation, and challenges with striga weed (Buleti et al., 2023). Soil sampling was carried out in the

24 selected farms which had met the criteria. Samples from each of the 24 farms were based on the number of plots per farm, complementing the different treatments accommodated on the farm. Some farms were small and could only accommodate one plot, while others were sufficient to accommodate all the four plots.

Soil sampling procedure

The field was divided into two or more plots, each approximately 200 square meters. During soil sampling it was further sub-divided into two plots to represent the different treatment taking note of borders. A distance of 1-3 meters was maintained to avoid any border effects by trees or nearby farm treatments. A reference point (mostly at the 1st corner of the field near the homestead) was identified and marked using a peg. Further Global Positioning System (GPS) coordinates for the reference point were also noted. Sampling was done before planting and when it was dry except for two farms which were sampled after it had rained and the farm had been ploughed. A unique code depicting the location (date, county, village, and name of the farmer) was developed for labelling the soil samples. During sampling, typical areas such as eroded sections, dead furrows, depressions, wet spots, boundaries, fence lines, tree areas, manure heaps and field edges were avoided.

Starting from the reference point, a 2-meter distance was measured, and surface litter at the sampling point was removed if present. A pre-cleaned soil auger was then driven to the specified depth starting with 0 - 15cm, the auger was then removed carefully; the soil was put in the bucket; the auger was returned and driven to 15-30 cm; the soil collected in a separate bucket. Systematically, samples were obtained within 8 to 12 points in a zigzag format to obtain a representative sample of the field. The distance between the trough and valley in the zigzag format was 2 meters and 3 meters to capture a representative of the entire area depending on the size of the plot. The sub-samples from each point were placed in buckets, labelled topsoil for 0 - 15cm and subsoil for 15 - 30cm.

Once all the sub-samples were collected from all points, they were placed on top of two polythene bags, one depth at a time, and gently mixed by hand to break clogs.

Through a series of mixing and subdividing of sub-samples, two composite samples per plot and four samples per farmer were obtained for those who had two plots. The composite amounting to 500 grams was placed in a ziplock bag and sealed. Soil for bulk density was obtained using core rings and a mallet at two different depths (0-15, and 15-30cm). Similarly, this was done by removing litter from the surface and drilling core rings into the ground with a mallet. The core ring was gently removed by clearing the soil on the side. Excess soil from either side of the core was trimmed. The auger was disinfected whenever switching plots using cotton wool and ethanol. The soil samples were later transported to the soil laboratory in the department of Horticulture and Food Security at the Jomo Kenyatta University of Agriculture and Technology where soil analysis was carried out.

Establishment of trials

A total of 15 plots were established on 25 farms (10 in Kisumu, 7 in Siaya and 8 in Vihiga) to test the effect of pigeon pea integration on soil fertility. On each farm, a selected field was used as a single plot or divided into two or more plots, approximately 200 square meters in size per treatment. The push-pull farms were established by intercropping maize and desmodium and planting Brachiaria or Napier grass along the borders (Ndayisaba et al., 2020). For push-pull + pigeon pea, the pigeon pea was grown between maize and desmodium and Brachiaria grass was grown on the border. Maize and pigeon pea were intercropped with 75cm between rows and maize monocrop was spaced at 30 by 75 cm intra and inter row.

Determination of soil physical and chemical properties

The effect of further intensifying push-pull system with pigeon pea on soil parameters was tested at the start and end of the experiment. Post experimental soil analysis was carried out after four seasons of cultivation, starting from the short rain season of 2021 to the long rain season of 2023, soil was sampled in the farms representing the different treatments; maize monocrop, maize + pigeon pea, push-pull and push-pull +pigeon pea. Soil parameters including; nutrient balance, soil pH, soil texture, Electrical Conductivity (EC), bulk density (only pre-experimental), macronutrients (available Nitrogen (N), available Phosphorus (P), exchangeable Potassium (K), soil organic carbon (SOC), Micronutrients (Manganese (Mn), Zinc (Zn), Iron (Fe), and cation exchange capacity (CEC), were monitored.

Soil analysis

Each sample was air dried, ground and passed through a 2 mm sieve prior to determination of different soil characteristics. Samples collected were analyzed for soil bulk density, soil organic carbon, pH, EC, total nitrogen (%), available nitrogen (NO_3 and NH_4), available phosphorus, exchangeable potassium, calcium and magnesium and soil texture. The soils' physical and chemical characteristics were determined according to the procedures of Okalebo et al. (2002) as described by (Akenga et al., 2014). Soil particle size was determined using the Bouyoucos hydrometer method. Soil pH was determined by the 1:2.5 soil: water suspension method. Soil organic carbon (SOC) was determined by the wet digestion method. Available phosphorus (Avail-P) was characterized with HCL and NH_4 in the Bray 2 method and determined by the molybdenum blue method. Total nitrogen was determined by the micro-Kjeldahl distillation method. Potential cation exchange capacity was determined using the summation method of exchangeable cations. Potassium, Sodium, Calcium and Magnesium were determined by extraction with 1M of ammonium acetate adjusted to pH 7. Potassium was measured using flame photometry and Ca and Mg ions were measured using an atomic absorption spectrophotometer. Exchangeable micronutrients Iron, Zinc and Manganese were determined by extraction with 1% ethylenediaminetetraacetic acid. The formulae below were used to determine the different soil parameters;

$$Bulk\ density\left(\frac{g}{cm3}\right) = Dry\ soil\,\frac{weight\,(g)}{Soil\ volume\ (cm3)} \qquad \textit{Equation 1}$$

$$\%Soil\ organic\ carbon = \left(1 - \frac{T}{S}\right) * 10mL * N * 0.003g * 1.33 * \frac{100}{W(g)}$$

Equation 2

Where T and S = volume of ferrous ammonium sulphate solution used in sample and blank titration (mL) respectively in blank titration (mL), 10 mL= volume of potassium dichromate ($K_2Cr_2O_7$) solution used for carbon oxidation, N = Normality of $K_2Cr_2O_7$ solution 0.003= equivalent weight of carbon in gram, 1.33 = correction or compensation factor for the incomplete combustion of organic Matter (if heat is not supplied) w =weight of sample in gram.

$$NH_4 + (\mu g\ kg - 1) = \frac{(a-b)*v*MCF*1000}{w} \qquad \textit{Equation 3}$$

Where a = concentration of N in the solution, b = concentration of N the blank, v = volume of the extract; w = weight of the fresh soil; MCF = moisture correction factor; f = multiplication factor.

$$NO_3\ (\mu g\ kg - 1) = \frac{(a-b)*v*MCF*1000}{w} \qquad \textit{Equation 4}$$

Where a = concentration of NO_3+-N in the solution, b = concentration of NO_3+-N the blank, v = volume of the extract; w = weight of the fresh soil; MCF = moisture correction factor

Calculations for potassium, sodium and calcium

$$K, Na, Ca\left(\frac{mg}{Kg}\right) = \frac{(a-b)*V*f*1000}{1000*w} \qquad \textit{Equation 5}$$

Where: a = concentration of K, Ca, or Na in the sample extract = concentration of element in the blank extract v = volume of the extract solution w= weight of the soil sample f = dilution factor

4.2.2 Data Analysis

Data derived from the soil analysis carried out in the laboratory was used to determine the treatment effect of the soil fertility pre and post experiment in the different sites. The data was subjected to analysis of variance (ANOVA), means were separated using Tukey's HSD test. All statistical tests were carried out to obtain significance levels at a value of $P \leq 0.05$. All data analysis was carried out in R statistical software and Microsoft Excel.

4.3 Results

4.3.1 Typology of Farming Systems

In general, the farms that were characterized in Kisumu, Siaya and Vihiga were heterogeneous. The type of cropping system observed was dependent on the size of the land and the particular growing season. In Vihiga, production was mostly twice in a year corresponding to the two rainy seasons and maize is a major crop. During the short rain season, farmers grow beans or vegetables. Some farmers grow maize during long rains seasons (March to July) and grow high value crop during the short rain season (September to December) such as African indigenous vegetables for economic value. Among the selected farmers, some grow crops in both seasons while others plant in a single season. Kisumu farmers were distributed in two villages (Lela and Seme). In Lela, farmers reported cultivation in two seasons corresponding to the two rainy seasons while in Seme production was mostly during the long rain season. At the time of soil sampling, most farms in Seme region of Kisumu were fallow. In Siaya production occurs during the long rain season except for a few farmers who cultivate both short and long rain season. In Vihiga farmers cultivate in both seasons (long rains and short rain) except when limited by finances. Trees were observed on farm mostly on the border and few on the farm. The most common tree species observed were *G. robusta*, *M. lutea* and Eucalyptus.

Initial Soil Characteristics

Soil Texture Fractions

The soil was categorized into sandy soil, loam soil and clay soil according to the sand, silt, and clay fractions. These categories represent coarse-textured soils (<20% clay), medium-textured soils (20-32% clay), and fine-textured soils (>32% clay), respectively. Table 4.1 shows the textural classification of the different soils from the three counties. Generally, soils in Vihiga and Kisumu were mostly loam and clay loam, while in Siaya were mostly sandy clay loam. In Vihiga, four farms (2 loam and 2 clay loam) had the same texture. In Kisumu five farms (4 clay loam and 1 loam) and Siaya three farms were sandy clay loam, clay loam, and sandy clay.

Table 4.1: Textural Classification of Soil Sampled from Selected Farms in Kisumu, Siaya and Vihiga Counties in Western Kenya

County	Clay (%)	Silt (%)	Sand (%)
Vihiga	$24.9^{a}\pm1.4$	$42.1^{c}\pm1.1$	$33.0^{b}\pm1.8$
Kisumu	$26.5^{a}\pm0.7$	$40.1^{c}\pm0.8$	$33.5^{b}\pm0.5$
Siaya	$30.7^{b}\pm1.6$	$20.0^{a}\pm1.6$	$49.3^{c}\pm1.2$

The values represent the means and standard error soil texture classes

Initial soil fertility varied across the study sites, with clear differences in acidity, soil organic carbon (SOC), bulk density, and nutrient status. Vihiga soils were acidic, had low electrical conductivity (EC), low to moderate SOC, and low bulk density. This pattern may reflect the intensive use of fertilizers and intercropping strategies in the area. Kisumu soils were also acidic, with low EC, medium to high SOC, and low bulk density. In contrast, Siaya soils were less acidic, had low EC and suitable bulk density, and contained higher phosphorus and SOC levels than soils from Kisumu and Vihiga.

Soil acidity was a major constraint in Vihiga and Kisumu, where soils from half of the sampled farms had pH values below 5.5 (Table 4.2), a threshold below which maize growth is considered unsuitable. Vihiga recorded the lowest SOC, phosphorus, calcium, and zinc levels, indicating poorer soil quality relative to the other sites. Kisumu soils were generally moderate across the measured parameters and were of better quality than Vihiga soils, although they remained less fertile than Siaya soils. Micronutrient concentrations did not differ significantly among sites for the same element; however, iron was consistently and significantly higher than manganese across sites. Generally, the highest soil carbon-nitrogen ratio was observed in soils sampled8 from Siaya at 14 followed by Kisumu at 11 and lastly Vihiga at 6. Siaya had the most favorable initial soil fertility conditions, Kisumu showed intermediate soil quality, and Vihiga had the most constrained soils, particularly in relation to acidity and low nutrient status.

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Table 4.2: Soil Properties in Selected Farms in Kisumu, Siaya and Vihiga before Establishment of Experimental Trials

County	Critical levels	farms below Critical level	Vihiga Range	mean	Kisumu Range	mean	Siaya Range	mean
pH	5.50	8	4.93-5.76	5.48^{b}	5.22-6.16	5.57^{ab}	5.81- 7.85	6.078^{a}
EC	4	All	0.028-0.082	0.046^{a}	0.036-0.062	0.049^{a}	0.039-0.05	0.044^{a}
Bulk density (g/m3)	1.6	All	1.09-1.30	1.19^{b}	1.10-1.22	1.205^{b}	1.27-1.39	1.33^{a}
Soil organic carbon (%)	2.70	9	0.983-1.93	1.77^{b}	1.75-4.44	3.11^{a}	3.40-3.64	3.54^{a}
Nitrogen (%)	0.20	1	0.22-0.389	0.298^{b}	0.187-1.06	0.39^{a}	0.268-0.338	0.29^{b}
Phosphorus(ppm)	30	13	6.11-11.2	10.64^{c}	16.9-48.7	27.2^{b}	44.9-52	44.95^{a}
Potassium(meq/100g)	0.04	none	0.09-0.984	0.34^{b}	0.298-0.86	0.59^{b}	0.83-0.98	0.89^{a}
Calcium(meq/100g)	2.0	4	0.703-4.66	3.76^{b}	17-35.8	31.1^{a}	18.75-29.2	20.88^{a}
Magnesium (meq/100g)	1.0	none	2.97-4.2	3.87^{a}	3.92-4.38	4.22^{a}	3.62-3.90	3.845^{a}
Iron (ppm)	10.0	none	215-399	340.3^{a}	$312\text{-}371^{a}$	347.6^{a}	356-360	358.2^{a}
Zinc (ppm)	5.0	1	5.67-24.5	17.1^{a}	5.39-14.1	8.12^{b}	4.39-18.83	6.35^{b}
Manganese (ppm)	20	none	185-190	188.4^{a}	189-190	189.74^{a}	188-190	189.71^{a}

Values for the means with similar letter are not significantly different

4.3.2 Post Experiment Soil Fertility under Different Treatments

Post-experiment analyses indicated only minor changes in the measured soil properties. Generally, the post-experiment results were consistent with the pre-experiment findings, with highest pH being recorded in Siaya, followed by Kisumu and finally Vihiga, though these differences did not differ significantly. When treatments were compared per site, maize monocrop had the highest pH in Kisumu (5.59), maize + pigeon pea had the highest pH in Siaya (5.99), and push-pull + pigeon pea had the highest pH in Vihiga (5.26). The lowest pH recorded was 5.17 in maize monocrop in Vihiga (Table 4.3). Soil organic carbon was highest in the maize monocrop at 2.43% in Kisumu and lowest in maize monocrop at 1.46% in Vihiga. This is because the initial status was lower for Vihiga and intermediate for Kisumu. The nitrogen content was enhanced in push-pull and push-pull further intensified with pigeon pea (Figure 4.3). In Kisumu, the lowest phosphorus content was observed in the maize monocrop at 24.34 ppm, while the highest was observed in the push-pull system at 30.87 ppm. In Siaya, the lowest phosphorus was noted in maize monocrop at 24.47 ppm, while the highest was in push-pull + pigeon pea at 64.08 ppm (Figure 4.4). Potassium was enhanced in push-pull + pigeon pea in Siaya, and push-pull and push-pull + pigeon pea in Vihiga (Figure 4.4). None of the soils in the different treatments were lower than critical level for potassium though. Significant differences were noted as a result of pigeon pea integration for nitrogen, phosphorus potassium and magnesium content in some of the sites (Figures, 4.1, Figure 4.2, and Figure 4.3).

Table 4.3: Electrical Conductivity, pH, Soil Organic Carbon for the Soil Assessed in the Different Treatments in selected farms in Kisumu, Siaya and Vihiga

Site and treatment	pH	EC	SOC (%)
Kisumu	5.44	0.051	1.62
Push-pull	5.47	0.050	1.6
Push-pull + pigeon pea	5.40	0.055	1.30
Maize monocrop	5.59	0.049	2.43
Maize + pigeon pea	5.36	0.043	1.59
Siaya	5.88	0.061	1.53
Push-pull	5.77	0.052	0.81
Push-pull + pigeon pea	5.63	0.047	1.7
Maize monocrop	5.86	0.082	1.89
Maize + pigeon pea	5.99	0.057	1.72
Vihiga	5.23	0.052	1.63
Push-pull	5.23	0.057	1.67
Push-pull + pigeon pea	5.26	0.047	1.49
Maize monocrop	5.17	0.052	1.46
Maize + pigeon pea	5.23	0.052	1.99

The nitrogen content was not significantly different across treatments per county but was highest in the push-pull + pigeon pea treatment. The nitrogen content was lowest for maize monocrop in Kisumu and Vihiga (Figure 4.1). The phosphorus content was significantly higher in push-pull and in push-pull + pigeon pea than maize monocrop in Kisumu. In Siaya the highest phosphorus content was recorded in push-pull + pigeon pea treatment (Figure 4.2).

