CLIMATE CHANGE MITIGATION THROUGH IMPROVED SOIL HEALTH: CARBON SEQUESTRATION, NITROGEN AND PHOSPHORUS AVAILABILITY UNDER THE PUSH-PULL TECHNOLOGY AS A CASE STUDY

PIERRE CELESTIN NDAYISABA

DOCTOR OF PHILOSOPHY

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Climate change mitigation through improved soil health: carbon sequestration, nitrogen and phosphorus availability under the push-pull technology as a case study

Pierre Celestin Ndayisaba

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DECLARATION

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

Signature: ……………………………….. Date: ………………………………..

Pierre Celestin Ndayisaba

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

Signature: ……………………………….. Date: ………………………………..

Dr. Shem Kuyah
JKUAT, Kenya

Signature: ……………………………….. Date: ………………………………..

Dr. Charles Aura Odhiambo Midega
ICIPE, Kenya

Signature: ……………………………….. Date: ………………………………..

Prof. Zeyaur Rahman Khan
ICIPE, Kenya

Signature: ……………………………….. Date: ………………………………..

Dr. Peter Njoroge Mwangi
JKUAT, Kenya

DEDICATION

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ABBREVIATIONS AND ACRONYMS

BNF	Biological Nitrogen Fixation
C	Carbon
GHG(s)	Greenhouse gas(es)
icipe	International Centre of Insect Physiology and Ecology
IPCC	Intergovernmental Panel for Climate Change
JKUAT	Jomo Kenyatta University of Agriculture and Technology
LR	Long rains
N	Nitrogen
P	Phosphorus
REDD	Reducing emissions from deforestation and degradation
SIC	Soil inorganic carbon
SOC	Soil organic carbon
SR	Short rains
SSA	Sub-Saharan Africa
USA	United States of America
WAP	Weeks after planting
WMO	World Meteorological Organization

ABSTRACT

Rebuilding up soil organic carbon (SOC) and by extension nitrogen (N) and phosphorus (P) fertility is a way to mitigating climate change. Push-pull technology could mitigate climate change through sequestering carbon in soils, biologically fixing N and availing P. However, information about this ability is still missing. This information would be used to optimize cropping systems towards sustainable intensification of agriculture. Objectives of this study were to: (1) establish effect of cropping system (push–pull and conventional maize systems), cropping time (years) and agro-ecological zones on carbon stocks, and (2) evaluate impact of cropping system on N and P availability. Three sites (agro-ecological zones); Bondo (LM3 zone) and Siaya (LM2 zone) in Siaya county, and Vihiga (LM1 zone) in Vihiga county, were selected. In each site, farmers who use push-pull were categorized according to how long they had practiced the technology; below 2 years, between 2–5 years, and above 5 years. Five farmers were randomly selected from each category in each site giving 45 farmers (15 from each site). Each farmer had a push-pull plot with maize (*Zea mays* L.) integrated with desmodium (*Desmodium intortum* (Mill. Urb.)) (push) and brachiaria (*Brachiaria brizantha* (Hochst. ex A. Rich.) Stapf. (brachiaria, Mulatto II cultivar) (pull) and one maize cropping system to serve as a control. In these farms, biomass carbon and soil organic carbon (SOC) were assessed. Concurrently, intercrops of maize-common bean (*Phaseolus vulgaris* L.), maize-crotalaria (*Crotalaria ochroleuca* G. Don), maize-desmodium, maize-groundnut (*Arachis hypogaea* L.), maize-cowpea (*Vigna unguiculata* (L.) Walp.), and maize-green gram (*Vigna radiata* (L.) R. Wilczek) were compared to maize mono crop (control) in a completely randomized design with four replications in Mbita Point, *icipe* research station. This experiment was used to study availability of N and P. In both studies (on-farm and on-station), soil sampling was done at 0-15 cm topsoil at around 20 cm from the maize row. Sampling happened immediately after harvesting maize (on-farm) and at 4, 8 and 12 weeks after planting maize (WAP) (on-station). The study covered three consecutive seasons; 2017 long rains (LR), 2017 short rains (SR), and 2018 LR. Push-pull farms stocked between 3.0 ± 0.3 and 4.0 ± 0.4 Mg ha^{-1} of carbon (C) in crop biomass and between 24.4 ± 2.1 and 37.0 ± 2.6 Mg C ha^{-1} in the soil. Non-push-pull farms stocked between 1.1 ± 0.3 and 2.1 ± 0.2 Mg ha^{-1} of carbon in crop biomass and between 19.2 ± 2.1 and 31.1 ± 1.7 Mg soil carbon ha^{-1}. SOC was higher in low rainfall area, Bondo than in Siaya. Farms where push-pull had been practiced for more than five years had higher SOC than those which had push-pull for less than 2 years ($P = 0.027$). Push-pull increased maize grain yield by 2.33 and 1.77 Mg ha^{-1} in Vihiga in 2017 LR and SR, and 2.15 Mg ha^{-1} in Bondo in 2018 LR. An increase in available N and P in maize-desmodium plots compared to maize monocrop plots was observed. Maize grain yield for maize-desmodium was 5.0, 3.1 and 4.3 Mg ha^{-1} in 2017 LR, 2017 SR and 2018 LR, respectively, compared to 0.5, 0.4 and 1.8 Mg ha^{-1} for maize monocrop in the three respective seasons. Other intercrops were comparable with maize monocrop. Push-pull technology offers opportunities to mitigate climate change through carbon sequestration in plants and soils in low, medium and high rainfall environments. It also increases availability of N and P and performance of maize. Further studies considering distribution of SOC in the whole soil profile and estimation of N contributed by BNF by desmodium are recommended. In the meantime, adoption of push-pull technology is recommended to farmers.

CHAPTER ONE

INTRODUCTION

1.1. General background information

Climate change is due to anthropogenic induced surge in the concentration of greenhouse gases (GHGs) in the atmosphere (Australian Academy of Science, 2015). Though gases with greenhouse effect are many, carbon dioxide (CO_2) accounts for a bigger portion to global warming, 76.0% (Australian Academy of Science, 2015). The history of emissions shows that the concentration of CO_2 in the atmosphere rose from 280 ppm in 1750s (Lal, 2004) to 403 ppm in 2019 (WMO, 2019). In the same period of time, the average temperature of the lower atmosphere rose by $0.8^{o}C$. Much of CO_2 is emitted through burning fossil fuel as a source of energy, land use change, and emissions from agricultural lands. Despite pledges by nations to curb their emissions, activities that increase them (emissions) are increasing.

Agriculture contributes 11.0% of total emissions of GHGs equivalent to 5.0 to 5.8 $GtCO_2$ equivalent per year. Emissions from agriculture are reported to increase at a rate of 1.1% per annum (Tubiello *et al.,* 2013; Wollenberg *et al.,* 2016; Arcipowska *et al.,* 2019). Emissions from agriculture can be from mechanical sources, such as farm equipment (for land preparation, harvesting, pesticide application, fridges and refrigerators) or non-mechanical sources such as land use, land use change and forestry, application of mineral fertilizers, manure, crop residues, drainage, etc. Emissions from soils are mainly due to respiration by microorganisms, nitrification-denitrification process, mineralization of organic matter, erosion, etc. Soils worldwide had lost between 30 to 75% of their SOC through these processes as of 2007 (Lal, 2007). A research done in Kenya showed that soils have been losing their SOC and this resulted in land degradation and decline of land productivity (Moebius-Clune *et al.,* 2011; Sommer *et al.,* 2018).

Agriculture offers a solution to climate change through sequestering carbon in soils and plant biomass. Through photosynthesis, plants fix atmospheric carbon into their tissues. Part of this carbon is partitioned to roots which normally remain in the soil after harvesting crops. Carbon in crop residues is added to the soil when residues are retained or returned as manure. Increase in SOC has benefits beyond climate mitigation; building up SOC improves soil health and increases farm productivity (Lal, 2016). By improving food production, agriculture reduces the pressure that would otherwise be exerted on forests and lands not yet opened for food production. Buildup of SOC also improves fertilizer use efficiency by increasing the responsiveness of crops to applied mineral fertilizers (Vanlauwe *et al.,* 2006; 2010; 2015). Improved fertilizer use efficiency reduces the use of mineral fertilizers and related emissions.

Another avenue through which agriculture can mitigate climate change is the use of biological processes in farming systems. For example, integrating N-fixing legumes in cropping systems can reduce dependency on synthetic N fertilizers (Lal, 2016), thereby reducing emissions related to fertilizer use. In environments where crop pests and parasites are a challenge, and pesticides and/or herbicides are used as control measures, adoption of biological control involving crop self defense mechanisms, trap crops, natural enemies and other biochemically mediated mechanisms (Khan *et al.,* 2002; 2006; 2018; Midega *et al.,* 2018; Mutyambai *et al.,* 2019), reduces the need for pesticides and/ or herbicides and related emissions. This ability of agriculture to mitigate climate change has been recognized and a number of cropping systems have been identified as climate-smart agriculture technologies because of their potential to increase productivity, adaptation and/or mitigation of climate change.

Push-pull technology is among technologies that offer diversified pathways of mitigating the effect of climate change. It is a cereal-based cropping system where maize (*Zea mays* L.) or sorghum (*Sorghum bicolor*) (main crop) are intercropped with desmodium (*Desmodium intortum* (Mill. Urb.) or *D. uncinatum* (Jacq.) DC.) (an understory and cover crop) in additive fashion (increased crop intensity). One meter (1 m) away from each side, Napier grass (*Pennisetum purpureum* Schumach.) or Brachiaria (*Brachiaria brizantha* (Hochst. ex A. Rich.) Stapf. (brachiaria, Mulatto II cultivar) surrounds the field in at least 2 rows. Tillage is done in strips between desmodium rows leaving around 60% of soils undisturbed. This technology controls stemborers (*Busseola fusca*); desmodium pushes stemborer moths from maize or sorghum, Napier grass or Brachiaria pulls them. They (moths) lay eggs fed on by natural enemies or crushed inside the pull crop body. Additionally, it (push-pull technology) controls striga (*Striga hermonthica*) through smothering and allelopathy by desmodium. Recently, push-pull was found to reduce the effects of fall armyworm (*Spodoptera frugiperda*) (Khan *et al.*, 2018; Midega *et al.*, 2018).

Based on the nature of push-pull technology (minimum/reduced tillage and cover cropping), push-pull has potential to increase soil organic matter, nitrogen (N) through BNF, and phosphorus (P) through the activity of legumes on soil fixed P. Push-pull embodies principles of conservation agriculture technology: reduced tillage and cover cropping (Khan *et al.*, 2011). So far, the information about the potential for climate change mitigation (push-pull compared to commonly practiced maize-based cropping systems) is scarce. This information is crucial as it would help in leveraging maize-based cropping systems (or cereal based cropping systems) towards sustainable intensification of cereal crop production. This study aimed therefore to assess differences in C stocks, and N and P availability for push-pull technology compare to commonly practiced maize-based cropping systems in western Kenya.

1.2. Statement of the problem

Push-pull technology is adopted in Kenya, Uganda, Tanzania, and Ethiopia, and is being disseminated to countries in east, south and west Africa because of its ability to control major cereal pests; stem borers (*Busseola fusca*), fall armyworm (*Spodoptera frugiperda*), and striga (*Striga hermonthica*), and to boost farm productivity. Comparative studies with cereal cropping systems in the region have been conducted and reported its comparative advantages relative to its counterpart cereal-based cropping systems in terms of productivity, pest control, socio-economic impact, and food safety (Khan *et al.*, 2000; 2008a; 2014; Midega *et al.*, 2015; Mutyambai *et al.*, 2019; Njeru *et al.*, 2019), but little is known about its comparative ability to mitigate climate change through sequestration of carbon and BNF. So far, existing literature about push-pull technology is alarmingly lacking information about its effect on soil organic matter and plant nutrients, especially N and P. Filling this gap is overdue to understand the role push-pull can play in mitigating climate change through storing carbon in farms and reducing emissions due to production and use of mineral N and P fertilizers. This can be achieved through assessing stocks of carbon in plant biomass and soils, and assessing comparative availability of N and P in soils with push-pull technology and those without.

1.3. Justification and significance of the study

Characterization of push-pull with regard to mitigation of climate change through carbon sequestration and BNF with reference to commonly practiced maize-based cropping systems in western Kenya is a contribution to achieving a bigger objective of assessing environmental footprint of cropping systems towards a complete shift to sustainable agriculture paradigm. This study contributes knowledge that can be used to achieve the targets set for sustainable development goals, especially the goal number 13: take urgent action to combat climate change and its impact (United Nations, 2018). This study also contributes information that can be used to achieve the target of 0.4% increase in SOC concentration yearly for healthy soils, food security and climate change mitigation in Sub-Saharan Africa (Minasny *et al.*, 2017). Findings from this study can be used by agriculture extension agents to further the adoption of push-pull technology. Information generated from this study can also be used in optimizing cereal-based cropping systems to reduce their environmental foot print without compromising farm productivity. This is very important as push-pull technology increases productivity and provides better management of crop pests such as stem borers, fall armyworm, and striga weeds.