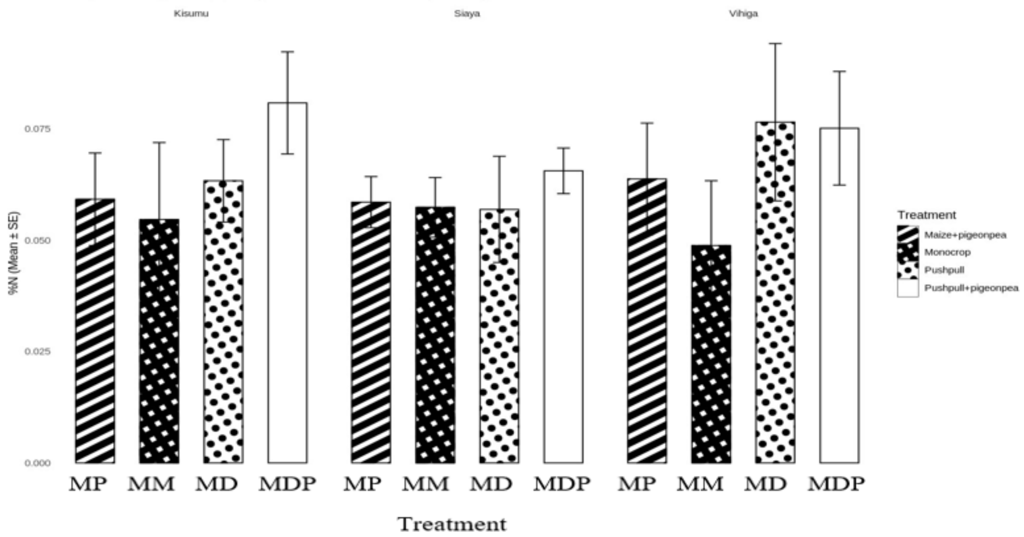

Figure 4.1: Nitrogen Content (%) Per Treatment in Kisumu, Siaya and Vihiga Treatment Abbreviations: Maize + Pigeon Pea = MP, Maize Monocrop = MM, Push-Pull =MD, Push-Pull + Pigeon Pea = MDP.

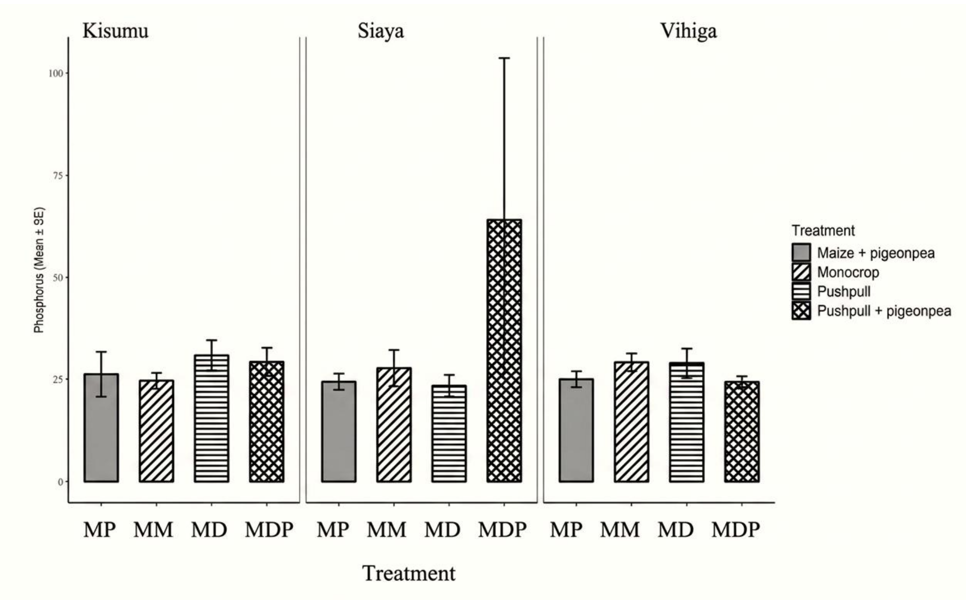

Figure 4.2: Site and Treatment Effect on Phosphorus Content for the Soils Assessed in Kisumu Siaya and Vihiga. Treatment Abbreviations: MP = Maize + Pigeon Pea; MM = Maize Monocrop; MD = Push–Pull; MDP = Push–Pull + Pigeon Pea.

Integration of pigeon pea had a positive effect on potassium. The potassium content was significantly higher in push-pull and push-pull + pigeon pea in Vihiga compared to other treatments. No significant differences were observed for treatments in Kisumu and Siaya (Figure 4.3). Magnesium content differed across treatments and across site, Vihiga soils had the lowest magnesium content (Figure 4.4).

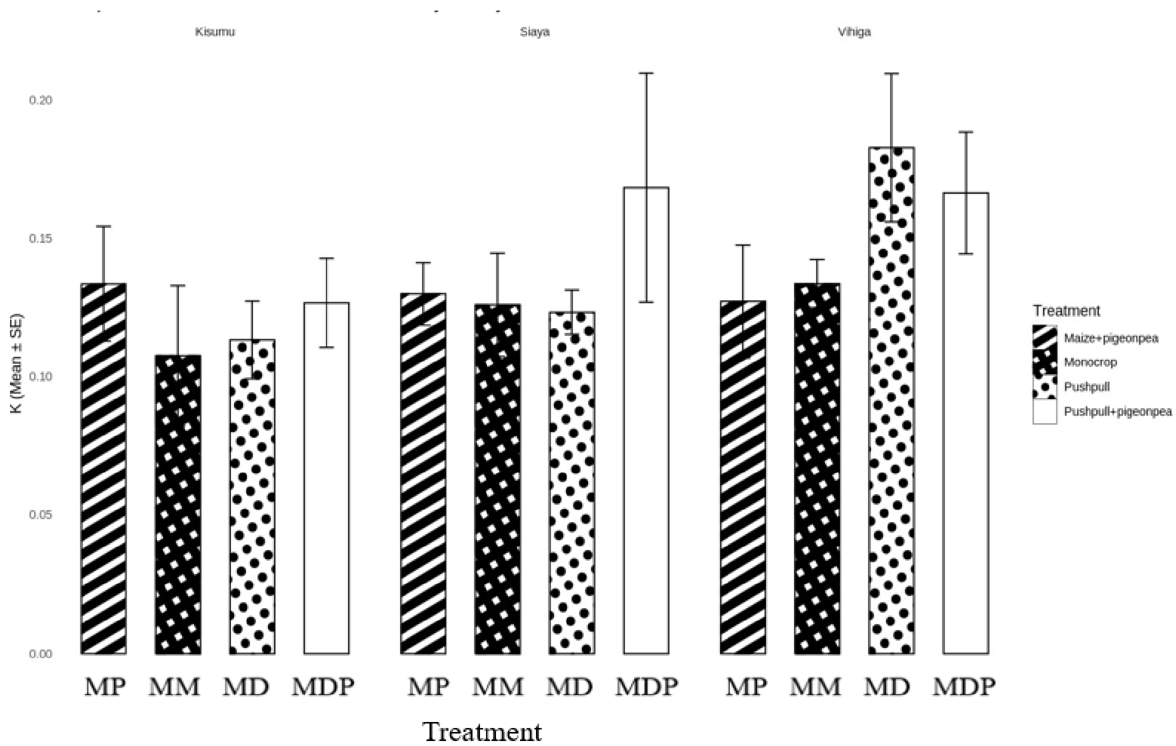

Figure 4.3: Potassium Content (Meq/100) Per Treatment in Soils Assessed in Kisumu, Siaya and Vihiga. Treatment Abbreviations: MP = Maize + Pigeon Pea; MM = Maize Monocrop; MD = Push–Pull; MDP = Push–Pull + Pigeon Pea

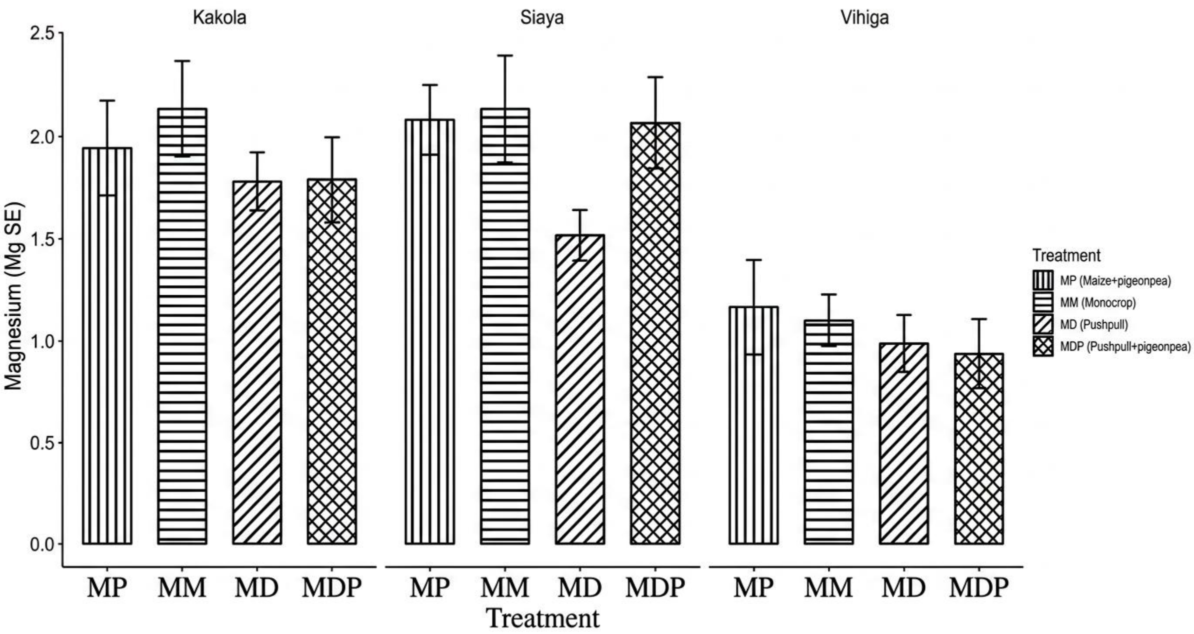

Figure 4.4: Site and Treatment Effect on Magnesium Content in Soils Assessed in Kisumu, Siaya and Vihiga. Treatment Abbreviations: MP = Maize + Pigeon Pea; MM = Maize Monocrop; MD = Push–Pull; MDP = Push–Pull + Pigeon Pea.

4.4 Discussion

Soil characteristics differed as a result of further intensification of push-pull and maize cropping systems in the different counties, reflecting variations in climatic conditions and previous cropping systems. The soils in the experimental fields were generally classified as loam and clay loam in Vihiga, clay loam in Kisumu, and sandy to sandy clay loam in Siaya. This classification differs slightly from an earlier report by NAAIAP and KARI (2014) which described Vihiga soils as light textured and those in Kisumu and Siaya as coarse textured. Across the sites, pre experimental establishment, soil pH was generally below the optimal range for maize growth, except on a few farms in Siaya. Maize performs best in soils with a pH of 5.5–7.3, with 6.0–6.5 considered optimal because nutrients are more readily available within this range. Therefore, high soil acidity limits maize productivity and reduces farm income. Liming is commonly used to reduce soil acidity; however, its long-term use may contribute to greenhouse gas emissions (Hijbeek et al., 2021).

Initial soil characteristics showed low nutrient contents for nitrogen and SOC. Low nitrogen content (below critical levels (0.20%)) has also been reported for soils in western Kenya. These soils are characterized by extreme nitrogen deficiency and are non-responsive to nutrient applications (Kwena et al., 2019). In Vihiga, low to moderate SOC was recorded; Kisumu had medium to high SOC, while Siaya had high SOC (Table 4.3). All farms sampled in Vihiga had SOC below 2.7%, 9 farms in Kisumu had below 2.7%, while farms in Siaya had a minimum of 3.29%. Guidelines on the interpretation of soil carbon test results as cited by Okalebo et al. (2002) classifies soil as having very low (0.5%), low (0.5-1.5%), moderate (1.5-3) and high (3%) SOC. A report on soil suitability evaluation for maize production in Kenya identified 2.7% as adequate SOC for maize growth. Soils with low organic matter tend to have low infiltration, low water holding capacity, and low microbial diversity and activities (Brempong et al., 2023). Low soil organic carbon in this region could also be associated with the removal of plant residues from the farm, a common observed practice. Farming systems in western Kenya are characterized by crop-livestock integration, which causes competition between residue and fodder (Peterson et al., 2020).

Integration of pigeon pea into push-pull system resulted in enhanced nitrogen, phosphorus and potassium content. Legume integration in farming systems in known to enhance soil nutrient such as nitrogen through fixation and available phosphorus nutrient cycling (Ndayisaba et al., 2021). There were minimal to no significant difference as a result of pigeon pea integration for soil organic carbon content. Crop intensification is an important pathway to soil nutrients replenishment over long periods of time. Similar to the current study, lack of significant differences between intercrops and mono-crops of maize and pigeon pea have been observed (Myaka et al., 2006). Soil organic carbon generally increases over time and is beneficial in several ways, including enhanced soil resilience to drought and heavy rains and enhanced soil physical properties. Soil organic carbon can be increased by applying compost or green manure or the inclusion of crops known to have the strongest effect on SOC accumulation (Kuyah et al., 2022).

The most identified limiting nutrient was phosphorus, which was below adequate levels on all farms in Vihiga and in 14 farms in Kisumu prior to the establishment of experimental trials. Phosphorus levels were above adequate levels in all farms sampled in Siaya before the experiment was established. Post-experiment soil analysis showed that only push-pull in Kisumu and push-pull pigeon pea in Siaya attained phosphorus level equal to or greater than the critical limit (30 ppm). The rest were lower than initial due to its utilization during the growth and development of the crops. Higher phosphorus content in push-pull plot compared to monocrops was noted previously due to extensive land cover and the nutrient recycling nature of the push-pull system (Ndayisaba et al., 2021). Pigeon pea on the other hand enhances phosphorus accumulation and recirculation of dry matter, as was noted in this study in Kisumu and Siaya. Long term effect on pigeon pea intercrop in enhancing nutrients in soil maize has been reported (Renwick et al., 2020), most of these nutrients are easily transported in the grain thus improving the quality of harvestable grain.

The Nitrogen content in push-pull + pigeon pea was highest and significantly different in Kisumu compared to monocrops in Siaya and Vihiga. This presents integration of pigeon pea in push-pull system as an alternative to contributing to rebuilding of soil fertility and reducing degradation that results from excessive use of synthetic fertilizers. The carbon: nitrogen ratio in soils in Siaya was significantly different (15) compared to the carbon-nitrogen ratio in Vihiga (5). This is important because carbon nitrogen ratio, determines microbial availability and nutrient cycling (Assmann et al., 2014).

The soils in the different treatments and sites were sufficient in micronutrients e.g. iron and manganese. This agrees with previous research, which showed lack of significant difference in micronutrient content for soils tested in western Kenya (Akenga et al., 2014). This implies that the focus on soil improvement at the studied site should emphasize macronutrient enhancement rather than micronutrients, since micronutrients are sufficient. Magnesium and potassium were adequately supplied in all farms sampled in all counties, meaning that the farmers do not have to supplement their crops with these nutrients. Post experiment, the magnesium content in Vihiga was at the edge which is critical level 1meq/100g and would require supplementation during continuous cultivation. Inadequate calcium levels in many farms predispose the crops to pests and disease infestation, and exposure to extreme weather. Liming is commonly practiced to minimize calcium deficiency though it is not sustainable, because one has to keep applying over a long period of time.

In this study, push-pull and push-pull + pigeon pea enhanced nitrogen, phosphorus and potassium. When these nutrients are enhanced, organic matter, soil moisture, and microbial activity are also enhanced (Mwalusepo et al., 2015). Strategically diversified intercropping systems involving pigeon pea can result in very high yield and a high land equivalent ratio compared to monocrops of the same (Njira et al., 2021). Pigeon pea can be incorporated in farming systems to enhance fertility, as was noted for phosphorus, nitrogen and potassium in this study. Further intensification of push-pull farming systems using pigeon pea is an opportunity to enhance soil fertility and increase farm productivity.

4.5 Conclusions

- Farmers in Kisumu, Siaya and Vihiga practice a variety of farming and cropping systems and they significantly influenced the soil properties, highlighting the importance of targeted specific soil management strategies.
- The soil in the study region was generally low in fertility, high in acidic and minerals were below critical levels. Comparatively, Vihiga had the lowest soil fertility, Kisumu had intermediate and Siaya the best soil fertility.
- Changes in nutrients because of further intensification of push-pull technology with pigeon pea were marginal but specifically nitrogen, phosphorus, and potassium content were enhanced.

4.6 Recommendations

- The acidity level of the sampled soils calls for the avoidance of pH-lowering fertilizers (such as DAP). Farmers can raise the soil pH by using green manures from the pigeon pea in the long term or liming where immediate intervention is required.
- Farmers and the county governments of Kisumu, Siaya and Vihiga are encouraged to consider integration of pigeon pea as one of the pathways to enhance soil fertility in their farming systems.
- Future research should focus on long-term studies (>5 years) on the effect of legumes on soil nutrient enhancement in soils

CHAPTER FIVE

EFFECT OF PIGEON PEA INTEGRATION IN PUSH-PULL SYSTEM ON PEST MANAGEMENT AND NATURAL ENEMIES

5.1 Introduction

The target to achieve global Zero hunger by 2030 is ambitious and requires strategies that improve food production and distribution systems and create social protection systems for farmers. Increasing food production can be achieved through sustainable agricultural practices (Kuyah et al., 2021). This is widely achieved by adopting practices that build soil fertility and prevent soil erosion, increase carbon in the soil, enhance biodiversity, conserve water, increase resilience to extreme weather and avoid air and water pollution (Brempong et al., 2023). Sustainable intensification practices are commonly practiced by smallholder farmers in Africa, who cultivate on small parcels (<2 ha). Smallholder farmers are faced by several challenges due to limited resources, poor infrastructure, lack of funding, gender biases, or other socioeconomic factors (Nyambo et al., 2022).