1.4. Research hypotheses

Following were null hypotheses:

1. Cropping system, cropping time (years) and agro-ecological zone do not affect levels of carbon stocks both in plant biomass and soils.
2. Commonly intercropped food legume species and desmodium do not affect the availability of N and P, and performance of maize.

1.5. The general objective

The general objective is to understand how improvement of soil health by push-pull technology through sequestering carbon and fixing nitrogen from atmosphere can contribute to mitigation of climate change.

1.6. The specific objectives

Specific objectives were:

1. To determine effect of cropping system (push–pull and conventional maize systems), cropping time (years) and agro-ecological zones on carbon stocks.

2. To evaluate impact of cropping system on nitrogen and phosphorus availability with a focus on the effects of desmodium and food legumes.

1.7. Conceptual framework

Maize based cropping systems that integrate legumes have the potential to mitigate climate change. For example, additive intercrops increase plant density per unit area and capture relatively higher amount of C from atmosphere through photosynthesis. This leads to increased production of biomass above and belowground, and improved SOC and its sequestration. Legumes fix N biologically from atmosphere. Additionally, they (legumes) have ability to increase availability of P. This (increased availability of N and P) leads to better plant nutrition and productivity. With increased availability of N and P, the dependency on mineral N and P fertilizers decreases and emission of GHGs due to their (mineral N and P fertilizers) production and use reduces. Increased food production due to better plant nutrition insures reduced encroachment on new lands leading to reduced emissions due to degradation and deforestation. Consequently, reduced emissions due to production and use of mineral N and P fertilizers, reduced emissions due to degradation and deforestation, together with carbon sequestration contributes to mitigation of climate change. Figure 1.1 summarizes this conceptual framework of mitigating climate change in cropping systems.

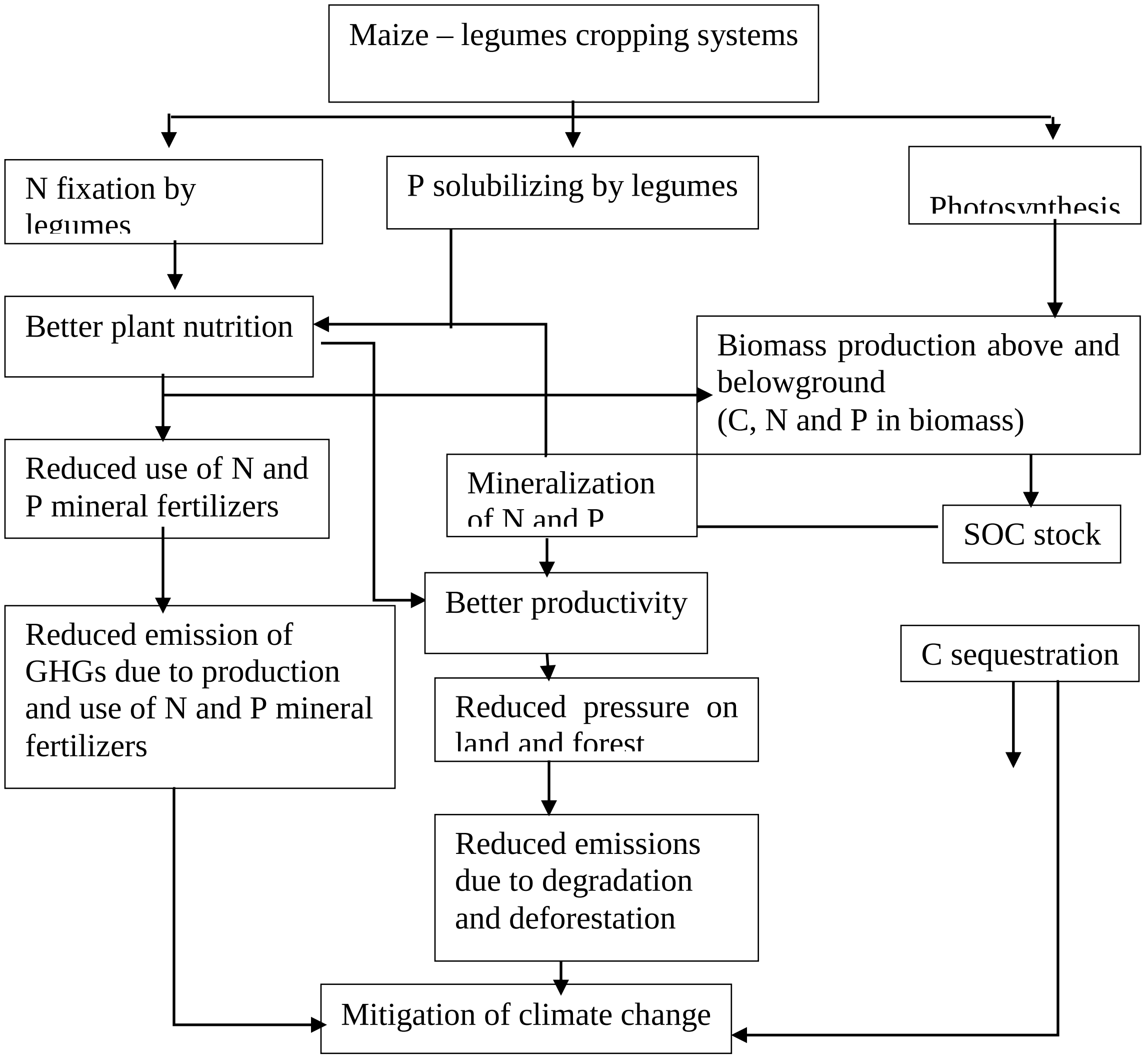

Figure 1.1. Conceptual framework of climate change mitigation through improved soil health

1.8. Scope of the study

This study involved both on-farm and on-station study using pre-established plots. On-farm, the study was done in three sites, Bondo and Siaya in Siaya county, and Vihiga in Vihiga county, representing respectively low, medium and high rainfall zones in western

Kenya. These sites belong to three different agroecological zones: LM3 (cotton zone), LM2 (marginal sugar cane zone) and LM1 (sugar cane zone), respectively for Bondo, Siaya and Vihiga. Findings of this study are relevant in similar environments. Additionally, these sites have striga as a challenge for cereal production. The performance of cropping systems reported herein can be used in environments having striga. Biomass C and SOC were used as indicators of C sequestration while N was used as proxy for BNF.

CHAPTER TWO

LITERATURE REVIEW

2.1. Introduction

Climate change, a shift in long term average of the weather for a given place and time (NOAA, 2007) is recognized to be a global challenge of the 21st century (FAO, 2004). Climate change, environmental degradation, and stagnating yields were recognized by FAO (2016) to threaten cereal production worldwide. With industrial evolution and invasion of cutting-edge technologies, humans triggered the rate of emission of GHGs through fuel combustion, cement making, land use and land use change (FAO, 2004). This led to the current climate change and global warming scenarios experienced today.

Soil health is the potential of soils to act as a crop nutrient reservoir (Singh and Ryan, 2015). It is characterized by good soil tilth, sufficient depth, good water storage and good drainage, sufficient supply but not excess of nutrients, small population of plant pathogens and pests, large population of beneficial organisms, low weed pressure, free of chemicals and toxins that may harm the crop, resistant to degradation, and resilient when unfavorable conditions occur (Moebius-Clune *et al.*, 2016). Soil organic matter is the backbone of soil health. It influences soil physical, chemical and biological properties (Singh and Ryan, 2015). Ways to increase soil organic matter include judicial use of mineral fertilizers combined with organic sources (FAO, 2011; Soka and Ritchie, 2016). Threats to soil health include soil compaction, erosion, acidification, salinization, contamination and organic matter decline.

For soil to be healthy, it needs to have a certain level of nitrogen and phosphorus and other crop nutrients to sustain crop production. The biological fraction of soils (soil microorganisms) plays an important role in availability and use of these essential plant nutrients. For example, inoculation of soils with arbuscular mycorrhiza fungi improve nitrogen and phosphorus uptake by soybean (Abdel-Fattah, 2001). However, excess of nitrogen in soils can lead to emission of N_2O. Therefore, management of soil health should be in a way which does not increase the rate at which GHG emission happens in the system.

Improvement of soil health positively affects the cycle of carbon, nitrogen and phosphorus, boosts carbon sequestration and reduces emission of GHGs in cropping systems. Cropping systems that produce high biomass sequester carbon and nitrogen in the system in the form of organic matter. When soil health is not sustainably managed, degradation takes place. This is indicated by decline of soil organic matter through emission of CO_2 and nitrogen oxides into the atmosphere and erosion. When soil is degraded, addition of mineral N leads to acidification through depletion of soil bases, buildup of soil aluminum, decreased soil pH and emission of N_2O (Singh and Ryan, 2015). In this case, P sorption becomes a challenge to plant P nutrition. Without adequate supply of N and carbon in the soil through addition of organic matter, beneficial soil biota is replaced by -harmful one and negatively affects soil processes. This reduces the ability of soils to supply nutrients to plants.

Efforts are being exerted to mitigate climate change through improving soil health. This can be achieved by sequestering carbon in soils and improving availability of N and P to crops. This chapter reviews the available information on mitigating climate change in agricultural systems through soil health improvement, with a focus on carbon sequestration, nitrogen fixation, and improved P plant nutrition.

2.2. Push-pull technology: Overview

2.2.1. Push-pull technology

Push-pull technology was developed years ago, to combat stem-borers in cereal-based cropping systems of smallholder farmers in east Africa. It is basically composed of a cereal crop (maize or sorghum) inter-planted with Desmodium. Desmodium is planted in mid spacing of maize (or sorghum) and maize (or sorghum) population is not affected (additive intercrop). One meter along the edge of the crop, Napier grass or Brachiaria or Sudan grass is planted in at least double row so that when one row is harvested the other one remains. Desmodium produces a smell which repels stemborer moths from maize fields. Napier grass (or brachiaria or Sudan grass) produces a substance which attracts female moths. Moths repelled by Desmodium are attracted by Napier grass (or Brachiaria or Sudan grass), and lay eggs on their leaves. When eggs hatch and larvae enter the stem, Napier grass produces a sticky substance which kills larvae (Cook *et al.*, 2007). In the case of brachiaria, trichomes limit the mobility of larvae and are fed on by their natural enemies recruited by brachiaria (Cheruiyot *et al.*, 2018). The pull effect of Napier grass/ brachiaria can extend up to 50 m; above that, another pull will be necessary. Recently, it was found that the push-pull technology controls the invasive fall armyworm that has become a new challenging scourge for cereal production in SSA (Khan *et al.*, 2018; Midega *et al.*, 2018).

Additional to its performance in limiting stem-borer and fall army worm, push-pull technology efficiently controls Striga weed due to smothering, provision of N through BNF, and allelopathic effect of desmodium (Khan *et al.*, 2002; Midega *et al.*, 2013). Push-pull technology is a crop-livestock production system as desmodium and Napier grass (and its substitutes) are fodder crops good for livestock feeding (Cook *et al.*, 2007).

2.2.2. Push-pull technology and nitrogen management

Push-pull technology, unlike monocultures of legume crops, is a cropping system associated with efficient N management. Nitrogen hazards due to deep percolation and emissions are reduced when legumes are intercropped with cereal crops than when legumes are grown in pure stands (Drinkwater *et al.*, 1998; Urbatzka *et al.*, 2009). When planted in pure stands, legumes leave high levels of mineral N in the soil. To recycle this N, it is recommended to immediately plant catch crops (Urbatzka *et al.*, 2009). Push-pull on the other hand, having maize or sorghum as the main crop might use the N that is produced by desmodium to improve its grain and biomass yield (maize or sorghum).

Annual legumes fix atmospheric N symbiotically and cater for even more than 50% of their N needs. However, due to the high N harvest index as a consequent of their high protein content of their grains, the balance is negative and their contribution of N to the soil is absent. Nevertheless, their soil N sparing effect results into positive effects on crops grown in rotation (Yusuf *et al.,* 2009). In push-pull technology, desmodium is a legume which fixes N symbiotically and is a perennial crop. Desmodium can provide both its soil N sparing effect plus the fixed N if it is ploughed in (not removed from the farm). If it is harvested, it will provide its soil N sparing effect to following crops. Additionally, roots and fallen leaves would provide N in the system. Push-pull technology is a conservation agriculture technology with minimum tillage and a permanent cover crop.

2.2.3. Economic and environmental implications of push-pull technology

Push-pull provides better returns to investment compared to conventional cereal-based cropping systems. Economic analysis of push-pull technology relative to conventional maize production, use of pesticides and mineral fertilizers reported benefit-to-cost ratio higher than 2.0 in push-pull, less in maize conventional cropping system, and more less when pesticides and mineral fertilizers were used (Khan *et al.,* 2014). An analysis based on 7 years of cropping period revealed that varying costs due to establishment and management of push-pull technology during initial year are enormous compared to conventional cropping systems of maize (Khan *et al.,* 2008b). Additionally, devotion of part of land to trap-plants and the impossibility of growing food legumes in push-pull were reported to be serious concerns by farmers (Khan *et al.,* 2009; Kebede *et al.,* 2018; Kuyah *et al.,* 2021). On contrary, the analysis revealed that the combination of all system outputs outbalanced all incurred expenses within the initial year (Khan *et al.,* 2008b). Since the end of first year of establishment, marginal benefits increase due to relative steady increase in yields, reduced management activities including weeding and land preparation activities (Khan *et al.,* 2014).

Higher economic returns in push-pull are due to considerable increase in maize yield compared to commonly practiced maize-legume cropping systems. Midega *et al.* (2014) did economic analysis of the push-pull technology compared to maize intercrops with food legumes including crotalaria, common bean, groundnut, green gram, cowpea, and the monoculture of maize. They (Midega *et al.*, 2014) reported higher net benefits and investment returns in push-pull technology compared to the rest of cropping systems tested (Midega *et al.,* 2014). Partial land equivalent ratio of maize varies between 0.8 and 2.6 for maize-legume intercrops (common bean, cowpea, crotalaria, green gram and groundnut), and 1.5 to 4.8 for push-pull, in Western Kenya (Midega *et al.,* 2014). This implies that push-pull controls environmental degradation and can restore soil fertility and productivity.

2.2.4. Push-pull technology and mitigation of climate change

Agricultural systems' management has significant bearing on GHG emissions, reduction, sequestration and mitigation processes (IPCC 2007, 2014). The report by IPCC (2007) endorsed 13.5% of anthropogenic emissions to agriculture, 70% of them being from nitrogen fertilizer manufacture and use with higher portions evolving from N_2O emissions. FAO (2016) recognized that integration of N fixing legumes in cropping systems adds N and decreases the need of synthetic N fertilizers, hence, reducing emissions. Additionally, intercropping maize and legumes limits weed germination and growth and suppresses the need of herbicides, hence reducing emissions (FAO, 2016). The same author praised push-pull system of East Africa to be a save and grow cereal production system with positive impact on livestock rearing.

A research by Urbatzka *et al.* (2009) on peas concluded that environmental risks of N are minimal when peas are grown in mixture with cereals thanks to increased N uptake by component crops, and storage in produced residues. A research done on monocultures of Desmodium intortum reported that desmodium can derive 94% of its N from atmosphere, and fix 24 to 183 kg of N ha^{-1} (Peoples and Crasswell, 1992). In western Kenya, desmodium can derive 34 to 64% of its N needs from atmosphere equivalent to 37 to 104 kg fixed N ha^{-1} per season (Ojiem *et al.*, 2007). Appropriate N use can contribute to restoring degraded soils through SOM improvement and increased biomass production, with consequent reduced loss of N as N_2O (Snyder *et al.,* 2009). Restoration of agroecosystems has the potential to sequester 1.2–3.1 billion tons carbon per year (Lal, 2011). Therefore, to assess the agro-system carbon stock or contribution to climate change mitigation calls for estimation of aboveground, soil, litter, and root carbon pools (Herold *et al.*, 2011; Powlson *et al.,* 2011).

2.3. Effect of cropping systems and cropping time on soil carbon stocks

2.3.1. Soil carbon

Soil carbon is composed of soil inorganic carbon, and soil organic matter. The soil inorganic carbon pool consists of elemental carbon and carbonate minerals. These (carbonate minerals) are gypsum, calcite, dolomite, aragonite, and siderite among others. Carbonate minerals are mainly subdivided into primary or lithogenic carbonate minerals derived from rock weathering (parent material), and secondary or pedogenic carbonate minerals formed through the dissolution of CO_2 in soil air to form carbonic acid which re-precipitate with Ca^{2+} or Mg^{2+} added into the soil as amendments or from other sources (Lal, 2007).

Soil organic matter on the other hand refers to all organic substances in the soil comprising of plant and animal residues at various decomposition stages, substances synthesized through microbial and chemical reactions, and biomass of live soil micro-organisms and other fauna along with their metabolic products (Lal, 2007). In agricultural systems, SOC is affected by plant shoot/root allocation together with root distribution through soil layers (Jobbagy and Jackson, 2000). Its balance (SOC) depends much on inputs from plant production and outputs through decomposition (Blair *et al.*, 1995; Jobbagy and Jackson, 2000).

2.3.2. Soil carbon sequestration and mitigation of climate change

Carbon sequestration in soils refers to transferring CO_2 from atmosphere into soil carbon pools and secure its long-term storage (Lal, 2007; 2008; Powlson *et al.*, 2011; Ontl and Schulte, 2012). Carbon sequestration is based on the natural process of photosynthesis (Lal, 2008; Ontl and Schulte, 2012).

Anthropogenic GHGs are increasing steadily (IPCC, 2014). The rate was 0.4 $GtCO_2$ eq per year between 1970 and 2000 and shifted to 1.0 $GtCO_2$ eq per year between 2000 and 2010. Anthropogenic GHGs are dominated by CO_2 (76%) followed by methane, nitrous oxides and fluorinated gases. The rate of increase of emissions of CO_2 from fossil fuel was 1.0% per year in 1990s and more than tripled to 3.2% per year between 2002 and 2011 (IPCC, 2014). During the same time (2002 – 2011), emissions due to deforestation and land use changes increased by 46.2%. Emissions recorded between 2000 and 2010 were from energy supply (47%), industry (30%), transport (11%) and building (3%)

sectors. Drivers of raise in GHG emissions are economic and population growth (IPCC, 2014).

Countries differ in emissions based on the level of economic development. In 2010, the median per capita GHG emissions from low economy countries was 1.4 tCO_2 eq per year, and was nine times less than per capita emissions from big economy countries. In low economy countries, emissions are mostly from agriculture, forestry and land use change. During the period of 2000 – 2010, emissions from agriculture were 5.0 to 5.8 Gt CO_2 eq/year (IPCC, 2014). These emissions from agriculture can be offset by building up SOC concentration (Keesstra *et al.,* 2016; Minasny *et al.,* 2017).

2.3.3. Cropping systems and soil carbon sequestration

2.3.3.1. Hidden costs of carbon sequestration in agro-ecosystems

Studies have been conducted comparing different cropping systems in terms of carbon sequestration. No till and conservation tillage have been reported to sequester more carbon than conventional tillage system. However, findings are not conclusive (Baker *et al.,* 2007). In addition, most of agricultural practices are sources of emissions. For example, application of N, P or K fertilizers per hectare of land emits 0.86, 0.17 and 12 kg C, respectively. Application of herbicides, fungicides and insecticides on one hectare of land emits 4.7, 5.2 and 4.9 kg C, respectively. The highest emissions are associated with chisel plowing or heavy tandem disking (1 ha emits 8 kg C), subsoiling and moldboard plowing (emits 11 and 15 kg C per ha, respectively), and pumping irrigation water (150 kg ha^{-1}) (Lal, 2004).

Schlesinger (1999) discussed hidden carbon costs associated with many of the techniques recommended to increase carbon sequestration in soils; (1) application of N-based mineral fertilizers to increase soil organic matter, (2) using irrigation to increase crop production on marginal and semi-arid lands, (3) growing plants under high CO_2

concentrations, and (4) use of manure. Hidden cost associated with these carbon management strategies are (1) high release of CO_2 through Haber-Bosch process for industrial production of ammonia, (2) emissions due to pumping water for irrigation, and (3) the need of relatively more land; 3 hectare are required to produce silage that can eventually produce manure for one hectare. On the contrary, conservation agriculture and regrowth of native vegetation on abandoned agricultural lands are proposed as clean strategies to sequester carbon in soils (Schlesinger, 1999).

Conservation agriculture reduces emissions and builds up SOC. In oxisols of Brazilian savanna, the natural savanna was converted into conventional agriculture in 1975 up to 1990. In 2000, the management of this land changed again to no-till crop land management. Assessment of carbon stocks at 0 to 40 cm of soil profile reported in 2017 shows improvement in carbon concentrations in soils, and no differences between cropland under no till and natural savanna when the assessment was based on equal soil mass methods, suggesting that no till maintains or improves soil carbon stock (Lammel *et al.,* 2017).

2.3.3.2. Carbon sequestration under different crop residue management and tillage systems

Cropping systems and residue management affect carbon sequestration into soil. For example, intercropping maize and soybean store more carbon into soils and produce enough crop residues to build-up satisfactory levels of SOC than monocrops of these crops; maize and soybean (Oelbermann *et al.,* 2017). Similarly, the monocrop of maize produces higher biomass and stores more carbon into soils than the monocrop of soybean (Oelbermann *et al.,* 2017). The differences are attributed to photosynthetic pathways of maize (C4) and soybean (C3); C4 plants are likely to be better mediators of soil carbon sequestration than C3 plants. The limitation of C3 plants is attributed to wasteful effects of photorespiration under tropical conditions (Bughio *et al.,* 2017).

Positive effect of crop residue addition on SOC sequestration was also reported from a nine-year experiment on a silt loam Typic Hapludults in Ohio, USA (Jha *et al.*, 2017). A significant increase in SOC within 10 cm upper soil layer was observed in that study (Jha *et al.*, 2017), and 80% of the quantified SOC was from added maize stover (Jha *et al.*, 2017).

No till, reduced till, and conservation agriculture affect the distribution of carbon along the soil profile (Baker *et al.*, 2007). Reduced soil tillage practices might increase soil compaction and soil strength, and increase resistance of soil to root penetration, leading to reduced movement of organic matter to lower soil profiles (poor distribution of SOC in the profile). On the contrary, conventional tillage loosens the soil and makes it workable by crop roots even below the plough layer. It may also bring about a high turnover of crop residue incorporation along soil profile during tillage, which may increase SOC stocks in soils. However, conventional soil tillage may on the other hand expose the pre-stored SOC to further oxidation and decomposition by microorganisms triggering release of stored carbon in the atmosphere. When loss of carbon becomes greater than its input, land degradation occurs (Lal, 2010).

Effect of tillage systems on carbon sequestration and farm productivity are still debatable. In France (temperate conditions), Viaud *et al.* (2011) studied the SOC and particulate organic matter in upper 40 cm soil layer under till with moldboard plough, shallow till, and no till. After 8 years of experiments, higher records of SOC and particulate organic matter were reported from upper 15 cm under no till and shallow till. However, moldboard plough showed greater records of SOC and particulate organic matter in lower layers (Viaud *et al.*, 2011). Bulk density was also greater under no till and shallow till. In the whole profile, there was no difference in carbon stock between no till, shallow till and moldboard plowing, suggesting a redistribution of organic matter and compensation between soil layers. Similar results were reported from Ireland by van Groenigen *et al.* (2011).

In China, practicing reduced till increased SOC in upper soil layers but reduced crop yield. When reduced till was reversed by deep tilling, yields were rehabilitated (Wang *et al.*, 2016). A study of a profile of 160 cm in the same country (China) reported reduction in SOC under till compared to no till, and increase of soil inorganic carbon (SIC) under till compared to no till (Bughio *et al.*, 2017), suggesting that carbon sequestration rates might be higher under till than no till. Therefore, the contribution of tillage systems on carbon sequestration is not yet conclusive especially on matters related to redistribution of SOC along the soil profile and the impact on farm productivity.

Cropping systems are hardly recognized as climate change mitigation avenues. In guidelines by the IPCC, estimation of carbon stock from biomass of annual crops is not accountable in climate change mitigation measures. This is because carbon stock in biomass of annual crops is assumed to be equal to annual losses through the same biomass. Only woody perennials are considered especially in agro-forestry systems (IPCC, 2006). Mitigation of climate change through residue management is only acceptable in regions where burning crop residues is common or when application of crop residues results in improved soil properties and biomass production to apply to soils or when application of crop residues leads to sustainable system productivity with relatively little use of synthetic inputs (Powlson *et al.*, 2011). In this case, the use of crop residues indirectly contributes to mitigation of climate change. Consequently, cropping systems that increase biomass production contribute to mitigation of climate change when the biomass is used to improve soil health.