In Kenya, most smallholder farmers face the pressure to cultivate all crops for subsistence and sale from the same portion of land. Productivity on these small plots continues to dwindle because of soil degradation, emerging from intensive cultivation, mono-cropping and lack of proper use of fertilizers (Dhillon & Moncur, 2023). The effects of climate change worsen the situation by contributing to further soil degradation, increased pest and diseases incidents and unpredictable precipitation patterns (Kimathi et al., 2023). This therefore means crop production must shift from conventional to suitable agro-ecological approaches that are adaptable for the current climate variabilities.

Cereals and legumes are the main food crop combinations with multiple benefits (Kermah et al., 2017). Maize is the leading cereal crop grown in Kenya, currently grown on about 2.196 million hectares (Njeru et al., 2022) and found in almost all farming systems in Kenya. Maize mixed, agro-pastoral, highland perennial, root and tuber crop, cereal-root crop mixed, tree crop systems, perennial mixed, urban and peri-urban systems (Dixon et al., 2019). Maize, sorghum and millets are commonly integrated with legumes, vegetables, tubers, fodder crops, fruit trees and shrubs, cash crops, and oil crops in this region (Buleti et al., 2023). The mode of crop integration is farm and region specific depending on the size of the farm and motivations of the farmer, majorly income, subsistence, pest management or soil fertility improvement. Crop integration in western Kenya comprises of intercropping, crop rotation, agroforestry, mixed crop and livestock and kitchen gardens (Buleti et al., 2023). Owing to the nature of small portions of land intercropping is a priority strategy as it attracts many benefits. Intercropping has previously been reported to improve soil fertility, reduce the risk of crop failure, and have variable effects on pests and weeds, and crop growth.

Maize is the main staple food and most widely cultivated cereal in western Kenya. Production of maize surpasses that of sorghum and millets though its productivity continues to dwindle due to low soil fertility and effects of agricultural pests (e.g. maize stalk borer and fall armyworm) and striga weed (Njeru et al., 2022). Maize stalk borer can cause 20-40 % crop damage during cultivation and 30-90% yield losses post-harvest and during storage. Fall armyworm was recently declared a national major pest in Kenya. Crop losses due to fall armyworm are estimated to be 1 million tons per year in maize (De Groote et al., 2020). Striga weed leads to stunted growth and reduced crop yields and is acknowledged as the most serious challenge to maize productivity in Kenya (Hailu et al., 2018). Striga competes with the host plant for nutrients and releases toxins that cause stunted growth and low grain yield (Midega et al., 2017). Effects of striga on crops vary depending on striga count, host crop species and genotype, current farming systems, soil nutritional status, and rainfall patterns (Hailu et al., 2018).

Several interventions are applied in controlling striga, including use of resistant crop varieties, herbicides, biopesticides, intercropping of cereals and legumes, crop rotation, use of trap crops that stimulate suicidal germination, application of manure and nitrogen fertilizer, and push-pull system (Kamara et al., 2020; Midega et al., 2017; Sibhatu, 2016). So far, no single management strategy has achieved complete elimination of striga (Kanampiu et al., 2018). The push–pull system is widely recommended for maize production in western Kenya because it simultaneously addresses the three major production constraints: Striga infestation, insect pests (including fall armyworm and maize stemborers), and declining soil fertility.

Push-pull has also demonstrated ability to increase biomass and eventually yield of maize and better livelihoods for the adopters (Cheruiyot et al., 2020). Application of push-pull system has been limited to small plots and it is hindered by the lack of diversity of food crops. In a recent needs assessment, participants proposed intercropping and, crop rotation as options for further intensification of push-pull system (Buleti et al., 2023). Pigeon pea was selected from a needs assessment as a candidate crop for further intensification of the push-pull system, with the potential to meet the need for diversified foods, fodder, firewood, and income in western Kenya. There is need to determine innovative ways of integrating pigeon pea with limited or no risk of compromising performance of the current push-pull system. Therefore, the objective of this study was to determine the effect of integrating pigeon pea into the push-pull system on the pests (stemborer and fall armyworm), striga weed, and natural enemies. The results present opportunities for modifying the push-pull technology to improve its functionality and customize it for the small-scale farmers' application.

5.2 Materials and Methods

5.2.1: Study Site

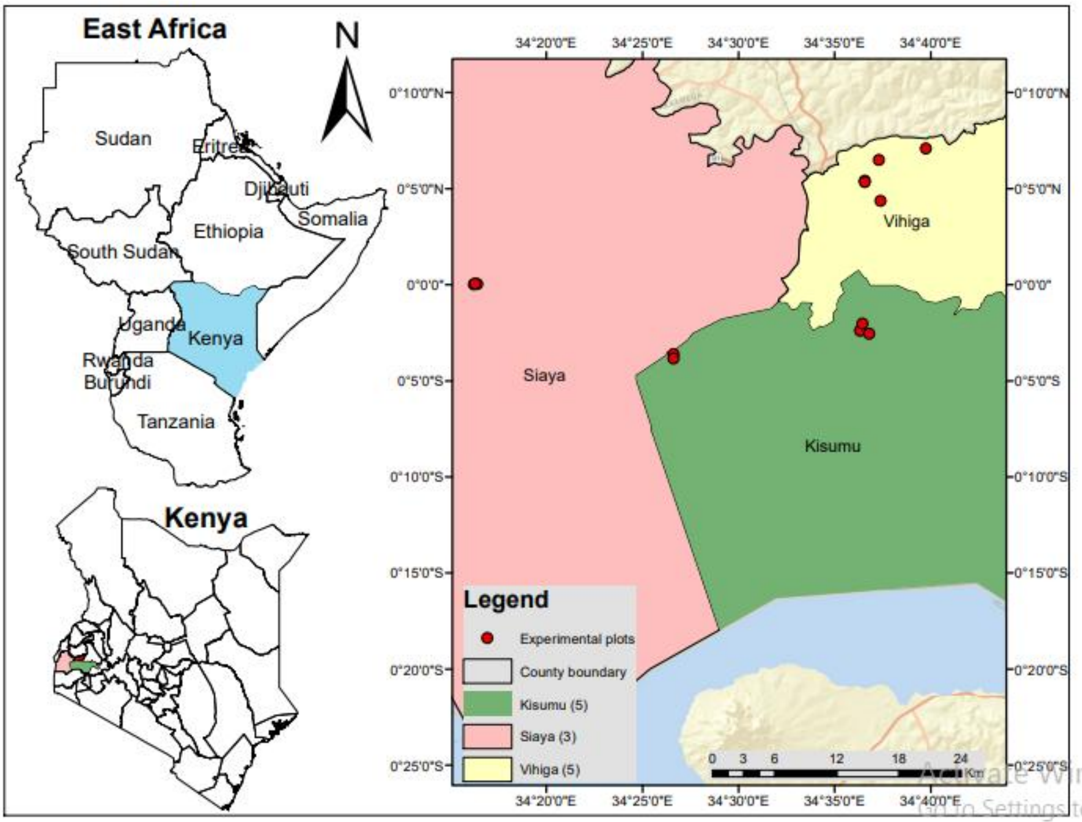

Figure 5.1: Location of Test-Fields in Kisumu, Siaya, Vihiga Counties in Western Kenya

5.2.2 Experimental Design

A randomized complete block design comprising four treatments: (1) typical push-pull, (2) push-pull with *C. cajan* (pigeon pea), (3) maize and pigeon pea, and (4) maize monocrop were established. Improved maize variety recommended for the region was planted in all treatments across the seasons: 2021 short rain (season 1SR), 2022 long rain (season 2LR), 2022 short rain (season 3SR), and 2023 long rain (season 4LR). The long-duration pigeon pea (MBAAZI II) was planted during the short rain seasons, initially in August 2021 and September 2022. This is because pigeon pea grows initially slowly as an intercrop, minimizing competition with the maize crop, and only grows rapidly after harvest as a sole crop.

In this study, pigeon pea was maintained as a crop cover during the dry season and was harvested during the long rain season. The experiment was carried out for four seasons. Maize was planted out at onset of the rains for 4 seasons (2021 Short rain season, 2022 short and long rain seasons, 2023 long rain season). During the short rain season, planting of maize and pigeon pea was carried out from mid-August (Kisumu and Vihiga) to early September (Siaya), and during the long rain seasons, mid-March (Kisumu and Vihiga) and early April in Siaya. (Table 5.1).

Table 5.1: Site, Season and Planting Time for Maize and Pigeon Pea Crops during the Study Period

Site county	Season	Planting time for maize	Planting time for pigeon pea
Kisumu	2021 SR/2022SR	Mid-August	Mid-August
Kisumu	2022 LR/2023LR	Mid-March	
Siaya	2021 SR/2022SR	Early September	Early September
Siaya	2022 LR/2023LR	Early April	
Vihiga	2021 SR/2022SR	Mid-August	Mid-August
Vihiga	2022 LR/2023LR	Mid-March	

5.2.3 Selection of Farms for the Establishment of Experimental Trials

Participatory approach involving FGD (9 groups of farmers and 1 group of field technicians), interviews with key informants (n=25) and validation of the results with the farmers (n=99) was carried out to determine suitable intensification practices for integration in push-pull in Kisumu, Siaya and Vihiga before the establishment of experimental fields. In this participatory research, respondents highlighted their aspirations, such as the need for further intensification of the push-pull system to diversify their productivity and meet requirements for firewood, fodder and food.

Pigeon pea emerged as the most suitable crop for further intensification in push-pull system to meet the three needs (Chapter three). Farms were visited to verify their suitability for inclusion in the study based on selection criteria which entailed; farmer practice of cereal production ii) the farmer reported or farm was observed to have history of striga, stemborer and fall armyworm, iii) size of farm was 1 ha or smaller, iv) farm was accessible v) the farmer was willing to have the experiment on their farm, vi) strategically positioned for demonstration were selected for field experiments.

A total of 15 plots were established on 25 farms (10 in Kisumu, 7 in Siaya and 8 in Vihiga) to test the effectiveness of the intensified system on pest management. The varying number of plots was because some farms were small and could not accommodate all four treatments. On each farm, a selected field was used as a single plot or divided into two or more plots, approximately 200 square meters in size per treatment. The push-pull farms were established by intercropping maize and desmodium and planting Brachiaria or Napier along the borders (Ndayisaba et al., 2020). For push-pull + pigeon pea, the pigeon pea was grown between maize and desmodium, for maize and pigeon pea they were intercropped with 75cm between rows and maize monocrop was spaced at 30 by 75 cm intra and inter row. Where the farm accommodated two or more treatments, a 2 m path was left between the treatments to act as a buffer. The distance between treatments located on different farms was limited to 500 m to minimize variations in microclimate, soil characteristics and social attributes.

5.2.4 Agronomic Management

At planting, on average, 10 tons/ha of manure and 60 kg/ha of inorganic fertilizers were applied during planting. These rates represent the quantities commonly used by farmers in the region, although the recommended rates vary depending on the type of fertilizer. Diammonium phosphate (DAP) was applied at a rate of 60 kg/ha in seasons 1 and 2, NPK compound fertilizer was applied at the same rate in seasons 3 and 4 while CAN (at 60 kg/ha equivalent to 27 kg N, 12 kg P and 4.8 kg Ca ha^{-1}) was applied at top dressing when the maize crop was knee length usually 6 weeks post planting. In the 3rd and 4th seasons, compound fertilizers (NPK) were applied instead of DAP due to the noted high acidity in the soils within the plots after soil sampling and nutrient analysis were conducted. Manure was, however, not used while planting pigeon peas. Two maize seeds were planted at 30 cm between plants and 75 cm between rows; 4 to 5 pigeon pea seeds were planted at 45 cm between plants and 75 cm between rows per hole and later thinned to 1 seedling at 3 weeks. Weeding was done once at 6 weeks manually.

5.2.5 Monitoring Striga, Stem Borer, Fall Armyworm and Natural Enemies

A 2 × 2 m subplot was randomly selected within the main experimental plot for data collection on the occurrence of pests, weeds, and natural enemies, avoiding the border crops. The number of emerged striga was counted from a radius of 12 cm around the base of each maize plant (Midega et al., 2017). Striga vigor was determined by measuring the striga height for 3 randomly selected striga plants. The data was expressed as the mean number of emerged striga per plant by dividing the total striga population by the total number of maize plants. The striga number obtained was used to estimate the number of striga per square meter by counting those within a 12 cm radius. Stem borer and fall armyworm effect were determined by observing maize plants non-destructively. Maize plants within the same subplot were examined for symptoms of stemborer and fall armyworm infestation on young leaves, leaf whorls and tassels. Symptoms of plants infected by stem borer include; small holes in straight lines on the youngest leaves; young plants show small holes and 'window-panes' in the leaf whorls where tissues have been eaten away (Midega et al., 2018b).

Older caterpillars tunnel in stems and eat out long frass-filled galleries, weakening stems and causing breakages (Midega et al., 2018b). The initial fall armyworm infestation was estimated as a percentage of plant damage. The number of leaves infested with fall armyworm or stem borer was noted for the two other seasons (Appendix III: Plate 1.5). Natural enemies of the stemborer (mainly predatory ants, parasitic wasps, and parasitic flies) and the fall armyworm (earwigs and beetles) were identified using two approaches. A trap was installed in the farm at two strategic positions, avoiding the borders. The traps were removed after a week and examined for the presence or absence of the main natural enemies including (ants, earwigs and beetles). In addition, a sweep net was used two meters in both directions across the plot. A manual collection of crawling insects within the plot marked for data collection was also carried out (Appendix III, Plate.1.6).

5.3 Data Analysis

Data were cleaned and standardized by checking the outliers and missing values. They were checked for normality using Shapiro-Wilk test. T-tests were carried out to determine the difference in performance of the intensified system in the two treatments with pigeon pea (push-pull + pigeon pea and maize + pigeon pea), because only two treatments had pigeon pea in place. Linear models were done for ANOVA to determine the effect of site, treatment and season on growth and their interaction effects. Means were separated using Tukey's HSD test to assess treatment effects on the different parameters. Analysis was carried out in R statistical software version 3.2.2. In all cases the p value was tested at $p \leq 0.05$ level of significance.

5.4 Results

5.4.1 Effect of Site and Treatment on Striga Weed Density and Striga Vigor

Integration of pigeon pea significantly reduced striga population and vigour compared with the other cropping systems ($p < 0.05$). The magnitude of this effect varied significantly across sites and seasons, as indicated by significant site × treatment × season interactions. Significant interactions were observed among site, treatment, and season (Figure 5.2). Across treatments maize monocrop significantly had the highest mean striga number per plant (3.44), while maize + pigeon pea had the lowest mean striga number per plant (1.87). Push-pull and push-pull + pigeon pea had 2.28 and 2.13 mean striga number per plant respectively (Figure 5.2). Kisumu had the highest striga number while Siaya had the least. The mean Striga density was highest in Kisumu (3.51), followed by Siaya (2.02) and Vihiga (1.07) (Figure 5.3).

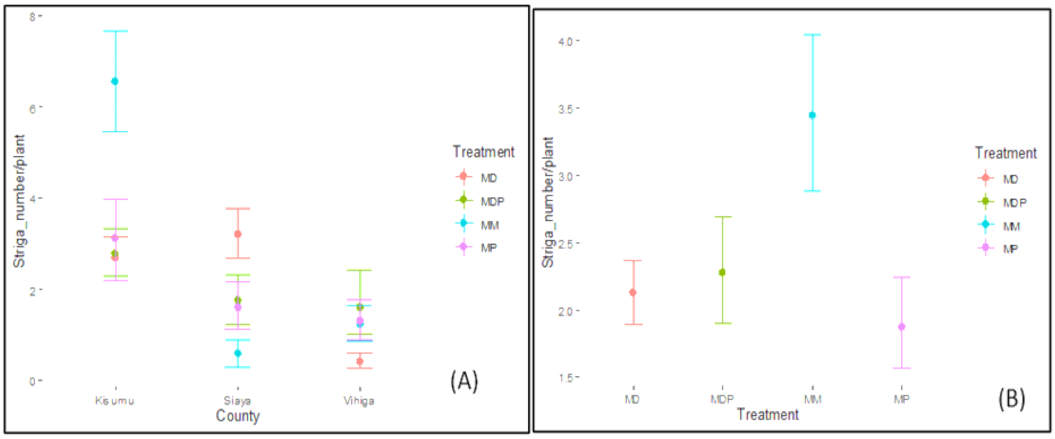

Figure 5.2: Site (A) and Treatment (B) Interaction Effect on Mean Striga Number per Plant. Treatment Abbreviations: MD = Push–Pull; MDP = Push–Pull + Pigeon Pea; MM = Maize Monocrop; MP = Maize + Pigeon Pea.