2.4. Effect of cropping systems on nitrogen and phosphorus availability

2.4.1. Biological nitrogen fixation by legumes

Nitrogen fixation refers to the process through which a stable atmospheric dinitrogen (N_2) is reduced to N-ammonia so that it can be biologically useful (Giller, 2001). Though it is abundant in the atmosphere (78%), its atmospheric form (N_2) is not directly usable by plants. In legumes, BNF is facilitated by the association of rhizobia bacteria and root hairs of the plant in the presence of nitrogenase enzymes. The product of the process benefits first the host plants as rhizobia bacteria are not diazotrophs. This process contributes a significant amount of N into cropping systems (Boddey *et al.,* 2000). Globally, the BNF contributes 50–70 Tg N per annum (Herridge *et al.,* 2008). This amount is from pulses (2.95 Tg), oilseed legumes (18.5 Tg), fodder legumes and pastures (12 – 25 Tg), rice (5 Tg), sugar cane (0.5 Tg), other non-legume crop lands (< 4 Tg), and extensive savannas (< 14 Tg). These estimations imply that annual BNF is equivalent to 108.7 to 152.2 Tg of urea fertilizer and avoids emission of 543.5 to 760.8 Tg CO_2 eq per year due to urea production and use.

Biological processes of nitrogen fixation provide a better option in sustainable crop production (Peoples *et al.,* 1995). It has been established that soils under legumes have high mineral N at legume harvest which is lost to environment when not judicially managed (Urbatzka *et al.,* 2009). Part of this mineral N is obviously from atmosphere through BNF. Some legumes are known to have positive balances of N fixation when N fixed from atmosphere and N removed by harvested parts is taken into account (Peoples *et al.,* 1995). Therefore, when N from atmosphere, reaches the soil system through BNF, it should be managed with similar care as N from synthetic fertilizers. Fortunately, N from BNF is less susceptible to losses than N from mineral sources (Drinkwater *et al.,* 1998).

Integrating legumes in cropping systems can be a source of nitrogen for crop nutrition. In Australia, perennial legume fodder species significantly contributed to building up soil organic nitrogen (Peoples *et al.,* 1995). This is a highly valuable soil characteristic along with soil carbon for agriculture sustainability. In Western Kenya, desmodium was fund to fix 35 to around 100 kg N per season (Ojiem *et al.,* 2007). In the same environment (Western Kenya), maize that received 120 kg N ha^{-1} produced around 2.0 Mg grain ha^{-1}, versus 5.0 Mg grain ha^{-1} and above obtained when maize was grown with desmodium (Midega *et al.,* 2013). This was partly due to BNF by desmodium and its suppressive effect on striga weed. The contribution of N by annual legumes is not as high as that for perennial legumes (Peoples *et al.,* 1995; Ojiem *et al.,* 2007), but their rotational effect is positive in most cases (Yusuf *et al.,* 2009). In Rwanda, growing maize after common bean or soybean increased the yield from around 1.0 to 2.0 Mg ha^{-1} to above 5.0 Mg maize grain ha^{-1} (Rurangwa *et al.,* 2018). This is due to relatively higher levels of Nitrate-N in soils directly after legumes and during the growth of the successor plant. This is because legumes have N sparing effect. They (legumes) use more of fixed N than soil N (Peoples *et al.,* 1995; Yusuf *et al.,* 2009). N from fallen leaves and residues, decaying roots and microbes contributes to nitrate-N in soils just after legumes. This shows that integrating legumes in cropping systems can substitute a considerable amount of N mineral fertilizer.

Using legumes as a source of N in cropping systems contributes to mitigation of climate change. This is because carbon sequestration in cropping systems is nutrient dependent. Eighty million tons of N (80 Mt N), 20 Mt of P, and 15 Mt of K are needed to sequester 1 Gt of carbon in agriculture ecosystems (Lal, 2004). Biological N fixation by legumes through adoption of complex or diverse cropping systems has been proposed in order to mitigate climate change (Lal, 2011). Endeavors to replace synthetic N fertilizers with N from BNF definitely leads to mitigation of climate change, but indirectly. This would be established by estimating N equivalency of BNF in cropping systems and compute costs associated with producing and using the same amount of N from synthetic sources. For example, to produce and use 1 kg of N generates emissions as high as 5 kg CO_2 equivalent which equates 1.36 kg C per kg N produced (Powlson *et al.,* 2011).

2.4.2. Phosphorus availability in cropping systems

Phosphorus limits crop production. This is due to its low diffusion and high fixation in soils (Shen *et al.,* 2011). Most soils from SSA are acidic and highly weathered. In these conditions, P is adsorbed by oxides and hydroxides of aluminum and iron (Shen *et al.,* 2011) and is not available to plants. Managing P in cropping systems is a challenge. It is supplied as P containing mineral fertilizer or rock phosphates. It is also supplied by applying manure, compost, and green manure (Pypers *et al.,* 2005; Cabral da Silva *et al.,* 2012), but its content in these organic sources is very low and can hardly sustain satisfactory yields (Nziguheba *et al.,* 2016). Uptake of P by plants depends on the orthophosphates in the soil solution, which is available to plant roots and the labile P from the solid phase which replenishes the P taken up by the plant from the soil solution (Pypers *et al.,* 2006). In Western Kenya, maize production is reduced by 50% when P is omitted from NPK fertilizer (Nziguheba *et al.,* 2016).

Soil microorganisms play a role in plant P nutrition. Studies have shown that there is a positive relationship between presence and low disturbance of soil mycorrhiza and uptake of P by maize (Miller, 2000). This is because plants develop inorganic P transporters which facilitate the uptake of phosphates from the plant's peri-arbuscular membrane, a trait which varies among plant species (Walder *et al.,* 2016). A review by Miyasaka and Habte (2001) documented other mechanisms through which plants increase their P uptake. To increase its P nutrition, the plant modifies the pH in its rhizosphere to solubilize phosphates held by calcium (by decreasing the pH) or aluminum and/or iron (by increasing the pH) (Miyasaka and Habte, 2001). To facilitate this process, it is advisable to apply NH_4^+ and/or NO_3^- containing mineral fertilizers.

Another mechanism is the release of root exudates which are basically organic acids (citric, oxalic, malonic, and piscidic acids) to solubilize the phosphorus bound by calcium, iron and aluminum (Miyasaka and Habte, 2001). It was reported that plants such as maize release sugars instead of acids. The released sugars are chemically transformed into organic acids by bacteria to serve the same purpose of solubilizing the inorganic phosphorus (Miyasaka and Habte, 2001). Plants also use the production of extracellular phosphatases, while others are believed to have cell wall bound sites which solubilize iron phosphates by means of phenolic acids, lignins, or enzymes which could chelate the iron (Miyasaka and Habte, 2001).

Integration of legumes in cropping systems increase available P to crops grown together. Intercropping maize and Faba bean in China resulted in increase of maize yield by 43.0% and that for faba bean by 26.0% (Li *et al.*, 2007). The yield obtained when maize was intercropped with faba bean was similar to the yield obtained when maize had received 112 kg P ha^{-1} in the form of mineral fertilizer. It was established that maize had uptaken P that was mobilized by faba bean through acidification of its rhizosphere (Li *et al.*, 2007). In Nigeria, Vanlauwe *et al.* (2000) observed the increase in P uptake by mucuna (*Mucuna pruriens (L.)*) when it was supplied with rock phosphate than when the rock phosphate was absent and showed that mucuna solubilized P contained in the rock phosphate. Therefore, legumes would solubilize aluminum and ion phosphate compounds in acidic soils and improve P crop nutrition.

CHAPTER THREE

MATERIALS AND METHODS

3.1. Introduction

This research was done in farmers' fields in western Kenya (on-farm) and at *icipe* Thomas Odhiambo Campus (on-station). On-farm studies were used to evaluate effect of cropping systems and cropping time on system productivity, biomass and soil carbon stock (section 3.2) while on station experiments were used to evaluate effect of cropping systems on nitrogen and phosphorus availability (section 3.3). This chapter gives details on materials and methods used in these experiments and analyses done.

3.2. Effect of cropping systems and cropping time on soil carbon stocks

3.2.1. Study sites

This study was conducted in three sites in western Kenya: Bondo and Siaya in Siaya county and Vihiga in Vihiga county (Figure 3.1). These sites represent regions with contrasting agro-climatic conditions: high rainfall (Vihiga, 1800–2000 mm), medium rainfall (Siaya, 1200–1800 mm) and low rainfall (Bondo, 750–1200 mm) (County Government of Siaya 2018; County Government of Vihiga 2018). The study sites also vary in elevation, with a gradient from low in Bondo (1100–1350 m), medium in Siaya (1140–1400 m) and high in Vihiga (1300–1800 m). The climate in the area is sub-humid tropical (Vihiga and Siaya) and semi-arid (Bondo). These sites belong to LM3 which is a cotton zone (Bondo), LM2 or marginal sugar cane zone (Siaya), and LM1 of sugar cane zone (Vihiga) (Jaetzold and Schmidt, 1982). Rainfall in western Kenya is bimodal. Long rains (LR) are received between April and July while short rains (SR) occur between September and November. Due to climate variability/irregular and unreliable rainfall, the onset of corresponding long and short rain seasons varies in subsequent years. Soils in the study area are mainly Acrisols, Ferralsols and Nitisols (Jaetzold *et al.*, 2009). Soil texture varies from sandy loam in Bondo and loamy sand in Siaya and Vihiga. Table 3.1 summarizes characteristics of study sites.

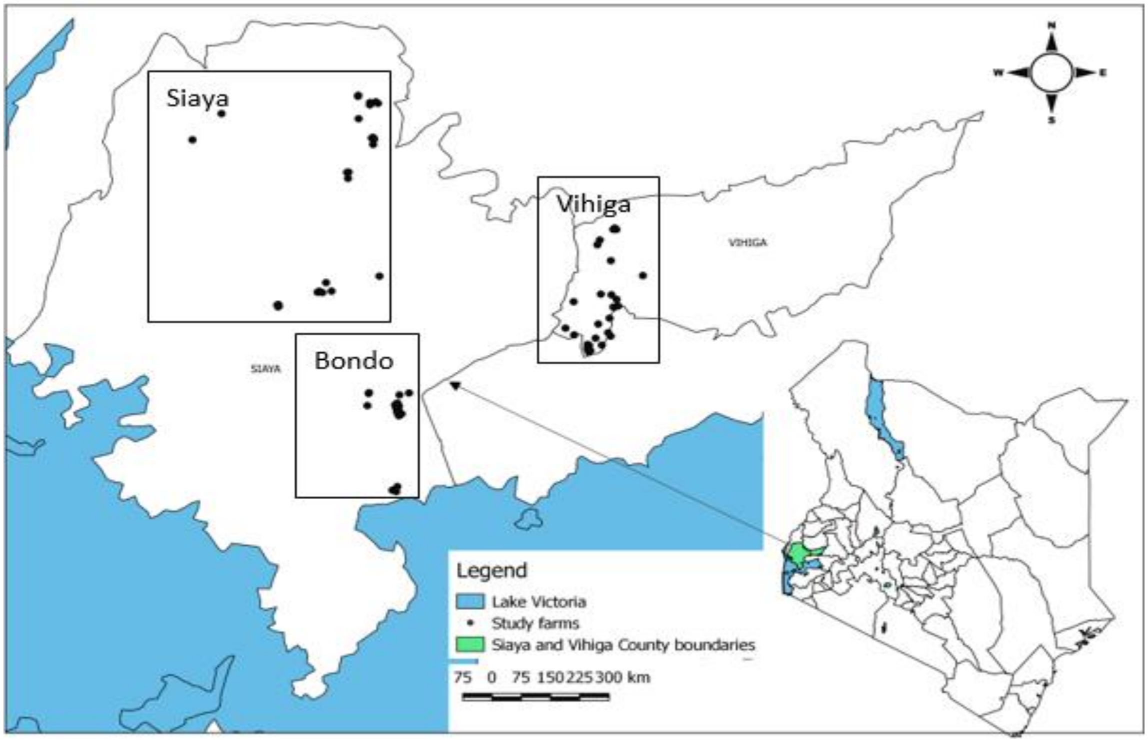

Figure 3.1. Location of study sites within Siaya and Vihiga counties in western Kenya Source: This study.

Table 3.1. Biophysical and climatic characteristics at three study areas for on farm experiments in western Kenya.