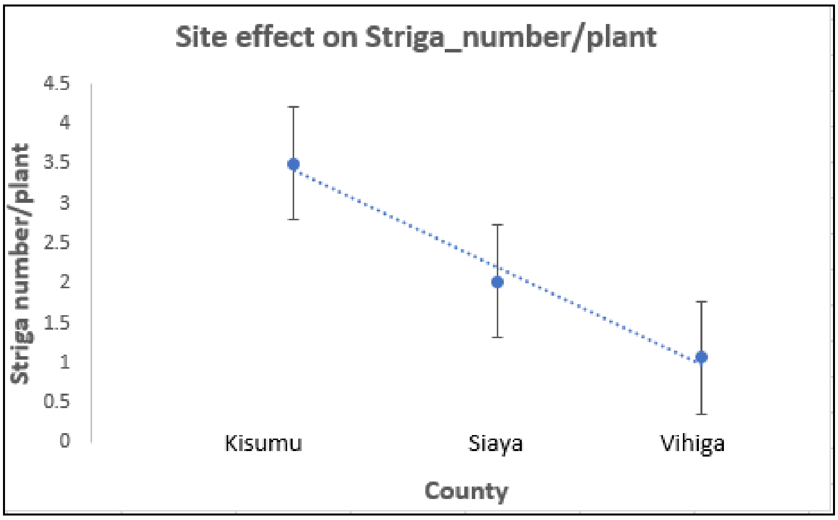

Figure 5.3: Effect of Site on Striga Density, Based on Average Number of Striga per Plant in 12 cm Radius

5.4.2 Interaction Effects of Site, Treatment and Season on Striga Density and Vigor

Significant differences were noted across treatments in the three sites and across the seasons. A significant interaction was observed between site and treatment, and season and treatment for striga number and striga vigor in cm (Table 5.2). There was a negative correlation between the height of maize crop and the number of striga plants. Striga numbers per plant were also significantly different across sites and treatments. The strongest negative correlation between the height in maize crop and striga number was recorded in Kisumu, followed by Siaya and Vihiga respectively (R^2=0.45).

Table 5.2: Interaction Effect of Treatment, Site and Season on Striga Density and Vigor

	Striga number				**Striga vigor**			
	df	**sumsq**	**Fvalue**	**p value**	**df**	**sumsq**	**Fvalue**	**pvalue**
Treatment	3	661	220.2	P< 0.05	3	1732	577	P<0.05
County	2	2705	1352.4	P< 0.05	2	17739	8869	P<0.05
Season	3	2876	958.8	P< 0.05	3	32571	16285	P<0.05
Treatment: County	6	1737	289.6	P< 0.05	6	1758	293	P<0.05
Treatment: Season	9	2498	277.5	P< 0.05	9	3142	524	P<0.05
Treatment: County×Season	22	3673	167.0	P< 0.05	12	2133	178	P<0.05

In all treatments, the mean population of striga per square meter in Kisumu was double or more than double that of Vihiga. For push-pull system, Siaya had the highest striga number compared to Kisumu and Vihiga. Maize + pigeon pea had the lowest striga number per square meter in Vihiga (Table 5.3). The highest striga was recorded in maize monocrop in Kisumu, lowest striga number was recorded maize + pigeon pea in Vihiga.

Table 5.3: Treatment Effect on the Population of Striga per Maize Plant and per Square Meter in Kisumu, Siaya and Vihiga

County	Push-pull	Push-pull+ pigeon pea	Maize monocrop	Maize + pigeon pea	Push-pull	Push-pull+ pigeon pea	Maize monocrop	Maize + pigeon pea
	Striga number per plant				Striga number per sqm			
Kisumu	2.37^{b}	2.38^{b}	6.64^{a}	3.1^{b}	52.14^{b}	52.36^{b}	146.08^{a}	68.2^{b}
Siaya	3.19^{a}	1.74^{b}	0.59^{c}	1.6^{b}	70.18^{a}	38.28^{b}	12.98^{c}	35.2^{b}
Vihiga	1.42^{b}	1.11^{b}	1.23^{b}	0.6^{c}	31.24^{a}	24.42^{a}	27.06^{a}	13.2^{b}

Letters represent significant levels. Numbers with different letters compared horizontally (across treatments) are significantly different at p ≤0.05.

In season 1, the striga numbers were not different across treatments, though maize monocrop had the highest. In season 2LR and season 4SR, maize monocrop had significantly high striga number per plant and per square meter striga incidence compared to the rest. For push-pull + pigeon pea and maize + pigeon pea striga number reduced consistently except for season 3SR (Table 5.4). Season 1SR (2021), season 2 and season 3 represent long and short rain seasons on 2022, season 4 represents long rains season of 2023. A negative correlation was observed between striga number per plant and height, this effect was more evident in maize monocrop. The highest striga vigor was observed in Kisumu and lowest in Vihiga, across treatments striga vigor did not differ significantly p=0.05 (Figure 5.4).

Table 5.4: Seasonal*Treatment Interactive Effect on Population of Striga per Maize Plant and Treatment

Season	Push-pull	Push-pull + pigeon pea	Maize monocrop	Maize + pigeon pea	Push-pull	Push-pull + pigeon pea	Maize monocrop	Maize + pigeon pea
	Striga number per plant				Striga number per sqm			
Season1SR	2.46^{a}	2.96^{a}	3.77^{a}	3.31^{a}	54.12^{a}	65.12^{a}	82.94^{a}	72.82^{a}
Season2LR	1.72^{bc}	2.61^{b}	6.09^{a}	1.01^{c}	37.84^{bc}	57.42^{b}	133.98^{a}	22.22^{c}
Season3SR	8.43^{a}	3.2^{b}	3.29^{b}	3.29^{b}	185.46^{a}	70.4^{b}	72.38^{b}	72.38^{b}
Season4LR	0.47^{a}	0.008^{b}	0.388^{a}	0.038^{b}	10.34^{a}	0.176^{b}	8.536^{a}	0.836^{b}

Letters represent significant levels. Numbers with different letters across the table (across seasons) are significantly different at p=0.05

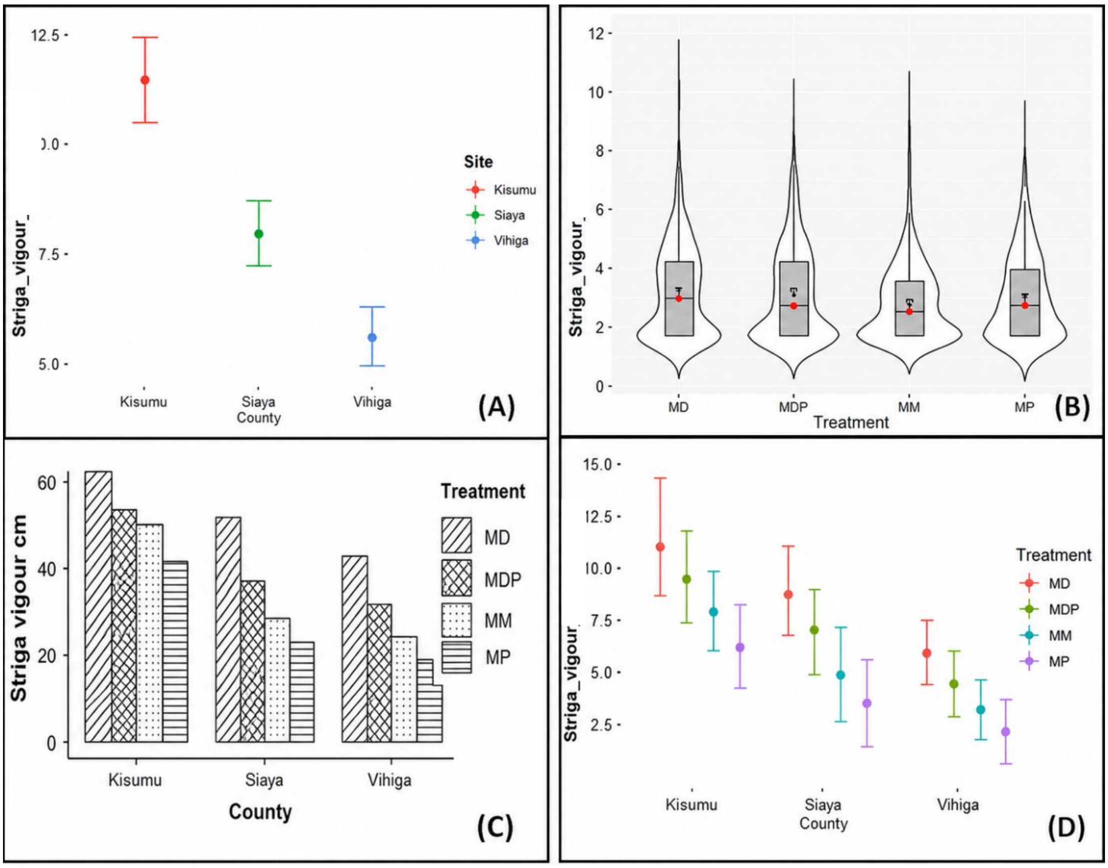

Figure 5.4: Effect of Site (A) and Treatment (B) on Striga Vigour (cm), Site and Treatment Interaction Effect on Striga Vigour Based on Striga Height in cm (C and D). Treatment Abbreviations: MD = Push–Pull; MDP = Push–Pull + Pigeon Pea; MM = Maize Monocrop; MP = Maize + Pigeon Pea.

5.4.3 Site and Treatment Effect on Fall Armyworm, Stemborer, and Natural Enemies

The number of fall armyworm-infected plants did not significantly differ across treatments, but treatment effects differed across sites. Vihiga had the highest infestation, while Siaya had the least infestation at $p<0.05$ (Figure 5.5). The number of plants infected was lowest in push-pull though not significantly different from those in maize monocrop, which had the highest number of infected plants in Kisumu. Push-pull + pigeon pea had the lowest number of plants infected by the fall armyworm in Kisumu and Siaya, though it was only significantly different from maize and pigeon pea in Kisumu (Figure 5.5). Seasonal effect on treatment was observed for fall armyworm density. The fall armyworm density per plant was lowest in season 1SR and season 4LR for the maize and pigeon pea intercrop. In Vihiga, the fall armyworm effect was lowest in maize + pigeon pea (Figure 5.7).

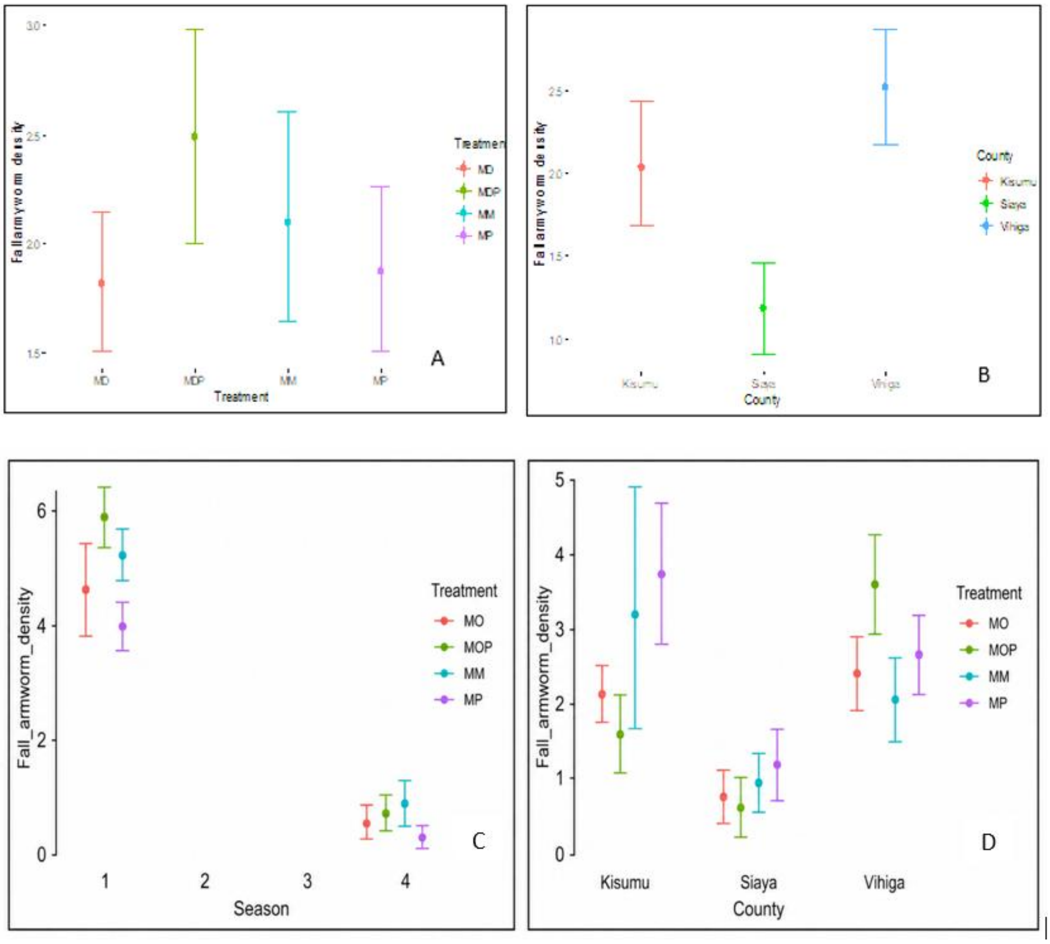

Figure 5.5: Treatment (A) and Site (B) Effect on Fall Armyworm Density, Season (C) and Site (D) Interaction Effect on Fall armyworm density. Treatment Abbreviations: MD = Push–Pull; MDP = Push–Pull + Pigeon Pea; MM = Maize Monocrop; MP = Maize + Pigeon Pea.

Stemborer density did not differ across treatments, but there were differences across sites (Figure 5.6 A) significantly (p=0.05) but not treatment (Figure 5.6 B); Siaya had significantly lower stemborer density compared to Kisumu and Vihiga. In Kisumu the stem borer density was significantly higher in maize monocrop compared to push-pull. However no significant differences were observed among treatments in Siaya and Vihiga. Stemborer density reduced for push-pull and push-pull+ pigeon pea from season 3SR to season 4LR.

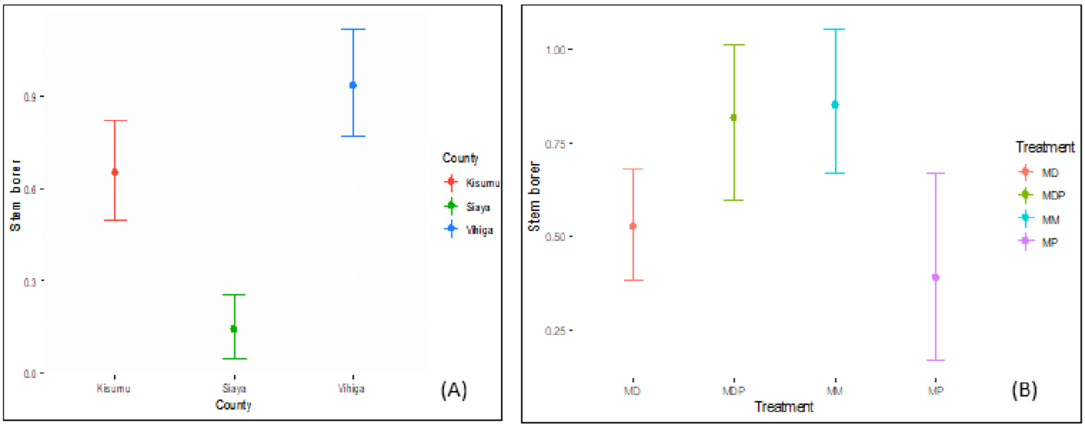

Figure 5.6: Stem Borer Density per Plant across Site (A) and Treatment (B). Treatment Abbreviations: MD = Push–Pull; MDP = Push–Pull + Pigeon Pea; MM = Maize Monocrop; MP = Maize + Pigeon Pea

Natural enemies differed significantly among treatments (Figure 5.7 (A). Treatment and site interaction significantly affected the mean number of natural enemies' species. Across sites (B). Maize monocrop had lower abundance of species of natural enemies (Figure 5.7 B). During sampling other species which were not identified were also noted. The results showed the total number of other species noted was highest in pigeon pea and push-pull + pigeon pea (Table 5.5).

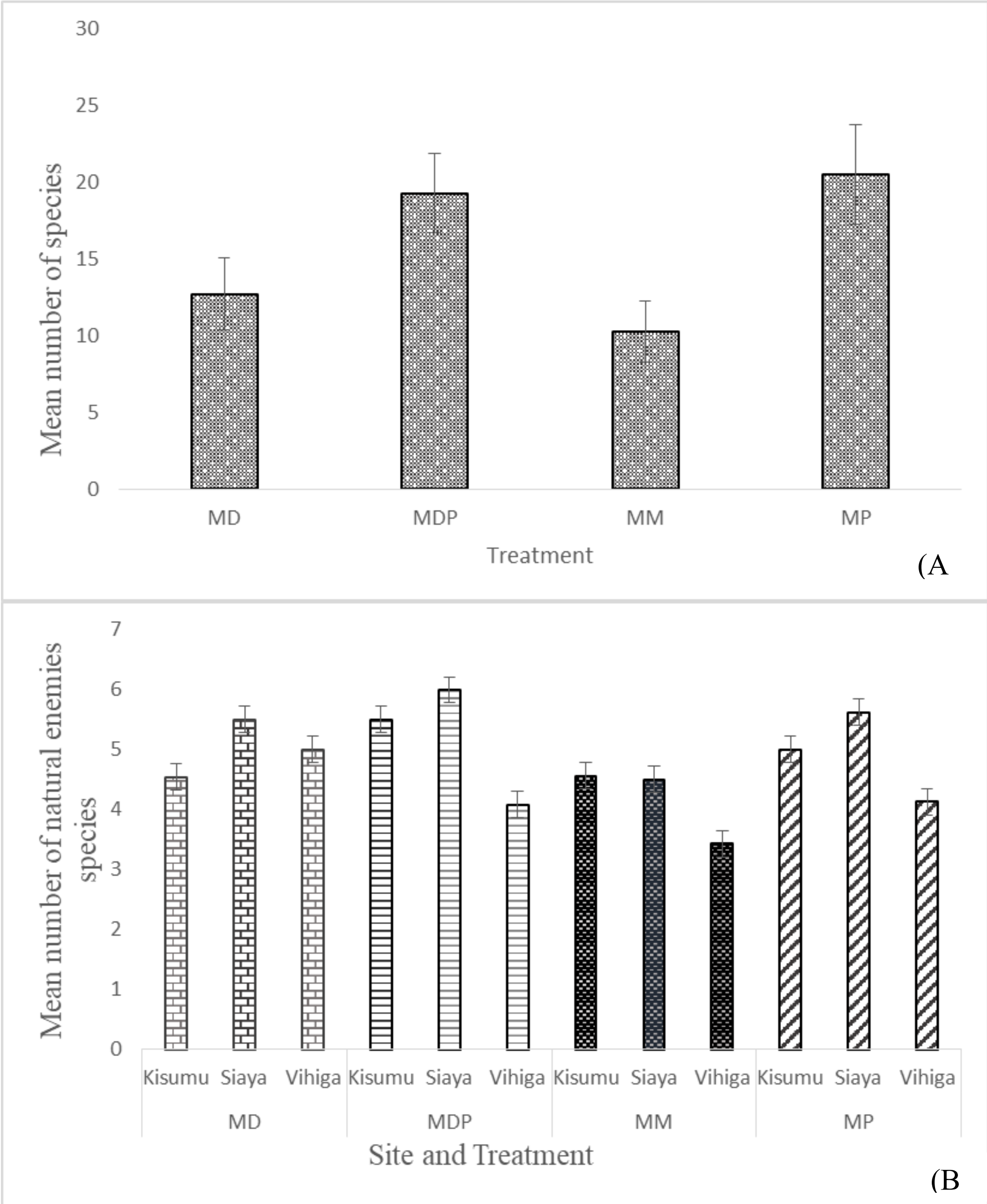

Figure 5.7: Mean Number of Species of Natural Enemies Per Treatment (A) and Site (B). Treatment Abbreviations: MD = Push–Pull; MDP = Push–Pull + Pigeon Pea; MM = Maize Monocrop; MP = Maize + Pigeon Pea

Table 5.5: Specific Number of Natural Enemies Distribution Assessed Per Site and Treatment

Treatment and Site	Flies	Others	Asian_ Beetle	ladybird beetle	Earwig	Moths	Net-winged beetle
Push-pull	67[b]	395[b]	28[b]	6[a]	4[a]	4[a]	**3[b]**
Kisumu	26	128	16	4	1	3	2
Siaya	24	129	9	1	1	1	1
Vihiga	17	138	3	1	2	0	0
Push-pull + pigeon pea	99[a]	618[a]	46[a]	0[c]	0[b]	3[a]	**15[a]**
Kisumu	38	165	31	0	0	3	5
Siaya	33	243	12	0	0	0	7
Vihiga	28	210	3	0	0	0	3
Maize monocrop	67[b]	278[c]	18[c]	2[b]	1[b]	4[a]	1[b]
Kisumu	31	152	14	2	1	3	1
Siaya	19	98	4	0	0	1	0
Vihiga	17	28	0	0	0	0	0
Maize + pigeon pea	63[b]	493[b]	15[c]	4[a]	1[b]	**3[a]**	**6[b]**
Kisumu	21	101	3	3	0	0	0
Siaya	34	236	11	1	0	2	5
Vihiga	8	156	1	0	1	1	1

Push-pull + pigeon pea had the highest natural enemies abundance compared to other treatments

5.5 Discussion

Integration of pigeon pea resulted in significant reduction of striga number per plant. Intensification via intercropping maize and pigeon pea significantly reduced striga density, suggesting that pigeon pea integration can contribute to striga suppression in maize-based systems. The striga number was much lower than in maize monocrop which had the highest striga weed density. Intercropping for pest and weed suppression is a common practice in smallholder farming systems (Silberg et al., 2020). Studies on cereal–legume intercropping as a strategy for managing striga weed have examined several legumes, including desmodium, cowpea, groundnut, and crotalaria. Among these, desmodium was found to be the most effective in reducing striga density in maize and sorghum systems. (Ndayisaba et al., 2020).

Contrastingly, in this study, maize and pigeon pea intercrop performed better than maize and desmodium intercrops. The results agree with (Makete et al., 2018) who showed that intercropping desmodium with cereals such as millet did not result in striga weed suppression. Tariq et al., (2019) noted decreased availability of light for weed growth, trap crops effect, suicidal striga germination and manipulation of microclimate as pathways for efficiency of intercropping in weed suppression. This is the first study in Kenya to demonstrate the reduced effect of striga number because of pigeon pea integration.

Highest striga density as a result of further intensification were observed in Kisumu compared with Siaya and Vihiga. Site differences may be attributed to the favorable environmental conditions for striga growth and development in the regions. Previous studies have shown that striga infestation increases at elevation of 1000 -1400 m, precipitation range of 1500 –2000 mm, and soil organic content between 3 and 5 g/kg (Kimathi et al., 2023). The same research also showed that temperature disparities and unpredictable rainfall patterns in Siaya county significantly affect the occurrence of striga (Kimathi et al., 2023). The current elevation and precipitation status for the 3 counties is: Vihiga, elevation 1300 - 1900 m, and precipitation, 1200 and 2763 mm, Kisumu elevation of 1134 - 1400 m and 1000 and 1800 mm, Siaya elevation of

1200 - 1500 m and precipitation of 1000 - 1250 mm, some parts are 1750 mm. This predisposes the counties to striga infestation.

Kisumu, Siaya and Vihiga counties are at risk of striga infestation expanding because of their current climatic and soil status. This creates the urgency for more integrated, resilient, and region-specific control strategies (Kimathi et al., 2023). To consistently, mitigate effects of striga on maize growth and yield, requires multifaceted interventions across different sites and seasons. (Kamara et al., 2020). Research has shown that the best option for reducing the impact of striga on households is applying integrated approaches which entail the use of improved varieties, good agronomic practices, biological control and intercropping (Sibhatu, 2016).

Integration of legumes influenced striga density during the different seasons. Striga population in maize monocrop was highest in three out of the four seasons assessed. Contrastingly, maize monocrop was not significantly different from the 3rd generation push-pull during long rain seasons (Cheruiyot et al., 2021). In the current study, striga number was lowest in season 4 (long rain season in 2023) compared to the rest. The reduction in striga number can be attributed to the enhanced effectiveness of the further intensified system over the seasons. A previous study (Makete et al., 2018) showed that Striga density was highest during short rains compared to long rain seasons. The results are similar to our study showing that the striga population density was higher in season 3 SR and least in season 4 LR which is long rain season. During the long rain season the plants are more competitive while during the short rain the drought stress may make the plants vulnerable to weed stress including striga. Interaction effects for striga among site, season, and treatment have been reported when comparing climate-smart push-pull, 3rd-generation push-pull, and maize monocrop in Bondo, Siaya County (Cheruiyot et al., 2021). Generally, striga effects on growth of maize can potentially suppress yield.

Differences in the number of plants affected by fall armyworm and stem borer were observed across treatments in the different sites. The maize monocrop was more affected than the intercrops; though the differences were insignificant. Similar results of maize monocrop recording higher infestation of stemborer and fall armyworm have been reported (Chidawanyika et al., 2014; Hailu et al., 2018). One of the challenges of push-pull systems is that it takes a long time for the benefits to be realized, including pest management. This could explain the lack of significant differences between plots with push-pull and monocrop. Contrastingly, effective cereal pest management has been reported in maize and legume intercrops; mostly as a result of herbivores reduction and boosting of predator and parasitoid abundance (Yousefi et al., 2024).

During this study, it was noted that the management of fall armyworms within farming systems requires a communal initiative whereby all neighboring farmers work together to minimize high reinfection rates. Climate-smart push-pull has been reported to significantly reduce fall armyworm compared to monocrop systems, even though the specific mechanism for its management has not been extensively studied (Midega et al., 2018a). To do this sustainably, all local farmers would need to plant simultaneously to eliminate potential hosts due to late planting. Applying the different intercropping strategies should also focus on collective community action. Differences in infestation across sites and seasons result from the different agroecological characteristics. As such, fall armyworm and stemborer infestations were highest in Vihiga and lowest in Siaya.

Natural enemy abundance was significantly lower in the maize monocrop compared to push-pull + pigeon pea. This suggests that integration of pigeon pea into push-pull system enhances conservation of biodiversity in intercrops as well as in other crop combinations. The more the diversity in crop combinations, the higher the rate of occurrence of natural enemies. Enhancement of fall armyworm natural enemies in maize - legume intercrops has been reported in another study (earwigs) (Soujanya et al., 2024). Abundance of natural enemies in smallholder farming systems has been on the decline though as a result of pesticides application. Currently, most of the farming systems apply pesticides for the management of major pests, especially fall armyworms, which do not have a one-fix it all strategy (Midega et al., 2018a). The effects of pesticides on human health cannot be undermined; hence, prompting the uptake of agroecological methods such as the integration of push-pull and pigeon peas in farming systems. To curb the problem of predisposition of farmers to health-related risks and the potential risk of non-target organisms by synthetic pesticide application (Matova et al., 2020), farmers can explore alternative intensification pathways, such as the ones in this study, pigeon pea integration with maize and within push-pull technology.

The findings of this study showed that integrating pigeon pea into push-pull systems did not reduce its effectiveness in stemborer, fall armyworm or striga weed management. On the contrary, the pest management component was enhanced, and the abundance of natural enemies also increased during the study period. Implementation of push-pull systems results in higher abundance and richness of predator populations, as well as an increased rate of parasitism (Da Silva et al., 2022); in our case, the results were similar, though not significantly different, for some of the organisms. Push-pull has been reported to effectively manage stem borer in maize farming systems (Chidawanyika et al., 2014; Hailu et al., 2018). The occurrence of natural enemies in the current study varied across treatments in the three sites with different agroecological conditions. Yousefi et al., (2024) describe that spatial management scale and ecological characteristics of arthropods determine the response of arthropod abundance to plant diversification. Knowledge of enhanced natural enemies due to intensification is important for designing and implementing biological control systems in smallholder farming systems.

5.6 Conclusions

- Integrating pigeon pea into push-pull and maize cropping systems contributed to striga suppression.
- Integration of pigeon pea into push-pull system and in maize cropping systems, reduced stem borer, fall armyworm density, and enhanced natural enemies’ occurrence.

5.7 Recommendations

- The study recommends integration of pigeon pea into farming systems as one of the options for further intensification of push-pull and maize cropping systems in Kisumu, Siaya, and Vihiga counties to manage striga, stem borer, and fall armyworm, and enhance natural enemies' abundance.

CHAPTER SIX

EFFECT OF SUSTAINABLE INTENSIFICATION OF PUSH-PULL SYSTEM WITH PIGEON PEA ON THE PRODUCTIVITY OF SMALLHOLDER FARMING SYSTEMS

6.1 Introduction

Ending hunger and achieving food and nutritional security is one of the key sustainable development goals that is pressing in low-income countries. There has been an increase in fixing and customizing food systems to meet all the nutritional needs in the food ecosystems. In Africa, there are large numbers of resource-poor smallholder farmers that produce on small portions of lands with low soil fertility. The low soil fertility in many parts of Africa is results from an overexploitation for many generations, and extractive agriculture (Nair, 2023). It is generally accepted that long-term nutrient depletion caused by continuous cultivation, inadequate nutrient replenishment, soil erosion, low organic matter inputs, unsustainable land management practices are the causes of low soil fertility in many parts of Africa.

Smallholder farmers with limited resources end up in cycles of poverty because of low yields stemming from degraded soils. The low production levels in terms of land size, poor yields, and no or low income from the efforts, traps farmers in agricultural poverty. To meet the needs of the rapidly growing population, there is an urgent call to transform these farming systems to be productive, profitable and resilient. It is required that the technologies used to increase productivity on smallholder farms be sustainable and adaptable to local conditions. This is because of the heterogeneity of smallholder systems in Africa. A study in western Kenya showed that farms vary greatly in terms of the crops and cropping systems, farmer's needs, aspirations and support systems (Buleti et al., 2023).

Smallholder farms are mostly intensively managed. The most common practices that have been used to intensify smallholder farming systems in Africa include intercropping, livestock integration, crop rotation, use of fertilizers, use of organic manure, agroforestry and push-pull system (Kuyah et al., 2021; Petersen & Snapp, 2015). Much of these practices are applied in isolation. Yet, most of the farms where these technologies are applied still cite food, fodder and firewood as some of the pressing needs (Buleti et al., 2023; Kuyah et al., 2019). For example, cereal-legume intercropping is the most common farming practice in western Kenya, and the most preferred pathway for sustainable intensification. However, the productivity of this system continues to decline because of low soil fertility, pests and climate variability. Combining intensification practices can create synergies that enhance ecological functions, improve productivity, and mitigate the negative environmental impacts of intensification (Jabbar et al., 2020). It remains unclear how such combinations of intensification pathways might affect the productivity of smallholder farms.

Push-pull technology is an intensive system comprising desmodium and Brachiaria or Napier grass. Desmodium acts as push crop while Brachiaria or Napier grass act as a trap crop. Push-pull system has been successfully applied in reduction of cereal pests, improvement of soil health, increased grain yield and biomass, while providing fodder for livestock (Cheruiyot et al., 2020; Midega et al., 2018b; Ndayisaba et al., 2021). These benefits, notwithstanding, adoption of the technology in the region has been low. This is because it is restricted to cereal systems and push-pull products are not edible. These limitations necessitate further intensification of push-pull system through intercropping and agroforestry to make it scalable, adaptable and increase its ability to meet specific farmers' needs.

Several attempts have been carried out to improve the functionality of push-pull system. The 1st generation push-pull structure which entailed (Napier grass and silver leaf desmodium) were replaced by Brachiaria and *D. uncinatum* respectively. This is because they are resilient to climate shocks (Cheruiyot et al., 2020). Efforts to make push-pull adaptable have previously focused on push-and-pull crops and less on companion food crops. The only research on inclusion of other crops (edible beans) in push-pull system showed the potential of legumes to enhance effectiveness of the technology on pest and weed management though labor was increased (Khan et al., 2009). Focus group discussions and interviews with key informants in Kisumu, Siaya and Vihiga highlighted the need to further intensify the push-pull system, specifically for food diversity, fodder and fuelwood enhancement. Vegetables, legumes and tubers were among the proposed options of crops for integration. For the legumes proposed, pigeon pea was the most suitable candidate crop that met a combination of diversified diets, fuelwood, and fodder needs. The effect on performance of the push-pull system when further intensified with pigeon pea remains unknown.

In Kenya, pigeon pea is a perennial legume managed as an annual or short-lived perennial. It is integrated into farming systems as an intercrop, ratoon and crop rotation, with cereals or through sole cultivation, mainly in arid and semi-arid areas of Kenya. Pigeon pea is cultivated to improve yield and soil health, enhance food and nutrition security and as a source of biomass, fuelwood, fodder and resilience of farming systems. Integration of legumes in cropping systems commonly targets improve soil fertility, management of pests of intercrops and also increase crop yield relative to monocrops (Kermah et al., 2017; Midega et al., 2014; Renwick et al., 2020). Less focus is put on potential of legumes to increase soil carbon sequestration which is a climate resilience attribute (Musokwa et al., 2020). The effects of climate change such as extended droughts are already being experienced in western Kenya, hence the need to integrate crops which are potentially a shield to climate shock as part of the already existing farming systems. The aim of this study was to test the effectiveness of push-pull intensified with pigeon pea–on crop growth, yield and productivity.

6.2 Materials and Methods

6.2.1 Selection of Farms and Test Crops, Establishment of Treatments and Agronomic Practices

A total of 15 test-fields were established on 25 farms (10 in Kisumu, 7 in Siaya and 8 in Vihiga) to test the effectiveness of the intensified system (Figure.5.2.1). The varying number of test-fields is because some farms were small and could not accommodate all the treatments. On each farm a selected field was used as a single plot or divided into two or more plots approximately 200 square meters per treatment. Where the farm accommodated two or more treatments, a 2 m path was left to act as a buffer. The distance between treatments located on different farms was limited to 1 km to minimize variations in microclimate, soil characteristics and social attributes.