Site	Agro-ecological zone	Location (latitude; longitude)	Population density (persons per km^2)	Soil texture	Elevation (m)	Rainfall regime	Study cropping seasons	Rainfall (mm)	Seasonal temperature (°C)	
									Minimum	Maximum
Vihiga	LM1, sugar cane zone	0° – 0°15’N; 34°30’– 35°0’E	1033	Loamy sand	1300-500	Bimodal (short and long rains)	2017 LR	1137.8	17	35
							2017 SR	1391.0	19	33
							2018 LR	1977.2	18	28
Siaya	LM2, marginal sugarcane zone	0°26’S – 0°18’N; 33°58’– 34°33’E	316	Loamy sand	1135-1500	Bimodal (short and long rains)	2017 LR	1137.8	17	35
							2017 SR	1391.0	19	33
							2018 LR	1977.2	18	28
Bondo	LM3, cotton zone	0°2’– 0°25’S; 34°0’– 34°33’ E	246	Sandy loam	1135-1350	Bimodal (short and long rains)	2017 LR	687.9	17	30
							2017 SR	856.3	18	31
							2018 LR	1108.5	17	27

Source: Jaetzold and Schmidt (1982), County Government of Siaya (2018), County Government of Vihiga (2018), Weather and Climate (2022).

Agriculture, particularly crop farming and livestock keeping are the main sources of livelihoods in western Kenya. Agricultural production is predominantly smallholder-rainfed for subsistence (Kuyah *et al.*, 2012, 2013). Land holdings are generally small due to fragmentation in the process of passing it from parents to offspring. Average farms are relatively bigger in Bondo (3.0 ha) than in Siaya (1.02 ha) and Vihiga (0.41 ha). Land preparation is mainly done by oxen or tractors in Bondo and Siaya and hand hoeing in Vihiga. Cereals (e.g. maize, sorghum, and millet) are traditionally intercropped with legumes such as common bean, groundnut, cowpea or green gram. Other food crops common in smallholder farms include sweet potatoes (*Ipomoea batatas* (L.) Lam.), cassava (*Manihot esculenta* Crantz) and vegetables (County Government of Siaya, 2018; County Government of Vihiga, 2018). Soil infertility, irregular and unreliable rainfall, pests (weeds such as striga and insect pests such as stem-borers and fall armyworm) are major constraints to crop production in the region. Push-pull technology is also practiced in western Kenya.

3.2.2. Experimental design

A factorial design was employed with agro-ecological zone (LM3 represented by Bondo, LM2 represented by Siaya and LM1 represented by Vihiga) as the main factor, followed by the duration of time push-pull had been practiced in a farm, and thirdly by cropping systems (push-pull and non-push-pull). In each site (agro-ecological zone), farmers who use push-pull were categorized according to how long they had practiced the technology; below 2 years, between 2-5 years and above 5 years. Four farms were randomly selected in each category (push-pull age), giving a total of 12 farms per site (agro-ecological zone) and 36 farms across the three sites (agro-ecological zone). Initially, five farms were selected per each category of period of adoption of push-pull, and four qualified for analysis. This was because some samples were lost in the process of sample handling before analysis was done. To select study farms, a list of farmers that adopted push-pull showing the year of adoption was provided by field agents working with *icipe* in Bondo, Siaya and Vihiga. Random numbers were generated in excel spread sheet and farmers whose number on the list corresponded to the generated random number was picked for the study. The number of farms was decided based on availability of funds and the minimum number of acceptable replicates. Each push-pull farm was assigned the control farm on which maize was practiced either as a monoculture or with a companion legume crop. Control farms were as close to push-pull farms as possible to minimize intra-farm soil fertility and management gradient or time for land use change to cropland. There was no soil sampling and analysis done at the beginning of experiments because adoption of push-pull was driven by control of stem borer and striga and not by improvement of soil fertility and health. It was assumed that soils in push-pull and non-push-pull farms were similar before push-pull was adopted, and therefore, any change that is observed in this study was due to adoption of push-pull technology. The study covered three cropping seasons: 2017 LR, 2017 SR, and 2018 LR.

3.2.3. Establishment of experiments and management of crops

Push-pull plots were established by intercropping maize with *Desmodium intortum* in 1:1 row arrangement and planting *brachiaria* on the border of the plot. Maize was planted at 0.75 m x 0.30 m inter and intra-row spacing. Desmodium was planted at equidistance between rows of maize (0.375 m from a row of maize). Desmodium seeds were drilled when the plots were established at the beginning of the first season and gap-filling done regularly to replace seedlings that had not geminated. At the beginning of subsequent seasons, desmodium was trimmed before planting maize and left to grow throughout the season to control striga, stem-borers and fall armyworm and to improve soil fertility. Three rows of brachiaria were planted at the farm border at 0.50 m between rows and 0.50 m within rows at the start of the first season. Bracharia was harvested depending on farmers' need for fodder. At least one row of fully grown brachiaria was always retained around the border to maintain the function of a "pull" function (trap insect pests) of push-pull. Push-pull farms were established following the model documented in push-pull curriculum for farmer field school (*icipe*, 2007). In control farms (maize monocrop, maize-bean, maize-cowpea, maize-green gram and maize-groundnut), maize was planted at 0.75 m x 0.30 m. Legumes in control farms (common bean, cowpea, green gram or groundnut) were planted in a 1:1 maize-legume row arrangement. The intercropped legume was planted approximately at 0.30 m in the row. Push-pull plot sizes varied between 13 m × 11 m and 42 m × 26 m. Control plots of approximate size as push-pull plots were used.

Land preparation was done using a hand hoe for both push-pull and control plots. In push-pull plots, the soil was worked in strips between desmodium rows leaving approximately 60% of the farm undisturbed. In control farms, the totality of the land was worked. Mineral fertilizers were applied in push-pull and control farms at a rate of 60 kg DAP ha^{-1} at planting and 60 kg CAN ha^{-1} at six weeks after planting equivalent to 27 kg N, 12 kg P and 4.8 kg Ca ha^{-1}. Weeding was done manually, twice in a season. There was no pesticide application in both push-pull and control farms during the study period. Crop residues were removed from farms. Regular visits and interaction with farmers ensured that farmers applied management activities uniformly in push-pull and respective control plots.

3.2.4. Estimation of biomass carbon and soil organic carbon

3.2.4.1. Estimation of biomass carbon stock

Biomass carbon was estimated as the total amount of carbon contained in aboveground biomass (shoots, grains and cobs) of crops grown in a farm. A four-step approach was used: 1. estimation of the dry matter of the shoot, grain and empty cobs of the crop grown in a farm, 2. estimation of the amount of carbon contained in each of these components using the carbon content value identified from published literature, 3. estimation of the total amount of carbon per crop grown in a farm by adding the amount of carbon stored in its different parts and 4. estimation of the amount of carbon stored aboveground in a farm by adding the amount of carbon for each crop grown in the farm. Maize plants were harvested from randomly selected 3 m x 3 m quadrats in push-pull and control plots. Cobs were separated from stovers and the plant cut at 5 cm above the ground. Cobs and stovers were immediately weighed in the field using a spring balance. A random sample of five cobs having grains and five stovers was taken and weighed immediately using a 6.0 kg weighing scale (0.1 g portable electronic weighing scale). The samples (stover and cobs) were transported to the laboratory, oven-dried at 65 °C to a constant weight and their dry weight determined using a 6.0 kg weighing scale (0.1 g portable electronic weighing scale). The ratio of the dry weights of the stover, cobs and grain to the respective sample fresh weight was multiplied with the fresh weight of the components determined in the field to obtain component dry weight. The amount of carbon contained in maize components was estimated by multiplying their dry matter with their respective carbon content. Values of carbon content that were used for maize are 22.2% for stover, 13.9% for grains and 4.3% for cobs, and were sourced from (Ma *et al.,* 2018).

Shoots of desmodium, brachiaria, common bean, cowpea, green gram and groundnut were harvested from randomly selected 1m long quadrats along their respective rows. Harvested material was stacked in a tared sack and their fresh weight determined in the field. The crop materials were transported to the laboratory, oven dried at 65 °C to a constant weight and their dry weight determined. The amount of carbon in these materials was estimated by multiplying their dry matter yield with a carbon fraction of 42.3% (Ma *et al.,* 2018). Estimation of biomass carbon was done in two last seasons of the study (2017 SR and 2018 LR). It was not done in 2017 LR due to limited equipment. This season (2017 LR) did not affect findings as analysis was done season by season. Additionally, a full cycle was achieved because data were collected in short and long rain season.

3.2.4.2. Estimation of soil organic carbon stock

The amount of carbon stored in soils was estimated for 0-15 cm topsoil layer. Soil sampling was done from the inner two-thirds of each plot between the maize rows. Nine random cores were taken from each of the push-pull and control plots immediately after harvesting maize. Visible plant debris deposited on soil surface was removed and soil cores collected using a 2 cm diameter soil auger. The nine subsamples were bulked to a composite sample and transferred to the laboratory, where they were air-dried, ground, visible organic debris removed and sieved through a 2 mm sieve. The soil samples were analyzed for total organic carbon content using Walkley and Black wet oxidation method together with colorimetric method using ultraviolet visible spectroscopy (UV-Vis). At the end of 2018 LR season, five random samples from undisturbed soil were collected from push-pull and control farms for determination of bulk density in the 0-15cm depth. The volume of soil in 0-15 cm topsoil layer (1,500 m^3) per hectare together with soil bulk density (g/cm^3) and soil carbon content (g of carbon per kg of soil) were used to estimate the amount of carbon stored in the 0-15 cm depth per hectare in both push-pull and control farms.

3.2.5. Striga counts

In each season, fifteen randomly selected plants (avoiding plant within one meter from the border because of possible edge effects) were used to assess striga emergence per m^2. The number of emerged striga were counted from a radius of 15 cm around the maize plant base (Midega *et al.,* 2014). The average per maize plant was calculated and extrapolated to a square meter surface by multiplying the average per plant with the number of plants per square meter.

3.2.6. Statistical analysis

Mixed effect model run by restricted maximum likelihood was used to determine differences between push-pull and control farms, and to test the effects of the duration of time push-pull had been practiced in a farm, sites and their interaction. The farm was fitted in the model as a random effect. Striga counts were analyzed by fitting the negative binomial model. The initial theta was set at 2, and the link was 'log'. The output of the model was analyzed for deviance using 'ANOVA function'. Mean separation was done using 'emmeans' function for mixed effect model and 'glht' function for negative binomial model; for both models, "Tukey" test was used to separate means at α=0.05. The analysis was done per season. All statistical analysis was done in R version 3.6.3 (R Core Team, 2020).

3.3. Effect of cropping systems on nitrogen and phosphorus availability

3.3.1. Study area

The study was conducted on a long-term experiment established in 2003 at the *icipe's* Mbita Point Field station located (latitude: 0°25'S, Longitude: 34°12'E; elevation: 1200 m) on the eastern shores of Lake Victoria in Suba North constituency, Homabay county in western Kenya (Khan *et al.,* 2007). The climate in the area is tropical with annual mean temperature of 27 °C (minimum = 15 °C, maximum = 30 °C). The area receives an annual rainfall of approximately 900 mm distributed in two seasons: long rainy (March–August) and short rain seasons (October–January). Mbita belongs to LM4 or marginal cotton zone agro-ecological zone. Climate change and variability brought about irregularity in season onset and end as well as rainfall amount and distribution within a season. During the study period, temperatures varied between 17 and 30°C in 2017 LR, 18 and 31°C in 2017 SR, and 17 and 27°C in 2018 LR (Weather and Climate, 2022). Figure 3.2 shows cumulative seasonal rainfall amount and distribution during the study period. Soils at the Mbita station are sandy clay loam.

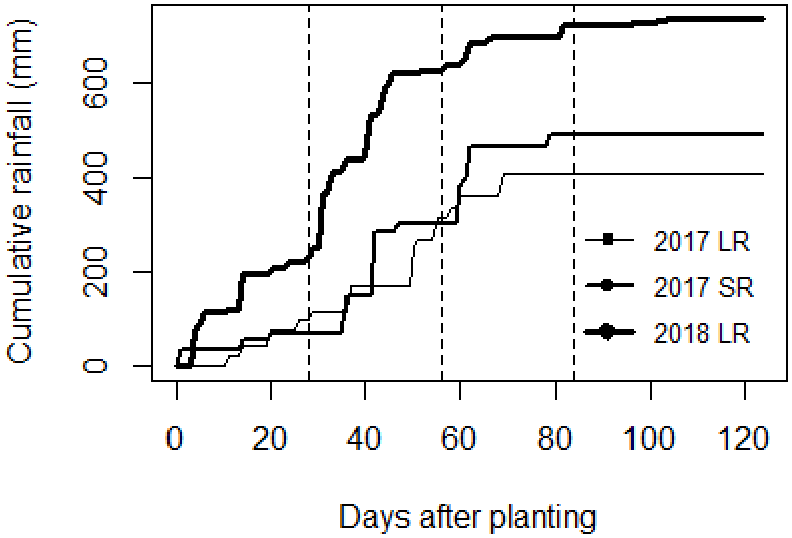

Figure 3.2. Cumulative rainfall in 2017 long rain (LR), 2017 short rain (SR) and 2018 LR at *icipe*-Mbita Point

3.3.2. Experimental design and management of crops

This study was conducted from a long-term experiment, and this section summarizes the history of establishment and management of the experiment till the end of this study. The experiment was established in 2003 with a completely randomized design with four replicates for each treatment. Treatments consisted of six maize-legume intercrops; maize-bean, maize-cowpea, maize-crotalaria, maize-desmodium, maize-green gram and maize-groundnut. A maize monocrop was used as a control. During the first four seasons (long and short rain seasons for 2003 and 2004), a commercial hybrid 503 that is medium maturing and susceptible to striga was used (Khan *et al.*, 2007). Since 2005 till 2018 (a period that includes the three seasons of this study), the maize hybrid WH505 from western seed company limited was used (Midega *et al.*, 2014). For legumes, the local varieties for bean (Nyayo), groundnut (Homabay), cowpea (ICV2), green gram and crotalaria were used since 2003. In the two seasons of 2017 (long rains and short rains), cowpea and green gram were severely affected by flies that attacked them at flowering causing abortion and falling of young pods. Therefore, in 2018 LR, the variety of cowpea and green gram were changed to K/80 and N/26, respectively. Similarly, Rosekoko 8 (KK 8) variety of common bean was used instead of Nyayo. These varieties (for cowpea, green gram and common bean) were from East Africa seed company limited, Nairobi.

Crops were planted at the onset of rainfall during three consecutive seasons (2017 long rain, 2017 short rain, and 2018 long rain) following the methods used since the beginning of the experiment (see Khan *et al.*, 2007) on plots measuring 5 m by 6 m, separated from each other by 2 m. Maize was planted at 0.75 m between rows and 0.30 m within rows and thinned two weeks after germination to one plant per hill. Common bean, cowpea, crotalaria, green gram and groundnut were planted every season at the middle of the maize rows. The within row spacing for legumes was 0.30 m, except crotalaria which was drilled. Desmodium which is perennial was planted in 2003 (when the experiment was established first) by drilling between maize rows, gap filled when necessary, trimmed every season before planting maize and left to grow throughout the season. At the beginning of the experiment in 2003, each plot was infected with 100 seeds of *Striga hermonthica* per 250 g of soil (Khan *et al.*, 2007).

Land preparation was done by oxen plough one month before planting, corresponding to mid – August and mid – February, respectively for short and long rains seasons. Plots were kept free from weeds (except striga) by hand weeding twice in a season. Di-ammonium phosphate (DAP 18-46-0) and calcium-ammonium nitrate (CAN 27-0-0) fertilizers were applied at 60 kg ha^{-1} each at planting and thinning, respectively, equivalent to 27 kg N, 12 kg P and 4.8 kg Ca ha^{-1}. Crop residues for maize and annual legumes (common bean, cowpea, green gram and groundnut) were removed from plots immediately after harvesting to simulate the practice of farmers in the region. Residues of crotalaria were cut down and removed at land preparation (one month before planting). Desmodium remained in the plot since it was planted in 2003 and trimmed at land preparation. Trimming removed desmodium parts from the maize planting strip (approximately 0.30 m wide) between two adjacent rows of desmodium. Trimmed materials were immediately removed from the plot. There was no application of pesticides throughout the study period.

Before planting for the 2017 long rains season, a composite soil sample was collected from each plot to characterize the status of plots before the study. Soils for experimental plots were alkaline (pH > 7.0) with relatively higher levels of P in plots for maize-desmodium and maize-groundnut, low available N in plots for maize monocrop and maize-green gram, and higher electric conductivity in plots for maize-crotalaria (Table 3.2). Additionally, levels of striga infestation were lower in maize-desmodium than maize monocrop and other maize-legume intercrops (Khan *et al.,* 2007; Midega *et al.,* 2014).

Table 3.2. Characteristics of soils for treatments at the beginning of 2017 long rains season (the 15th year of experiment) at the on station trial at Mbita station

Characteristic	Unit	Maize – monocrop	Maize – desmodium	Maize – crotalaria	Maize – bean	Maize – groundnut	Maize – green gram	Maize – cowpea
pH (H_2O)		7.9 ± 0.4	7.7 ± 0.2	8.4 ± 0.3	7.8 ± 0.4	7.2 ± 0.0	7.6 ± 0.2	8.1 ± 0.6
Nitrate	mg kg^{-1}	0.0 ± 0.0	1.1 ± 0.8	2.4 ± 0.1	0.3 ± 0.3	0.4 ± 0.3	0.1 ± 0.1	0.3 ± 0.0
Ammonium	mg kg^{-1}	4.4 ± 0.1	5.1 ± 0.0	4.7 ± 0.0	5.6 ± 0.7	5.5 ± 0.7	4.5 ± 0.1	5.4 ± 0.1
Total available N	mg kg^{-1}	4.5 ± 0.1	6.3 ± 0.8	7.1 ± 0.0	5.9 ± 1.0	5.9 ± 1.0	4.7 ± 0.0	5.8 ± 0.1
Phosphorus	mg kg^{-1}	16.7 ± 7.9	38.6 ± 6.7	8.4 ± 3.1	16.4 ± 5.9	25.8 ± 1.4	18.9 ± 0.6	13.2 ± 10.2
Cation Exchange Capacity (CEC)	meq/100 g	50.4 ± 8.7	45.1 ± 3.2	55.3 ± 6.6	47.3 ± 1.2	41.6 ± 0.8	42.9 ± 0.0	52.5 ± 8.0
Electric Conductivity (EC)	µS/cm	68.4 ± 36.5	86.1 ± 27.9	111.9 ± 18.1	56.1 ± 18.2	38.6 ± 1.5	47.6 ± 3.0	81.0 ± 42.9
Potassium (K^+)	mg kg^{-1}	299.5 ± 27.5	312.5 ± 8.5	272 ± 5	294.5 ± 18.5	241.5 ± 1.5	260.5 ± 21.5	255.5 ± 5.5
Calcium (Ca^{2+})	mg kg^{-1}	6715.0 ± 1585.0	5865.0 ± 465.0	7610.0 ± 990.0	6060.0 ± 390.0	5210.0 ± 100.0	5450.0 ± 40.0	6795.0 ± 1285.0
Magnesium (Mg^{2+})	mg kg^{-1}	1695.0 ± 85.0	1560.0 ± 100.0	1670.0 ± 130.0	1705.0 ± 85.0	1555.0 ± 35.0	1575.0 ± 35.0	1810.0 ± 100.0
Sodium (Na^+)	mg kg^{-1}	60.8 ± 2.3	75.4 ± 23.6	238.0 ± 135.0	79.2 ± 12	58.2 ± 4.8	67.7 ± 12.4	257.0 ± 184.9
Soil bulk density	g/cm^3	1.20 ± 0.03	1.22 ± 0.06	1.31 ± 0.09	1.19 ± 0.04	1.19 ± 0.05	1.29 ± 0.01	1.25 ± 0.05

3.3.3. Estimation of N and P availability, biomass and grain yield

3.3.3.1. Estimation of N and P availability

Available N and P were measured at 4, 8 and 12 WAP corresponding to V6 (stem elongation), V14-V15 (critical for kennel formation), and R4 (dough) growth stages, respectively, critical for growth and grain yield (Wu *et al.*, 2008; Ransom, 2013). These measurements are proxies of levels of N and P available to plants in a cropping system in a season. A composite sample of nine cores (three from upper, three from middle and three from lower part of the plot) was collected from each plot at 0-15 cm topsoil. Sampling was done at 18.75 cm from a row of maize (1/4 the inter-row spacing) corresponding to the mid-distance between the row of maize and the row of intercropped legume (in intercrops). Soil samples were air-dried, ground and sieved through a 2 mm sieve prior to analysis. Nitrate and ammonium were extracted using 2 M KCl and analyzed colorimetrically using automated discrete analyzer. Phosphorus was extracted by Mehlich 3 solution and determined using inductively coupled plasma optical emission spectroscopy (ICP-OES). Soil bulk density was estimated by taking five random cores per each plot, drying the sample in oven till constant weight, and calculating its mass per volume (g/cm^3). N and P concentration in soil and soil bulk density were used to estimate available quantities of N and P in kg ha^{-1} at 4, 8, and 12 WAP (availability at sampling time).

3.3.3.2. Estimation of biomass and grain yield, and striga emergence

At the time of soil sampling, five randomly selected maize plants were cut for estimation of shoot weight. The plants were oven-dried at 65°C to a constant weight and their dry weight determined. Legume biomass was assessed by sampling a band of 1.0 m selected randomly in a row picked randomly in a plot. Sampling was done at maximal growth of legume species which corresponds to 50% podding for grain legumes. Desmodium was sampled at physiological maturity of maize. Samples of legumes were oven dried at

65°C to a constant weight and their dry weight was recorded. To avoid edge effect, the two extreme rows of maize and two maize plants at either side of each row were ignored during final harvesting. Maize plants were counted, cobs separated from stover, and stover cut at 5 cm above soil level. The stover was immediately weighed using a spring scale and weight from farm recorded. Five random stovers were then collected and immediately weighed at the farm, oven-dried at 65°C to a constant weight to determine their dry weight which was used to estimate stover yield per hectare. Cobs were air-dried, threshed, and grain weight recorded at 12.5% moisture content. Legumes grain yield was estimated by hand picking pods, drying them in the sun and separating them from grains by hands. Grain yield was estimated at 12.5% moisture content. Striga counts were recorded following the method described in section 3.2.5.

3.3.4. Statistical analysis

Differences in N and P and maize shoot weight between cropping systems were compared at every growth stage (4, 8 and 12 WAP) for every season. Measurements at 4 WAP were not taken in the first season (2017 LR). Similarly, maize grain and stover yield and legume biomass and grain yield were compared per season. Comparison of N and P, shoot weight, grain and stover yield, and legume biomass and grain yield was done using mixed effect models run by restricted maximum likelihood. The replication was used as a random factor. To compare means, 'emmeans' function was used. 'Tukey' test was used to separate means. Striga counts were analyzed as described in section 3.2.6. Unless stated otherwise, the level of significance was $\alpha = 0.05$. All statistical analyses were done in R software version 3.6.3 (R Core Team, 2020).

CHAPTER FOUR

RESULTS

4.1. Introduction

This chapter presents results in two major sections. The first section reports carbon stocks while the second reports effects of legumes on availability of N and P. Each section contains results on crop yield and striga counts. The chapter ends with a summary of key findings to be discussed.

4.2. Effect of cropping system, cropping time and agro-ecological zones on carbon stocks

4.2.1. Biomass carbon

The amount of biomass carbon was significantly higher in push-pull farms than non-push-pull farms in all the two seasons in the three sites (agro-ecological zones) (Table 4.1). In 2017 SR, biomass carbon in push-pull farms was 3.5±0.3, 3.6±0.3 and 3.5±0.2 t ha^{-1}, respectively in Bondo (LM3), Siaya (LM2) and Vihiga (LM1). The corresponding values for non-push-pull farms were 1.2 ± 0.3 t/ha^{-1} in Bondo, 1.1 ± 0.3 t ha^{-1} in Siaya and 1.7 ± 0.2 t ha^{-1} in Vihiga. This represents an increment of 2.3±0.4 (191.6%), 2.5±0.4 (227.2%) and 1.8±0.3 (105.8%) tones of biomass carbon per hectare compared to non-push-pull farms in 2017 SR, respectively in Bondo, Siaya and Vihiga (Figure 4.1).