The push-pull farms were established by intercropping maize and desmodium and planting Brachiaria or Napier along the borders (Ndayisaba et al., 2020). For push-pull + pigeon pea, the pigeon pea was grown between maize and desmodium, maize and pigeon pea were intercropped with 75cm between rows and maize monocrop was spaced at 30 by 75 cm intra and inter row. Where the farm accommodated two or more treatments, a 2 m path was left between the treatments to act as a buffer. The distance between treatments located on different farms was limited to 1 km to minimize variations in microclimate, soil characteristics and social attributes.

At planting, on average, 10 tons/ha of manure and 60 kg/ha of inorganic fertilizers were applied. These rates represent the quantities commonly used by farmers in the region, although the recommended rates vary depending on the type of fertilizer. Diammonium phosphate (DAP) was applied at a rate of 60 kg/ha in seasons 1 and 2, NPK compound fertilizer was applied at the same rate in seasons 3 and 4 while CAN (at 60 kg/ha equivalent to 27 kg N, 12 kg P and 4.8 kg Ca ha^{-1}) was applied at top dressing when the maize crop was knee length usually 6 weeks post planting. In the 3rd and 4th seasons, compound fertilizer (NPK) was applied instead of DAP due to the noted acidity in the soils within the plots after soil sampling and nutrient analysis had been conducted. Manure and fertilizer were, however, not used while planting pigeon peas. Two maize seeds were planted at 30 cm between plants and 75 cm between rows; 4 to 5 pigeon pea seeds were planted at 45 cm between plants and 75 cm between rows per hole and later thinned to 1 seedling at 3 weeks. Weeding was done once at 6 weeks manually.

6.2.2 Monitoring Growth and Productivity

A 2 m x 2 m sub plot was randomly selected within the main experimental plot avoiding the border crops and used for data collection. Plant height, leaf length, leaf width of fully expanded leaves of the same plant were measured for monitoring growth. These were used as indicators of growth for maize plants. Crop yields and biomass were quantified as indicators of productivity. Number of maize plants within the plot were counted, and the height of each maize and pigeon pea measured from the base of the plant to the tip of the plant using a 1 m ruler. The lengths and the widths (the widest part) of fully expanded leaves were measured for the same plants. Pigeon pea circumference was measured (at 10 cm above ground) twice during the season (indicated as height 1 and height 2) at two developmental stages.

At maturity, all the maize plants in the sub plot were harvested from the plot and separated into cobs, and stover and their fresh weight determined using a weighing scale. Three stovers were randomly picked, chopped, mixed, and an approximately 250 g sample was collected into khaki bags. The fresh weights of the stover sample were determined using a top-pan balance. Ten cobs were selected per sub-plot and weighed. Brachiaria and desmodium were harvested within 1 m x 1 m quadrat and total fresh weight determined. These and stover were chopped, mixed and 250 grams sample collected into khaki bags. In cases where the sample was less than 250 grams all the available sample was collected. The samples were transported to JKUAT where they were dried in an oven in the Sino-Africa Joint Research Centre (SAJOREC) biodiversity laboratory at 70°. The dry weight of the samples (10 maize cobs, empty cob weight, threshed grain weight, stovers samples and 100 seed weight) was determined in the laboratory after oven drying to a constant weight at 70° C. The ratio of the dry weight-to-fresh weight was multiplied by the total fresh weight of the biomass of the maize stover and pigeon pea. Grain and stover yield was determined using the formula by Ndayisaba et al., (2020).

$$Grain\ Yield = Cob\ FW * \frac{Cob\ Sample\ DW\ with\ grain}{Cob\ Sample\ FW\ with\ grain} * \frac{Cob\ sample\ grain\ weight\ after\ threshing}{Cob\ sample\ grain\ weight\ before\ threshing} * \frac{10000m^2}{4m^2}$$

Equation 6

$$Stover\ yield = Stover\ FW\ per\ plot * \frac{Stover\ Sample\ DW\ with\ grain}{Stover\ Sample\ FW\ with\ grain} * \frac{10000m^2}{4m^2}$$ *Equation 7*

Where DW = Dry weight, FW = Fresh weight,

6.2.3 Measurement of Height and Biomass of Pigeon Pea

All the pigeon pea within a 3 m x 3 m subplot was cut at ground level (10 cm from the ground) at maturity. They were divided into various plant components; stems, twigs, pods and roots and the fresh weight measured. The fresh weight of the chopped pigeon pea plant parts were determined and recorded. Samples (250 g) of pigeon pea plant components were collected except for pods where all the pods were sampled. Below ground biomass was estimated through destructive root sampling for the plants. The root biomass was sampled in the same demarcated 3 m x 3 m sub plot. Pigeon pea plants were cut at 10 cm above ground level. At the base of the plant, within a distance of 45 cm x 37.5 cm, a pit was hand-dug to a depth of 60 cm to remove the roots with soil. Using a shovel, soil was scooped from the hole where the root mass was removed. The roots were cleaned in clean water to remove soil debris and their fresh weight measured for all the plants. The samples were clearly labelled and packed in khaki bags labeled with date and farm identification. These samples were transported to SAJOREC laboratory, where they were dried and their dry weigh measured to determine root:shoot ratio.

6.2.4 Data Analysis

Data was cleaned and summarized to obtain the general trends, means to compare further intensified system with typical push-pull technology. T-tests were carried out to determine effect of the pigeon pea integration as push-pull + pigeon pea and maize +pigeon pea across the two seasons Analysis of Variance was carried out to determine the effect of the integration on growth and yield across the three sites and the seasons. Means were separated using Tukey's HSD test to assess treatment and site interaction effects on the different parameters at $P \leq 0.05$.

6.3 Results

6.3.1 Treatment Effects on Leaf Width, Leaf Length and Height of Maize across Site and Season

Among the treatments, push-pull + pigeon pea showed the best performance in seasons 1 SR and 3 SR, with mean leaf widths of 8.21 cm and 8.68 cm, respectively. The effect of push-pull on maize growth became more pronounced in seasons 3 and 4, while maize monocrop maintained relatively similar performance across seasons, except in season 2. For leaf length, treatment responses varied by site: push-pull recorded significantly higher leaf length in Kisumu, push-pull + pigeon pea had the highest leaf length in Siaya, while maize + pigeon pea showed no significant variation across sites. Treatments involving push-pull, particularly push-pull + pigeon pea, showed stronger seasonal and site-specific effects on maize leaf growth.

Integration of pigeon pea influenced leaf length. In Kisumu, maize leaf length for maize monocrop was significantly lower than that of maize plants in push-pull +pigeon pea, push-pull and maize + pigeon pea. In Siaya, maize leaf length in push-pull + pigeon pea and maize monocrop were significantly higher than push-pull and maize + pigeon pea for leaf length. In Vihiga there were no significant differences across the different intensification pathways for maize leaf length. In season 1 and 2 no differences were observed for leaf lengths among treatment; leaf length in season 3 push-pull + pigeon pea was highest and maize + pigeon pea was significantly lower than all other treatments. In season 4 no differences were observed but push-pull + pigeon pea was the highest (91.2 cm).

Intensification had an effect on the height of maize across sites and season. Height of maize in push-pull and push-pull + pigeon pea in Kisumu was 201 cm while that of maize in push-pull + pigeon pea Siaya, was 195 cm. In Siaya maize from the push-pull + pigeon pea, was significantly taller than maize+ pigeon pea, and push-pull. In Vihiga, the treatments did not differ significantly. When treatments were compared height of maize (170 cm) in push-pull + pigeon pea and push-pull differed significantly from maize monocrop and maize+ pigeon pea at 161 cm. Treatment effect on height differed across seasons i.e. maize+ pigeon pea was tallest in season 1SR and 2LR (180 cm ,186 cm respectively) though not significantly different from the rest. In season 3SR push-pull + pigeon pea (147 cm) was significantly different from maize monocrop and maize + pigeon pea (Table 6.1).

Table 6.1: Treatment Effect on Maize Growth Based on Leaf Width, Leaf Length and Height of Maize Plants across Site and Season

	Site and treatment effect on leaf width			Treatment and season effect on leaf width			
Treatment	**Kisumu**	**Siaya**	**Vihiga**	**Season1**	**Season2**	**season3**	**Season 4**
Push-pull	7.99±1.78	7.29±2.1	7.25±2.5	7.81±2.0	6.53±2.5	8.15±1.4	7.88±1.9
Push-pull + pigeon pea	7.73±1.96	8.75±1.5	7.46±2.3	8.21±2.0	6.74±2.4	8.68±1.3	7.27±1.64
Maize monocrop	7.59±2.10	8.76±1.7	7.66±2.5	8.18±2.1	6.65±2.8	8.22±1.5	7.98±2.1
Maize + pigeon pea	7.42±1.82	7.21±2.1	7.32±2.5	8.18±2.1	6.55±2.3	7.66±2.0	6.3±1.59
	Site and treatment effect on height				Treatment and season effect on height		
Push-pull	189.2±50	143.7±52	161.2±52	172.6±47	181.9±44	139.1±48	179.8±69
Push-pull + pigeon pea	172.9±45	195.1±53	156.4±46	176.6±42	175.7±35	146.6±42	173.4±66
Maize monocrop	156.4±54	201.4±45	160.4±58	170.7±43	175.8±52	129.4±47	181.9±73
Maize + pigeon pea	163.8±36	155±57	163.8±47	179±32	186.3±33	123.1±48	140.2±56
	Site and treatment effect on leaf length				Treatment and season effect on length		
Push-pull	90.4±17	79.5±22	85.2±20	87.6±20	81.8±21.7	85±21	90.3±15.8
Push-pull + pigeon pea	87±22	94.3±12	88.1±18.7	87.8±24	83.9±17	92±14.3	91.2±16.8
Maize monocrop	80.8±20	95±10	90.2±14.2	90.1±16.9	81.7±20	85.1±14.5	90.4±16
Maize + pigeon pea	86.6±20	82.5±23	88.9±13	90.7±13	84.9±15	81.1±24	86.0±18

6.3.2 Effects of Treatment on Brachiaria Grass and Desmodium Biomass across Site and Season

Intensification with pigeon pea did not significantly affect the yield of Brachiaria grass and across sites and seasons, but it did for desmodium. Push-pull and push-pull + pigeon pea did not differ significantly in Brachiaria grass biomass per square meter across sites or seasons, with push-pull producing 0.85 kg and push-pull + pigeon pea producing 0.75 kg. However, treatment effects were more evident for desmodium biomass. Push-pull + pigeon pea consistently produced higher desmodium biomass than push-pull across all three sites, with increases of 226 g in Kisumu, 200 g in Siaya, and 141 g in Vihiga. Site-specific differences were also observed, with both treatments performing best in Kisumu, where Brachiaria grass and desmodium biomass were highest at 1.2 kg and 0.938 kg per square meter, respectively. Brachiaria grass biomass was lower in Vihiga at 0.537 kg per square meter and 0.448 kg desmodium, and lowest in Siaya, with 0.34 kg Brachiaria grass and 0.28 kg desmodium. In this study, while Brachiaria grass biomass did not differ significantly between the two treatments across sites or seasons, push-pull + pigeon pea significantly increased desmodium biomass compared with push-pull, particularly in Kisumu.

6.3.3 Effect of Treatment on Stover Yield and Grain Yield per Site and across Season

Stover yield differed in the treatments across sites, although the overall site differences were not significant. Across sites, maize monocrop recorded the highest stover yield (3475 kg/ha), followed by push-pull (3338 kg/ha), maize + pigeon pea (2782 kg/ha), and push-pull + pigeon pea (2719 kg/ha) (Figure 6.1B). In Kisumu, push-pull produced significantly higher stover yield (3428 kg/ha) than push-pull + pigeon pea (2451 kg/ha). In Siaya, maize monocrop had the highest stover yield (4446 kg/ha), followed by push-pull + pigeon pea (3258 kg/ha), and both were significantly different from push-pull (2411 kg/ha) and maize + pigeon pea (2667 kg/ha). In Vihiga, push-pull recorded significantly higher stover yield (3788 kg/ha) than maize + pigeon pea (2653 kg/ha). Although stover yield was highest in Vihiga

(3219 kg/ha), followed by Kisumu (2987 kg/ha) and Siaya (2959 kg/ha), these site differences were not significant. Treatment effects on stover yield varied by site, while seasonal effects were most evident during season 4 long rains.

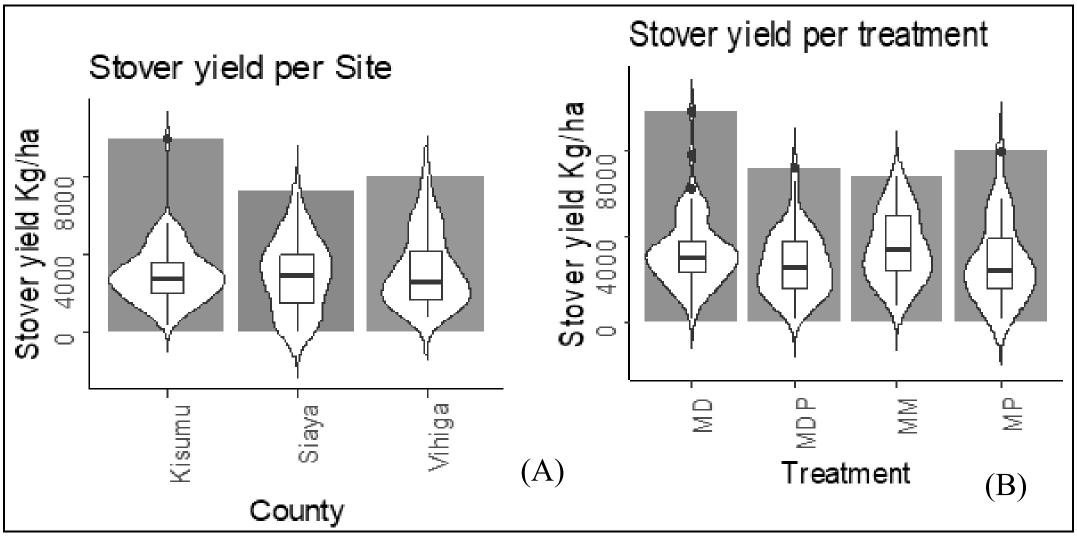

Figure 6.1: Effect of Pigeon Pea Integration on Maize Stover Yield in Kg/Ha across Sites. Treatments: MD = Push–Pull; MDP = Push–Pull + Pigeon Pea; MM = Maize Monocrop; MP = Maize + Pigeon Pea

Integration of pigeon pea in push-pull system did not have a significant effect on grain yield. Grain yield was generally maintained as a result of intensification with pigeo pea across sites, indicating that intensification did not reduce maize productivity (Figure 6.2A and Figure 6.2B). However, there was a significant season × treatment interaction ($p<0.05$), this showed that treatment performance varied across seasons. Across sites, push-pull performed best in Kisumu, maize + pigeon pea performed best in Siaya, and maize monocrop performed best in Vihiga.

There were no significant differences overally in the sites as a result of pigeon pea integration. Kisumu recorded the highest grain yield (2479 kg/ha), followed by Siaya (2352 kg/ha) and Vihiga (2106 kg/ha), although these site differences were not significant. Across seasons, push-pull produced the highest yield in seasons 1 and 2, with 2245 kg/ha and 2721 kg/ha, respectively, while push-pull + pigeon pea had the highest grain yield in season 3 and maize monocrop had the highest grain yield in season 4. The performance of push-pull + pigeon pea and maize + pigeon pea increased from season 1 to season 3, suggesting improved treatment response over time. Maize + pigeon pea had significantly lower maize grain yield in Vihiga than in Kisumu and Siaya. In this study, treatment effects on maize grain yield were more evident through their interaction with season and site rather than as independent main effects (Table 6.2).