Table 4.1. Summary of analysis of biomass carbon stock, soil carbon content, soil bulk density and soil carbon stock in 2017 long rain (LR), 2017 short rain (SR) and 2018 LR in Bondo (LM3), Siaya (LM2) and Vihiga (LM1)

Source of variation	Biomass carbon stock		Soil carbon content			Soil bulk density	Soil carbon stock		
	2017 SR	2018 LR	2017 LR	2017 SR	2018 LR		2017 LR	2017 SR	2018 LR
Site (Agro-ecological zones)	0.495	0.165	**0.016**	0.094	**0.010**	0.843	**0.018**	0.118	**0.022**
Age of push-pull in a farm (Age)	0.950	0.175	0.761	0.669	0.359	0.702	0.632	0.455	0.158
Cropping system	**< 0.001**	**< 0.001**	0.998	0.921	0.117	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**
Site x age	0.954	0.726	0.744	0.901	0.645	0.115	0.229	0.704	0.350
Site x cropping system	0.464	0.179	0.054	0.369	0.850	**0.013**	0.508	0.192	0.845
Age x cropping system	0.941	0.344	**0.005**	0.888	0.789	0.392	0.067	0.353	0.903
Site x Age x cropping system	0.756	0.755	0.288	0.656	0.685	0.576	0.505	0.915	0.962
Bondo (LM3 zone)									
Age	0.786	0.078	0.989	0.775	0.364	0.193	0.477	0.360	0.140
Cropping system	**< 0.001**	**< 0.001**	0.206	0.246	0.409	**0.002**	**0.016**	0.105	**0.025**
Age x cropping system	0.863	0.546	0.130	0.451	0.999	0.902	0.173	0.748	0.990
Siaya (LM2 zone)									
Age	0.992	0.693	0.676	0.537	0.663	0.487	0.656	0.363	0.481
Cropping system	**< 0.001**	**0.001**	0.058	0.878	0.486	**< 0.001**	0.097	**0.008**	**< 0.001**
Age x cropping system	0.568	0.744	**0.036**	0.537	0.264	0.186	0.284	0.396	0.874
Vihiga (LM1 zone)									
Age	0.997	0.687	0.113	0.987	0.458	0.184	**0.014**	0.920	0.902
Cropping system	**< 0.001**	**0.002**	0.688	0.327	0.252	**< 0.001**	**< 0.001**	**0.003**	**< 0.001**
Age x cropping system	0.645	0.331	0.702	0.863	0.485	0.815	0.737	0.784	0.448

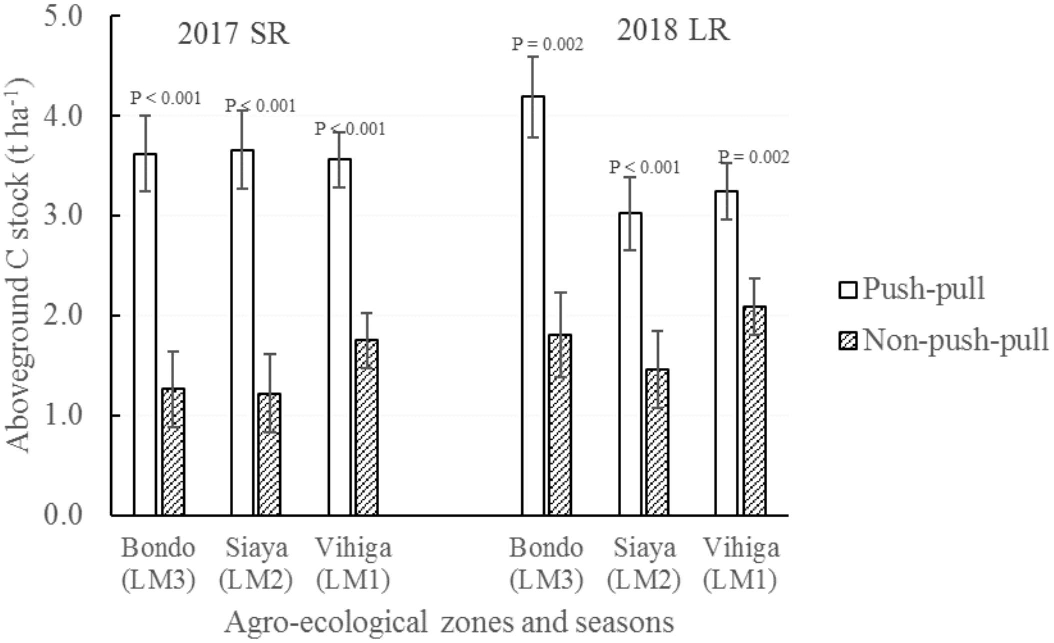

Figure 4.1. Aboveground biomass carbon estimated in push-pull and non-push-pull farms in Bondo (LM3 zone), Siaya (LM2 zone) and Vihiga (LM1 zone) in 2017 short rain and 2018 long rain season

In 2018 LR, biomass carbon in push-pull farms was 4.0±0.4 t ha^{-1} in Bondo (LM3 zone), 3.0±0.3 in Siaya (LM2 zone) and 3.2±0.2 t ha^{-1} in Vihiga (LM1 zone) compared to 1.8±0.4, 1.5 ± 0.3 and 2.1 ± 0.2 t ha^{-1} in non-push-pull farms, respectively (Figure 4.1). The duration of time push-pull had been practiced in a farm and climatic conditions (represented by sites) and their interaction did not affect the amount of biomass carbon stored in the farms (Table 4.1).

4.2.2. Soil organic carbon concentration, bulk density and carbon stocks

4.2.2.1. Soil organic carbon concentration

The concentration of SOC in push-pull and non-push-pull farms was influenced by the period of time push-pull had been practiced in a farm. This phenomenon was observed in one out of the three seasons; 2017 LR (Table 4.1). In 2017 LR, the concentration of SOC in farms where push-pull had been practiced for more than five years was higher than that for non-push-pull farms by 1.4 ± 0.6 g kg^{-1} (df = 11, t ratio = 2.2, P = 0.048). On the contrary, there was no significant difference observed between push-pull and non-push-pull farms where push-pull had been practiced for less than 5 years (Figure 4.2).

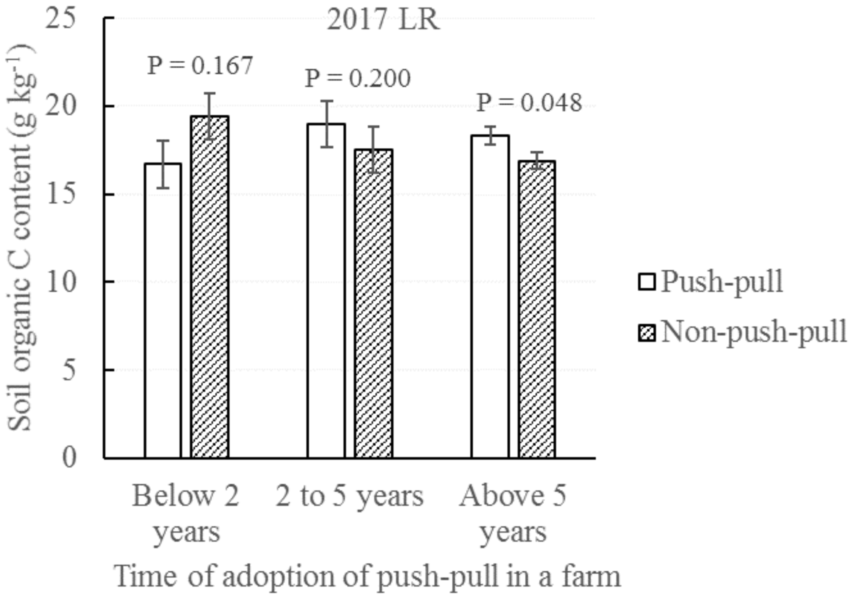

Figure 4.2. Effect of duration which push-pull had been practiced on farms on the concentration of organic carbon in soils in Bondo (LM3 zone), Siaya (LM2 zone) and Vihiga (LM1 zone)

In the same season (2017 LR) in Siaya (LM2 zone), there was a large but not significant difference between the concentration of SOC in non-push-pull farms compared to farms where push-pull had been practiced for less than 2 years (7.8 ± 2.3 g kg^{-1}) and the gap narrowed for farms where push-pull had been practiced for 2 years and above (Figure 4.3, Table 4.1). The comparison of periods of time push-pull was adopted in a farm showed no significant difference between these three groups (below 2 years, 2 to 5 years, above 5 years). The same observation was made from the comparison of non-push-pull farms as well.

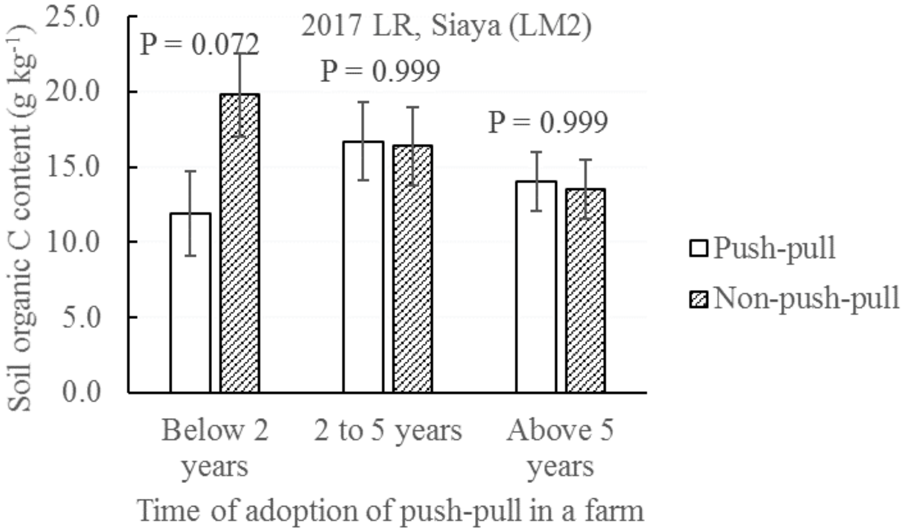

Figure 4.3. Effect of duration push-pull lasted in a farm on the concentration of soil organic carbon in soils in Siaya (LM2 zone)

In the three study seasons, the concentration of SOC was lower in Siaya (LM2 zone) compared to Bondo (LM3 zone), while Vihiga (LM1 zone) had intermediate values

(Figure 4.4, Table 4.1). The concentration of SOC for Bondo site was higher than that for Siaya site by 4.5 ± 1.3 g kg^{-1} (2017 LR), 5.3 ± 2.0 g kg^{-1} (2017 SR) and 4.4 ± 1.2 g kg^{-1} (2018 LR) for three consecutive seasons (Figure 4.4).

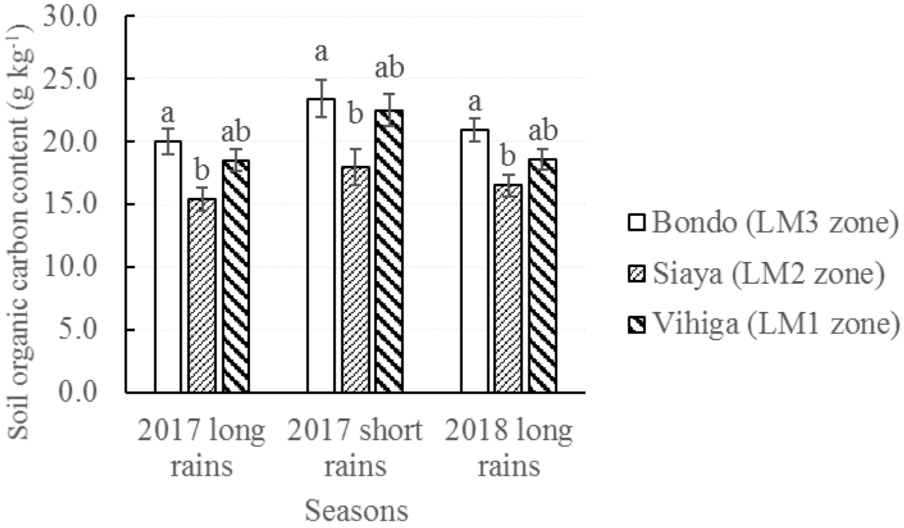

Figure 4.4. Concentration of soil organic carbon in three agro-ecological zones: Bondo (LM3 zone), Siaya (LM2 zone) and Vihiga (LM1 zone) in 2017 LR, 2017 SR, and 2018 LR

4.2.2.2. Soil bulk density

Bulk density was higher in push-pull than non-push-pull farms in all the three sites (agro-ecological zone) (Table 4.1, Figure 4.5). On average, bulk density was higher in push-pull farms i.e. 1.0 g/cm^3 in Bondo (LM3) and Vihiga (LM1) and 1.1 g/cm^3 in Siaya (LM2) compared to non-push-pull farms (mean: 0.8 g/m^3) across the three sites (agro-ecological zones). Bulk density for push-pull farms was higher than that for non-push-pull farms by 0.1, 0.3 and 0.2 g/cm^3 in Bondo, Siaya and Vihiga, respectively (Figure 4.5).