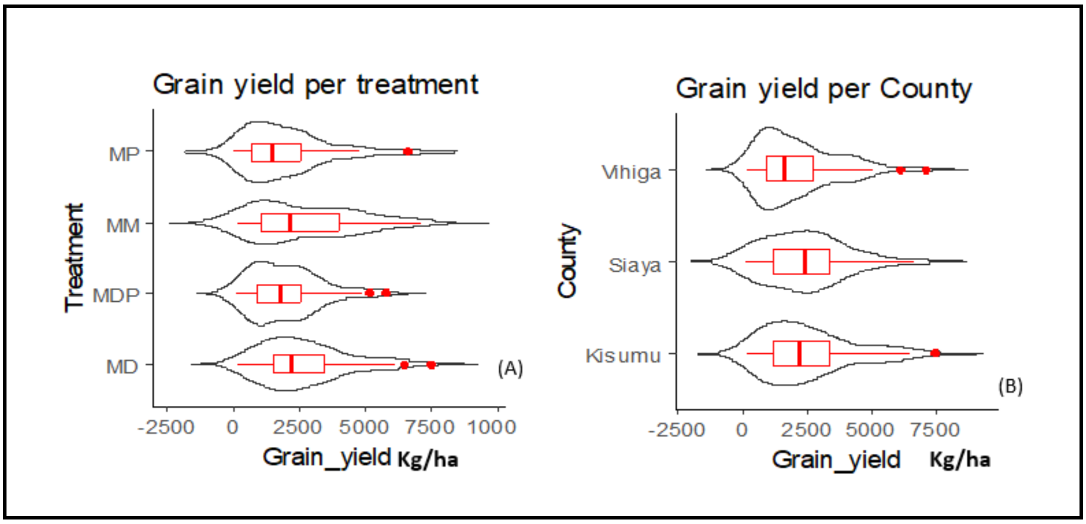

Figure 6.2: Effect of Pigeon Pea Integration on Maize Grain Yield in Kg/Ha Across Treatments and Site. Treatment Abbreviations: MD = Push–Pull; MDP = Push–Pull + Pigeon Pea; MM = Maize Monocrop; MP = Maize + Pigeon Pea

Table 6.2: Pigeon Pea Integration Effect on Maize Stover and Maize Grain Yield in Kg/Ha Across Sites and Season

	Site and treatment effect on Stover yield (kg/ha)			Treatment and season effect on Stover yield kg/ha			
Treatment	**Kisumu**	**Siaya**	**Vihiga**	**Season1**	**Season2**	**season3**	**Season 4**
Push-pull	3428±1726	2411±1205	3788±1922	3258.3±1361	3360±1531	3444±2852	3308±1291
Push-pull + pigeon pea	2451±1194	3258±2178	2891±1630	2794.4±1444	2877.4±891	3717±1746	1559±1208
Maize monocrop	3231±1275	4446±1114	3354±1879	3162.1±1258	3818±1730	3312±1818	3592±1741
Maize + pigeon pea	3164±1509	2667±2070	2652±1896	3011±2112	3539±1277	3250±2225	1205±490
	Site and treatment effect on Grain yield kg/ha			Treatment and season effect on Grain yield kg/ha			
Push-pull	3259±1797	1853±1056	2407±1610	2245±1245	2721±1863	2318±1562	3347±1895
Push-pull + pigeon pea	1964±1389	2333±1565	1826±1138	1725±914	1799±1085	2779±1698	1639±1319
Maize monocrop	2431±2068	3828±1019	2471±2014	1883±1266	2107±1716	2770±1844	3754±2275
Maize + pigeon pea	2141±1729	2148±1890	1606±1057	1859±1266	2356±1445	2195±2162	1165±691

6.3.4 Treatment effect on Pigeon Pea Productivity across Site and Season

Further intensification of push-pull system resulted in better productivity of pigeon pea crop. Differences in pigeon pea growth parameters across the two treatments were observed for season and site. These differences were significant (P=0.05) for pigeon pea height (m) and girth (cm) only for season, with season 3SR performing better than 1SR. In contrast, height, girth, root collar diameter, root weight and root height were significantly different across treatments, with push-pull + pigeon pea performing better than maize + pigeon pea. Fresh leaf and fresh twig weight which are sources of fodder and fuelwood, were not significantly different even though their weights were higher in push-pull + pigeon pea. Treatment affected pigeon pea growth and yield across sites. Pigeon pea growth and yield performance were superior in Siaya and Kisumu compared to Vihiga. Intensification of push-pull with pigeon pea enhanced its performance. Root weight did not significantly differ across sites and treatments but was highest in Siaya, followed by Kisumu, and Vihiga was the lowest. Pod fresh weight differed across counties and treatments. It was highest in Kisumu, lowest in Vihiga and higher in push-pull + pigeon pea compared to maize + pigeon pea (Table 6.3).

Table 6.3: Effect of Intensification on Pigeon Pea Growth and Productivity across Season and Sites

Season / County treatment		Pigeon pea height (m)	Plant diameter (girth) 1	Plant girth 2(cm)	root collar diameter (cm)	Root weight (g)	Root height (cm)	Fresh leaves (g)	Fresh twigs (g)	Fresh stems (g)	Root: shoot ratio	Dry matter (g)
Seasons	1	2.13^{b}	0.49^{b}	12.8^{a}	15.7^{a}	65.9^{a}	32.3^{a}	665^{a}	684^{a}	2183^{a}	0.23^{a}	1626.2^{a}
	3	2.52^{a}	16^{a}	13.44^{a}	16.7^{a}	68.9^{a}	33.3^{a}	619^{a}	925^{a}	2253^{a}	0.26^{a}	1408.2^{b}
	Push-pull + pigeon pea	2.43^{a}	6.24^{a}	14.1^{a}	18.1^{a}	79^{a}	33.8^{a}	644.9^{a}	828.7^{a}	2245^{a}	0.23^{a}	1563^{a}
Treatment	maize+ pigeon pea	2.17^{b}	4.89^{a}	11.8^{b}	14.1^{b}	52^{b}	31.8^{a}	713^{a}	749.8^{a}	2176^{a}	0.263^{a}	1487^{a}
	Kisumu	2.48^{b}	7.36^{a}	13.9^{b}	16.7^{b}	63.3^{b}	34.3^{a}	699^{b}	992^{b}	2653^{b}	$0.24a^{b}$	1932^{a}
	Siaya	2.72^{a}	6.65^{a}	16.6^{a}	21.1^{a}	110^{a}	33^{a}	1095^{a}	1228^{a}	3393^{a}	0.31^{b}	2257^{a}
County	Vihiga	1.73^{c}	3.14^{a}	9.02^{c}	11.8^{c}	40.6^{c}	30.2^{b}	395^{c}	289^{c}	875^{c}	0.202^{a}	655^{b}
Season*treatment		P< 0.05	P<0.05	ns	P<0.05	P<0.05	P<0.05	P<0.05	P<0.05	P<0.05	p<0.05	P< 0.05
County*treatment		P<0.05	ns	ns	P<0.05	P<0.05	ns	ns	P<0.05	P<0.05	P<0.05	ns

6.4 Discussion

Integration of pigeon pea into push-pull and maize cropping systems had an effect on the growth and yield of maize across sites and seasons. Push-pull + pigeon pea and push-pull enhanced growth in Kisumu and Siaya respectively. Double legume combinations such as pigeon pea and groundnut intercrops with maize, enhanced the height of maize compared to maize monocrops in Zambia (Mwila et al., 2021). Integration of pigeon pea in push-pull resulted in better growth of maize (height and leaves) in season 1 and 3. The rainfall pattern in parts of Kisumu and Vihiga is highly predictable and reliable compared to Siaya. Integration of pigeon pea improved growth of maize in push-pull system impacting growth of maize except in season 4LR where height of maize was compromised as a result of excessive rainfall and windy conditions which caused a shading effect. Similar enhancement of growth resulting from intercrops of maize and pigeon pea have been reported though without desmodium (Kermah et al., 2017). The nexus between soil fertility and climate variabilities resulted in significant interaction effect between treatment with site, and season for all growth parameters, which influence yield outcomes.

Further intensification of push-pull system enhanced the fodder component of the system by improving the production of desmodium and Brachiaria grass. In this study 2.92 tons/ha of Brachiaria grass and 2.2 tons/ha of desmodium were produced. This is critical because the farming systems in western Kenya are characterized by crop livestock integration. Other studies in the same region have reported contribution of 6.7 tons/ha of fodder production (Cheruiyot et al., 2020) as a result of push-pull implementation. This fodder production has potential to increase livestock production and consequently milk production, diversify income and improve livelihoods. Farm diversification to meet all farmers' needs is the most sustainable way for improving livelihoods among small-scale farmers.

Generally, maize grain yield was not compromised as a result of intensification in all three sites. This is an indication that on the same portion of land, the farmer can cultivate to get their maize grain and stover yield and at the same time increase the productivity in terms of reduced striga population and soil fertility improvement by the presence of pigeon pea in the farm. Push-pull is reported to produce 0.3–1.1 t ha^{-1} more maize compared to non-push-pull creating need for adoption of push-pull system to reduce shock in farming systems (Ndayisaba et al., 2020).

Maize grain yield for this study ranged from 1.8 to 2.6 t ha^{-1} which was not significantly different in all treatments and across sites. However, comparison across site showed significant difference for specific treatments for example in Kisumu maize + desmodium and maize monocrop at $p=0.05$ but not (push-pull + pigeon pea) and (maize + pigeon pea). This implies that farmers in the three counties can employ intensification such as (push-pull + pigeon pea) or (maize + pigeon pea) depending on the farmer's preference and availability of space. This is an indication that a farmer can be able to diversify their productivity for fodder and yield and improvement by the presence of pigeon pea in the farm which can be utilized for food fodder and firewood. This adds to previous reports on yield enhancement by push-pull (Ndayisaba et al., 2020).

The non-significant reduction in maize yield also supports the likelihood of increased land equivalent ratio (LER), because additional pigeon pea yield and other products are obtained from the same land area. Previous studies have shown that maize–pigeon pea integration can increase LER even where maize yield is slightly suppressed (Njira et al., 2021), and maize–pigeon pea intercropping has been reported to have one of the highest LER values among cereal–legume combinations (Renwick et al., 2020). In the current study, combining push-pull technology with pigeon pea may therefore provide an even greater land-use advantage by maintaining maize yield while generating additional outputs such as pigeon pea grain, fodder, biomass, fuelwood from stems and twigs, and soil organic matter from litter inputs.

The findings in this study suggest that push-pull intensification with pigeon pea can improve whole-system productivity and resource-use efficiency without significantly reducing maize grain or stover yield. Although intercropping may sometimes reduce maize yield because of competition for nutrients, water, and light between component crops (Kimaro et al., 2009). The yield reduction observed when pigeon pea was integrated into push-pull was not significant in the current study. Suggesting that intensification maintained maize grain yield while potentially improving overall system productivity.

The effectiveness of the intensification varied across seasons. Planting pigeon pea in the short rain season holds promise for additional pigeon pea products during the dry months of January to March when it matures as opposed to monocrop systems. In addition, the farmers are shielded from climate shocks because they have alternative crops produced, in case maize fails to grow. The pigeon pea- provides other products such as dietary diversity since pigeon pea is a rich source of protein. In this study, effect of integration varied based on season, grain yield increased across seasons. Research show that increased maize productivity as a result of pigeon pea intensification is season independent but time dependent (Kwena et al., 2019).

Precipitation is a critical element for maximum maize productivity. During the study period rainfall increased steadily from short rain season in 2021 to long rain season in 2023. It was noted that during short rain season of 2022 the precipitation was higher than long rains season of 2022, which is an indication of climate change. With this evidence of climate change effects there is need for a shift from conventional crops to more adaptive and resilient crops. It was noted that the performance was better across the seasons, since the effectiveness of the pigeon pea function increases with time. The system can be applied as an alternative to reduce application of synthetic fertilizers. Kiwia et al., (2019) reported that maize and pigeon pea intercrops can replace synthetic fertilizers without compromising on maize grain yield.

Productivity of the intensified system for pigeon pea was best in Siaya County followed by Kisumu and Vihiga counties respectively. Despite Siaya experiencing extreme drought seasons, the performance of pigeon pea productivity was not compromised. The productivity was, however, not significantly different. Pigeon pea being a diverse and resilient crop, can grow in any of the 3 sites that are different in terms of climate variability. Intensification with pigeon pea provides alternatives to the system such as fodder, firewood and diversified diets while enhancing the land equivalent ratio which is a result of double legume intercropping (Mwila et al., 2021). Intensification with pigeon pea provides additional food such as alternative diets in dry season pigeon pea planted during the short rain season of October to December matures in the period of January to March which is the driest month in the region thus providing food in this season. Pigeon pea being a source of protein complements the constrained diets in these smallholder communities in western Kenya where cereals and cereal products form part of the common meals. (Kwena et al., 2019).

When push-pull was further intensified with pigeon pea, fodder production was enhanced. Farmers in the region mixed pigeon pea leaves and twigs and combined with desmodium and Brachiaria grass and stover to make fodder for livestock. Twigs and stem from pigeon pea are rich sources of fuelwood to farmers continuously during and after whole crop harvest. Shortage of fuelwood is one of the major challenges facing smallholder farmers in western Kenya (Buleti et al., 2023). In addition, the availability of firewood reduces the time wasted by women to go and fetch firewood and reduces dependence on other trees for fuelwood which take a longer time to mature. Agroforestry provides fuel through firewood that is used in cooking and boiling drinking water, thus, ensuring sanitation and preventing diseases (Jemal et al 2021). With the increasing population demands for fuelwood there is necessity to diversify fuel production and agroforestry is the promising option.

Farmers in the region use pigeon pea residues as an important organic resource for manure preparation before planting. Whole crop remnants and leaves are commonly mixed with desmodium, Brachiaria grass, and livestock or poultry waste, then stored for about three months before field application. This practice allows crop and animal residues to decompose and contribute nutrients and organic matter to the soil. Pigeon pea contributes to soil fertility through several mechanisms. It fixes atmospheric nitrogen, functions as a cover crop, produces substantial residues, enhances soil organic matter, contributes to carbon sequestration, and supports soil conservation (Renwick et al., 2020). These functions make pigeon pea valuable in smallholder farming systems where soil fertility is often low and external inputs are costly.

Beyond soil fertility improvement, pigeon pea also provides broader ecosystem services similar to fertilizer trees. Fertilizer trees improve farming systems by providing fodder and shade, increasing organic matter, and strengthening smallholder farmers' resilience to climate-related stresses (Apuri et al., 2018). In erosion-prone areas such as Siaya, pigeon pea may also help reduce soil erosion through ground cover, residue retention, and improved soil structure. Given the declining sustainability of maize productivity in western Kenya, pigeon pea offers a practical option for diversifying maize-based farming systems. It can be grown as either an annual or perennial crop and matures faster than many tree species commonly integrated into farming systems. Therefore, integrating pigeon pea into maize and push-pull systems can provide soil fertility benefits, additional biomass, erosion control, and alternative farm products while supporting more resilient smallholder production systems.

6.5 Conclusions

- Integration of pigeon pea in push-pull system enhanced maize growth and stover yield, and maintained maize grain yield in the different sites (Kisumu, Siaya and Vihiga).
- Integration of push-pull with pigeon pea resulted in enhanced growth and productivity of pigeon pea and provision of additional benefits such as provision of fodder, food and fuelwood.

- Intensified push–pull system has potential for wider application in smallholder farming systems while sustaining maize yield.

6.6 Recommendations

- Pigeon pea integration into push-pull and maize cropping systems can be considered as one of the pathways for intensifying smallholder farming systems by the county governments and agricultural extension agencies in Kisumu, Siaya, and Vihiga as climate resilience initiative for food.

- Smallholder farmers in Kisumu, Siaya, and Vihiga are encouraged to integrate pigeon pea into maize-based and push-pull farming systems because it maintains maize grain yield while providing additional harvestable products, including food, fodder, fuelwood, and biomass for manure or compost preparation.
- For successful integration into push-pull farmers need to be facilitated by training and to access quality desmodium and pigeon pea seed to enable wider implementation.

CHAPTER SEVEN

GENERAL DISCUSSION AND CONCLUSIONS

7.1 General Discussion

Smallholder farming systems require target specific interventions for improving sol health and managing pests. Diversification of smallholder farming systems requires region and crop-specific strategies. This includes crops and cropping systems that are variable and primarily influenced by need for food (subsistence) and income generation, and for improving crop yield, increasing the number of harvestable products, and ensuring food security and mitigation to climate change. Push-pull technology has been applied to mitigate the triple problems but its applicability has been restricted. The study identified the need to integrate pigeon pea into push-pull system to support in provision of multiple benefits including diversified food, fodder, and firewood. Differences in regional preference of crops across the three counties, Kisumu, Siaya and Vihiga, exist as a result of the existing cultures, land sizes and availability of land. Selection of pigeon pea as a candidate crop for intensification was informed by its potential to meet the very need for crop combination targets such as intercropping for food, fodder, pest management and improvement of soil fertility.

Integration of pigeon pea into push-pull system pigeon pea enhanced crop growth, reduced pest infestation and improved soil fertility across the three counties. For optimal results, staking of pigeon pea is highly recommended in seasons of extreme rainfall as a management strategy. Better growth in push-pull + pigeon pea and push-pull could be attributed to soil improvement and conservation strategies as nitrogen fixation, reduced soil erosion and reduced effect of striga as a result of presence of desmodium and pigeon pea. This strategy holds promise for increased land equivalent ratio among smallholder farming systems and also an alternative striga management strategy. This is the first research carried out to evaluate effect of integrating pigeon pea into push-pull systems for management of striga and insect pests in western Kenya.

This leaves intercropping as a most preferred and practical intervention. The superiority of push-pull in managing stemborer, fall armyworm and striga weed compared to other strategies has been observed (Kassie et al., 2018). The current study presents an alternative which involves integrating push-pull technology with pigeon pea, which enhances the functionality of push-pull systems on pest management, maize growth and natural enemies' enhancement.

The integration of pigeon pea in push-pull and maize intercrops generally maintained the crop yield. Intercropping can reduce yield of the individual intercrops as a result of competition for nutrients or increase yield of maize in some cases especially with fertigation. Site and treatment interactions showed better crop performance in Siaya for push-pull + pigeon pea, resulting from enhanced soil fertility. Comparison of yield output from experiments involving maize and pigeon pea shows that the combined yield for maize and pigeon pea is higher compared to sole crops. There is evidence for complementarity of pigeon pea and maize, which is useful for increasing the yield of both crops (Rusinamhodzi et al., 2017). Yield is improved as a result of increasing abundance and diversity of beneficial soil microorganisms some of which result in biological nitrogen fixation (Musokwa et al., 2020) and weed management (striga weed) which is a factor of seasonality and soil quality (Mugi-Ngenga et al., 2021) and enhanced diverse population of natural enemies.

Intercropping with legumes is the most helpful strategy with dynamic benefits ranging from soil fertility improvement, pest management, increased productivity, and alleviation from complete crop failure. Soil is improved as a result of increased rhizobia which enhances nitrogen fixation. Pests are managed through allelopathic mechanisms, with reduced effects on target crops, and overall productivity is improved through increased dry matter in residue and biomass accumulation. Finally, the resilient system is a pathway to food and nutrition security, soil stability and crop insurance against climate shocks.

Despite the many benefits of pigeon pea integration, it came with new challenges in the region. Introduction of new farming technologies and systems creates a gap for increased knowledge, which was best disseminated through continuous training for both conventional push-pull systems and the intensified push-pull systems. Climate variability, such as hailstorms, delayed rainfall, and sometimes droughts, were experienced during the study period; this caused poor germination and replanting on some farms was carried out as a mitigative strategy, which affected the overall performance of the intensified systems. Most practitioners of intensification do not understand the value of the process; they prefer the quick fix methods, yet sustainable intensification takes time for one to realize the results. It was noted that successful pest management requires community involvement in planning and executing the planting calendar to avoid reinfection. Disaggregated planting times is the biggest cause of reinfection in smallholder farming systems for the fall armyworm.

7.2 General Conclusions

Intercropping, agroforestry, crop rotation, and crop-livestock integration represent viable pathways for sustainably intensifying push-pull systems. These priority options for further intensification of push-pull system can improve its ecological and economic performance. Intercropping and crop rotation with vegetables and legumes provide an opportunity to diversify diets, incomes and farming systems. Limited diversification options, lack of knowledge, lack of support system, and market access were identified as overarching challenges with sustainable intensification.

Integration of pigeon pea in the push-pull and maize farming systems enhanced soil fertility. The integrated systems supported the functionality of push-pull technology in pests (fall armyworm and stem borer) and striga weed management by increasing the number of natural enemies and suppressing striga density in the system which resulted in improved growth and maintained grain and stover yield.

Integration of pigeon pea in push-pull and as maize + pigeon pea maintained the maize grain and stover yield across Kisumu, Siaya and Vihiga counties and provided additional harvestable products contribute to food and nutritional diversity, provision of fodder and fuelwood which are critical elements for diversification of the smallholder farming systems.

7.3 General Recommendations

- Integration of pigeon pea in push-pull and maize cropping system, can be incorporated as one of the integrated striga management initiatives in Kisumu Siaya and Vihiga.
- To enhance adoption of pigeon pea integration, desmodium and pigeon pea seed/ planting material need to be made available and affordable for farmers for successful application.
- The local and county government agricultural initiatives can integrate pigeon pea into climate-resilient initiatives in Kisumu, Siaya and Vihiga as it maintains grain yield and to diversify production systems

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APPENDICES

Appendix I: Cropping Systems and Practices for Yield Improvement Identified Through Elicitation during Participative Focus Group Discussion in Western Kenya

Cropping system (*) / sustainable intensification ($) / intensification practice (#)	Description	Motivation for the practice	Limitations
Intercropping*$	Cultivation of two or more crops on the same piece of land at the same time. For example, maize and common bean (most common), maize and other legumes (cowpea, soybean, or green grams) or maize and vegetables (emerging)	Minimize risk of total crop failure, increase harvestable products, diversify income, reduces cost of inputs	Difficulty in management such as weeding
Crop rotation*$	Growing single or mixed crops in succession on the same piece of land. For example, maize in the first season followed by a legume (e.g. common bean) or another crop (e.g., sweet potato) in the	Reduce soil compaction	It is not possible with perennials such as desmodium or trees

	second season.		
Monocropping*#	Growing of a single crop exclusively, and also in successive seasons, on a piece of land.	Higher yields in the short-term, easier management of pests	Lower yields in the long-term, soils become vulnerable to erosion, risk of total crop failure.
Crop-livestock integration*$	The combination of crop cultivation with livestock and or poultry farming.	Increase farm productivity, reduce external inputs (fertilizer, manure and animal feed).	Labor intensive because of multiple activities
Agroforestry*$	An integration of woody perennials around or within crop fields or pastureland.	Provides multiple products and services, currently used for youth and women empowerment	Lack of seeds and seedlings, takes longer to realize benefits.
Push-pull system*$	A companion cropping system that involves intercropping maize with a forage legume (desmodium), and planting a forage grass (brachiaria) around the intercrop. Vegetable integration is still in the experimental phase.	Improve crop yield, control of insect pests (stemborer, fall armyworm), regulate striga weed, and improve of soil fertility, provide fodder	Currently restricted to maize in small plots, labor intensive, seeds are expensive and not readily available, desmodium can become weedy

Use of improved varieties$^{\$\#}$	Cultivation of improved varieties for different crops	High crop yield	Heavily depends on external inputs, prone to pests (e.g., maize weevils), affected by the existence of poor seed quality in the market and farmers' preference for local varieties
Conservation agriculture$^{\$}$	A set of soil management practices that minimizes soil disturbance and maintains permanent ground cover (e.g. with crop residues or live mulches, use of grass leaves or other material).	Soil conservation, improve yields	Lack of knowledge on the practice, competing needs for residues, residues makes ploughing or planting difficult, some cover crops do not have immediate benefits to the farmer
Manures$^{\$}$	Application of compost (rotted organic matter made from waste residues from plants), farmyard manure (decomposed mixture of dung and urine of farm animals along with litter and leftover material from roughages or fodder fed to the cattle) or green manure (leafy biomass, e.g., from *T. diversifolia* incorporated in the field prior	Improves overall soil health, makes the farm resilient to drought and floods, adds organic matter	Requires knowledge on composting process and material for composting, is time consuming, labor intensive and bulky to transport. Inadequate material for composting

	to planting).		
Inorganic fertilizer$^{\$\#}$	Use of inorganic fertilizers during planting and top-dressing, mainly Di-ammonium Phosphate (DAP) or Calcium Ammonium Nitrate (CAN), respectively	Improves crop yield in the short term (first two seasons)	Reduces crop yield in the long-term, poor soil health when used extensively over time, expensive to purchase
Good agronomic practices$^{\$}$	A set of agricultural practices that are aimed to achieve maximum productivity, including right choice of seed, proper spacing, proper timing	Increases crop yield, mitigate effects of climate change	Limited knowledge and skills, time consuming for proper spacing
Fallowing*$^{\#}$	A set of farming practices whereby arable land is left uncultivated for seasons or years.	Improve soil fertility, soil moisture retention, pest management	Limited size of land to allow fallowing

Note: Data was classified such that, the asterisks (*) indicate practices mentioned by respondents as a cropping system, the dollar sign ($^{\$}$) indicates practices considered by respondents to be sustainable intensification practices, and ($^{\#}$) indicates intensification practices not considered to be sustainable. Monocropping, use of inorganic fertilizers and use of improved varieties are intensification practices, which some, but not all farmers perceived as sustainable

Appendix II: Consent Form

FOCUS GROUP DISCUSSION CONSENT FORM AND QUESTIONNAIRE

Informed Voluntary Consent to Participate in Research Study

Project Title: Upscaling the benefits of Push-pull system for sustainable agricultural intensification in East Africa (UPSCALE)

A study on sustainable intensification practices for integration in push-pull systems

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Invitation to participate, and benefits: We are a team of researchers from Jomo Kenyatta University of Agriculture and Technology carrying out a research to determine sustainable intensification practices that farmers would want integrated in push-pull systems in Kisumu, Siaya and Vihiga. You are invited to participate in a focus group discussion to help us identify the most suitable sustainable intensification practices for integrating in push-pull systems in your area. I believe your experience would be a valuable source of information and hope that by participating you may gain useful knowledge too. The outcome of this study will be shared with participating farmers and used within UPSCALE project.

Procedures: During this study, you will be asked to give some information related to farming in the area, such as the most common sustainable intensification practices, ease of integrating these practices into push-pull, as well as what hinder the implementation of these practices on farms. You may also be asked some questions related to type of crops and trees found on your farm and the use of manure and fertilizers. The discussion will take approximately 1 hour.

Risks: We are not aware of any risk that would arise from participating in this research.

Disclaimer/withdrawal: Your participation is completely voluntary; you may refuse to participate, and you may withdraw at any time without having to state a reason and without any prejudice or penalty against you. Should you choose to withdraw, the researcher commits not to use any of the information you have provided without your signed consent. The researcher may also withdraw you from the study at any time.

Confidentiality: All information collected in this study will be kept confidential. Personally, identifiable information will be anonymized.

What signing this form means:

By signing this consent form, you agree to participate in this research study. The aim, procedures to be used, as well as the potential risks and benefits of your participation, have been explained verbally to you in detail, using this form. Refusal to participate in or withdraw from this study at any time will not affect you in any way. You are free to contact me (+254 736 488 885), to ask questions or request further information at any time during this research, as well as for the results.

I agree to participate in this research (tick one box) – each participant should sign this consent

☐ Yes ☐ No _________

______________________	______________________	________
Name of Participant	Signature of Participant	Date
______________________	______________________	________
Name of Researcher	Signature of Researcher	Date

Appendix III. Focus Group Discussion and Key Informants Tools

Assessment of sustainable intensification practices for integration in push-pull systems in your area

The purpose of this KII is to characterize farming systems to obtain insights on various SI practices for integrating in push-pull in western Kenya. It is also intended to give a broader understanding of the importance of these practices, and the constraints or challenges and opportunities on the same.

Checklist for discussion

A. *Characterising farming system*

1. What are the main farming systems practiced by smallholder farmers in this area?

2. Which crops are commonly grown in the area?

3. What are the benefits of growing the crops mentioned in (2) to households?

4. What are some of the practices that farmers employ to produce more food on the same amount of land but with less negative environmental or social impacts?

5. Of the practices listed in 4 above, which are the three most preferred? (Hint: as practised by a majority [more than 6] of farmers)?

b. Which crops, trees and/or animals do farmers integrate in the practices listed in 5(a) above?

c. Can you please list other benefits (other than improved yields) derived from the practices listed in 5(a) above? d Could you please list some of the challenges faced in implementing the practices listed in 5(a) above?

6. Apart from the practices named in number 5 above, would you be willing to implement other SI practices, if introduced to you? (Hint: here we can ask about other SI practices that the farmers are not practising or have not mentioned)

7. What would be the main challenges faced by farmers in this area, if they were to implement new technologies such as those suggested in (6) above? (Hint: access to credit, lack of technical support etc.

8. Have you heard about push-pull? What has been your experience with push-pull? (including practicing and non-practicing farmers)

b. What are the benefits and draw-backs of push-pull system? (experienced, heard about or foreseen) c Which practices would you be willing to include in push-pull? (Hint: if you were to further intensify push-pull and improve its performance or address its weaknesses, which other practices would you include?

d. What benefits would you derive from such an integration?

9a. Do farmers commonly include trees on their farms?

b. Please rank, in order of priority, trees that farmers commonly integrate in their farms.

c. Where on the farm are these trees found (Hint: along boundaries, scattered in cropland, in wide spaced rows in the farm, in blocks used to produce fodder

d. Which trees would you be willing to include in push-pull systems? e What are the reasons for including such trees on farms?

10. Which other crops would you be willing to include in push-pull? (please rank)

b. What are the reasons for including such crops in push-pull?

11. Have you received any information or training on implementing any of the practices mentioned? (Hint: this will be a Yes or No answer, followed by recording number of farmers reporting affirmative

b. Where do you get this information or training on implementing practices (Hint: NGOs, extension officers, researchers, other farmers, television, radio, religious groups. This is a follow up on if the answer is Yes in 11a)

c. Are there challenges faced in accessing such information? (Hint: reliability, accessibility, availability, timeliness)

d. Which actors do you think are most important in ensuring more farmers integrate other sustainable intensification practices with push-pull in this area? (Hint: extension officers, NGOs, community groups, other experienced farmers)

Appendix IV: Photos

Plate 1. 1 Focus Group Discussion in Vihiga at Emusutswi, Kisumu at Yenga and Siaya at Nga'yo (A,B,C respectively), Validation of focus group discussion results in D) Vihiga

Plate 1.2 :Soil sampling A) before experiment B) Soil sampling and processing during experiment, C) Soil sampling post experiment D).

Plate 1. 3: Establishment of the experimental field, including land preparation by demarcation A) and B) planting of the crops (maize, pigeon pea, desmodium Brachiaria grass)

Plate 1. 4 Established experimental fields with the different treatments A) Push-pull, B) push-pull + pigeon pea, C) maize + pigeon pea, D) maize monocrop

(B)

Plate 1. 5 Monitoring pigeon pea height (A) stemborer effect (B) striga height (C) fall armyworm (D)

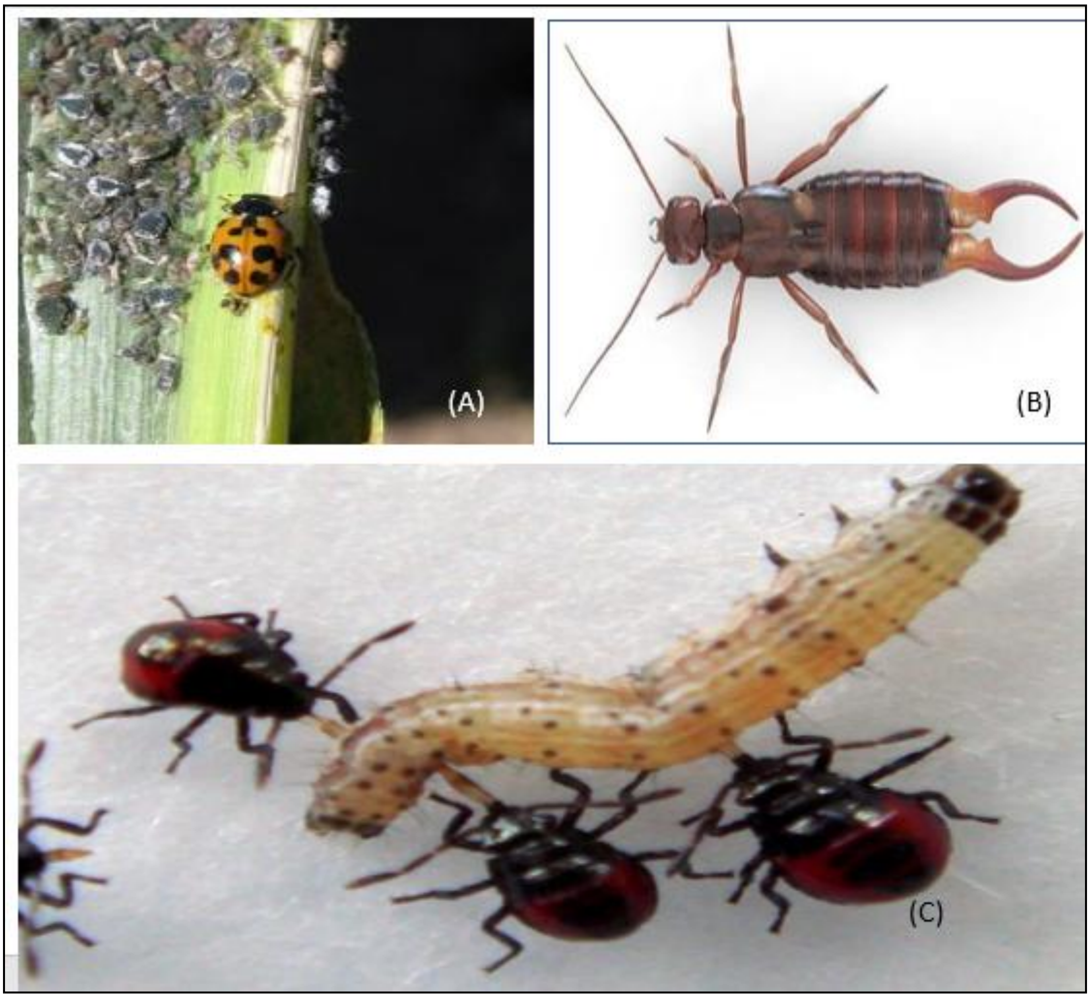

Plate 1. 6 Photos of the most common natural enemies of stemborer and fall armyworm A) ladybird beetle, B) earwig, C) ants

Plate 1. 7 Measuring biomass of A) Brachiaria grass, B) weight of maize cob, C) Sample weight of desmodium and (D) dried sample weight of stover in grams at the field and in the laboratory