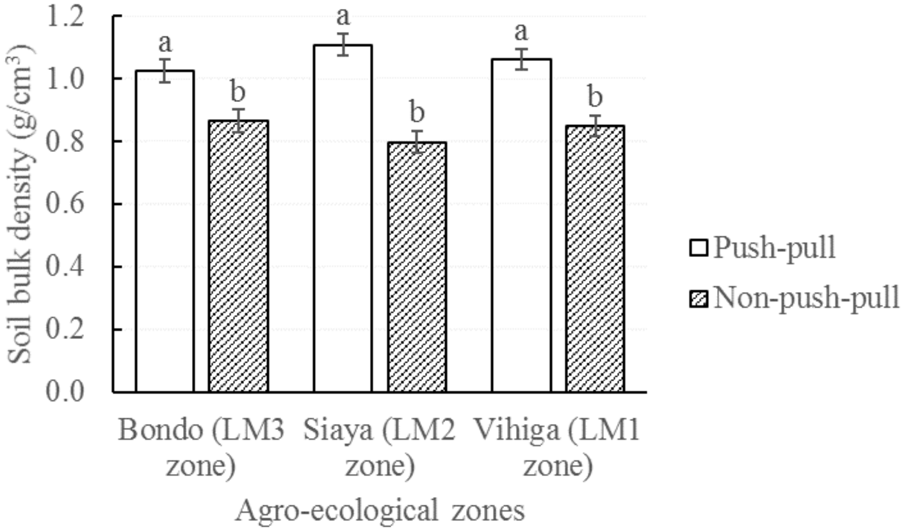

Figure 4.5. Effect of push-pull on soil bulk density in Bondo (LM3 zone), Siaya (LM2 zone) and Vihiga (LM1 zone). Sampling happened after harvesting maize in 2018 long rain season

4.2.2.3. Soil organic carbon stock

The amount of soil carbon stored in push-pull farms was consistently higher than that stored in non-push-pull farms, but the magnitude of difference depended on sites (agro-ecological zones) and seasons (Table 4.1). During the study period (three seasons) in all the three sites (agro-ecological zones), soil organic carbon stocks in push-pull farms was higher than that in non-push-pull farms by between 5.2 ± 2.1 Mg ha^{-1} in Siaya (LM2 zone) during 2017 LR and 9.4 ± 2.6 Mg ha^{-1} in Vihiga (LM1 zone) during 2017 SR. An exception to this was 3.8 ± 1.7 Mg SOC ha^{-1} difference observed in Bondo in 2017 SR (SOC stock being higher in push-pull than non-push-pull farms) (Figure 4.6).

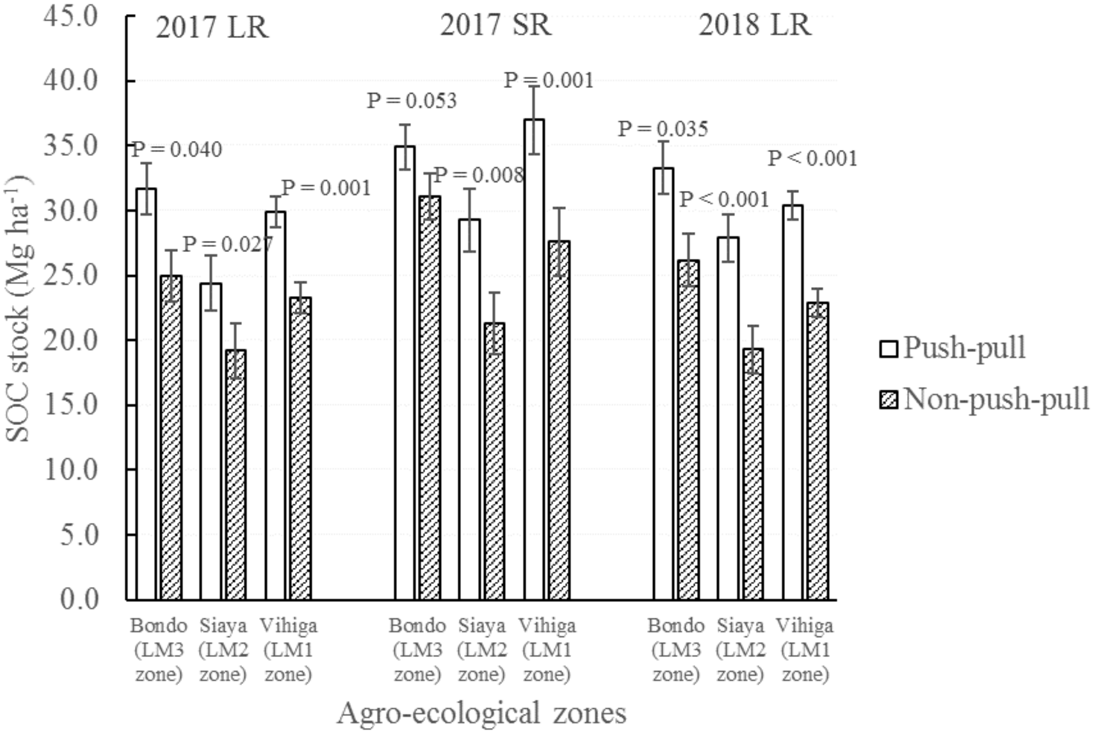

Figure 4.6. Effect of push-pull technology on soil carbon stock in three agro-ecological zones: Bondo (LM3 zone), Siaya (LM2 zone) and Vihiga (LM1 zone) during 2017 long rain (LR), 2017 short rain (SR) and 2018

Soil carbon stock for farms in Siaya (LM2) was lower than that in Bondo (LM3) for the three seasons, and Vihiga (LM1) in one out of three seasons; 2017 LR (Figure 4.7). The SOC stock for Bondo was higher than that for Siaya by 6.5 ± 2.0, 7.6 ± 3.0 and 6.1 ± 2.0 Mg ha^{-1} in 2017 LR, 2017 SR, and 2018 LR, respectively (Figure 4.7) while the SOC stock for Vihiga was higher than that for Siaya by 4.7 ± 1.8 and 7.0 ± 2.8 Mg ha^{-1} in 2017 LR and 2017 SR, respectively (P = 0.053 for 2017 SR).

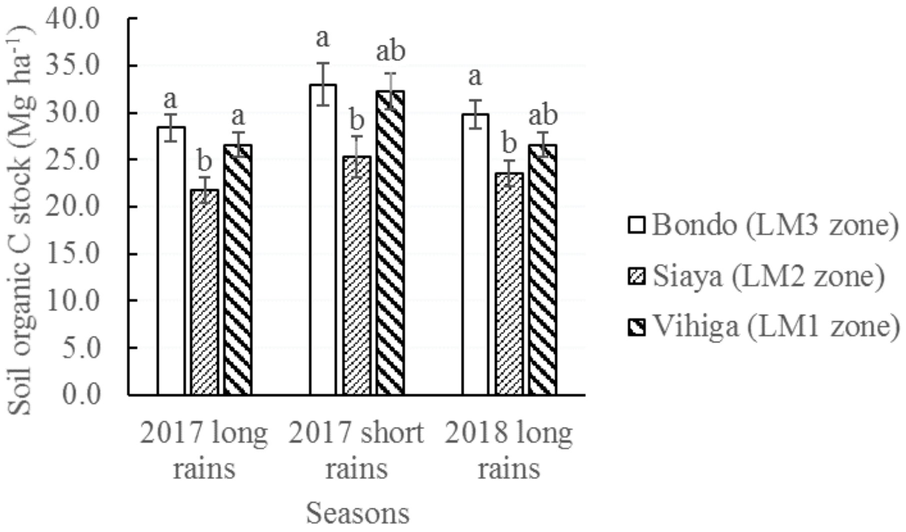

Figure 4.7. Soil organic carbon stock in three agro-ecological zones: Bondo (LM3 zone), Siaya (LM2 zone) and Vihiga (LM1 zone) in 2017 LR, 2017 SR and 2018 LR

The period of time push-pull had been practiced in a farm affected soil carbon stocks, but this was observed only in one season (2017 LR) in Vihiga (LM1 zone). During this period (2017 LR), farms where push-pull had been practiced for more than 5 years had more soil carbon stocks than those where push-pull had been practiced for less than 2 years. Moreover, farms where push-pull had been practiced for a period between 2 – 5 years had an intermediate mean between farms that practiced push-pull for more than five years and those that practiced it for less than two years (Figure 4.8). In fact, farms where push-pull had been practiced for more than 5 year had 5.5 ± 1.7 Mg C ha^{-1} more soil carbon stocks than those which had push-pull for less than 2 years (P = 0.027). Additionally, farms that practiced push-pull for 2 to 5 years had 4.6 ± 1.8 Mg C ha^{-1} soil carbon stocks than those that practiced push-pull for less than 2 years (P = 0.078).

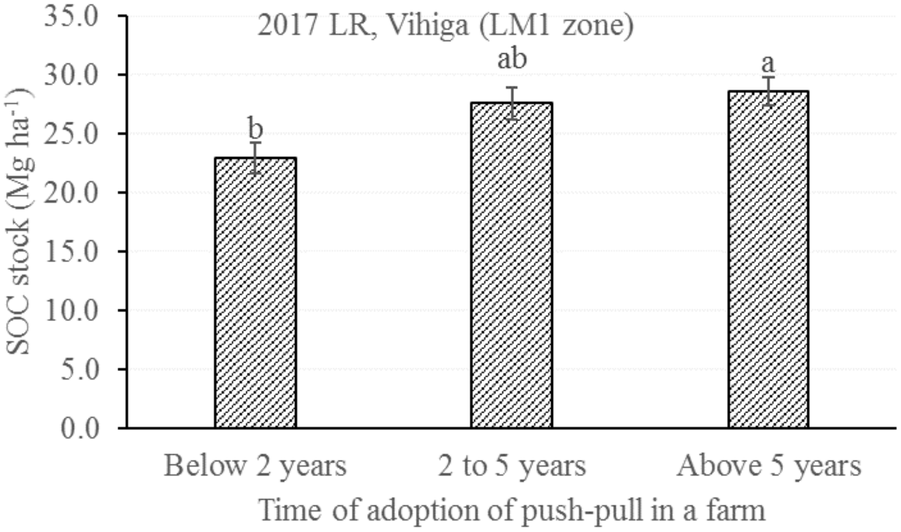

Figure 4.8. Effect of the period of time push-pull lasted in the farm on soil organic carbon stock in Vihiga (LM1 zone) in 2017 LR

4.2.3. Maize grain yield, total biomass and striga counts

4.2.3.1. Maize grain yield

Maize grain yield for push-pull and non-push-pull farms depended on sites (agro-ecological zones), and the period of time push-pull had been practiced in a farm in all the three study seasons (Table 4.2).

Table 4.2. Analysis of variance for maize grain yield, aboveground biomass, and number of striga per m2 for push-pull and its control farms in western Kenya

Source of variation/comparison	Grain yield	Aboveground biomass	Number of striga
Site (Agro-ecological zones)	**0.011**	0.079	**0.001**
Season	**<0.001**	0.065	**<0.001**
Cropping system	**<0.001**	**<0.001**	**<0.001**
Push-pull age	0.670	0.800	**0.006**
Site x Season	**<0.001**	**0.023**	**<0.001**
Site x Cropping system	**<0.001**	**<0.001**	**0.010**
Season x Cropping system	0.283	**0.002**	**<0.001**
Site x Push-pull age	0.495	0.775	0.090
Season x Push-pull age	0.382	0.911	**0.045**
Cropping system x Push-pull age	0.366	0.934	**0.036**
Site x Season x Cropping system	**<0.001**	**0.015**	0.071
Site x Season x Push-pull age	0.686	0.548	0.063
Site x Cropping system x Push-pull age	0.683	0.493	0.053
Season x Cropping system x Push-pull age	**0.011**	0.098	0.571
Site x Season x Cropping system x Push-pull age	0.645	0.887	0.995

In the first and second season (Figure 4.9), push-pull farms in Vihiga (LM1) had 76.6% (2.33 Mg ha^{-1}) and 73.4% (1.77 Mg ha^{-1}) more maize grain compared to non-push-pull farms (5.37 Mg ha^{-1} for push-pull farms versus 3.04 Mg ha^{-1} for non-push-pull farms in 2017 LR, and 4.19 versus 2.41 Mg ha^{-1} in 2017 SR; $P < 0.001$ for both seasons). In the third season (Figure 4.9), maize grain yield for push-pull farms in Bondo (LM3) (6.12 Mg ha^{-1}) was higher than the yield for non-push-pull farms (3.97 Mg ha^{-1}) by 2.15 Mg ha^{-1}, equivalent to 54.1% ($P < 0.001$). During the three study seasons, the yield for push-pull and non-push-pull farms was statistically similar in Siaya (Figure 4.9).

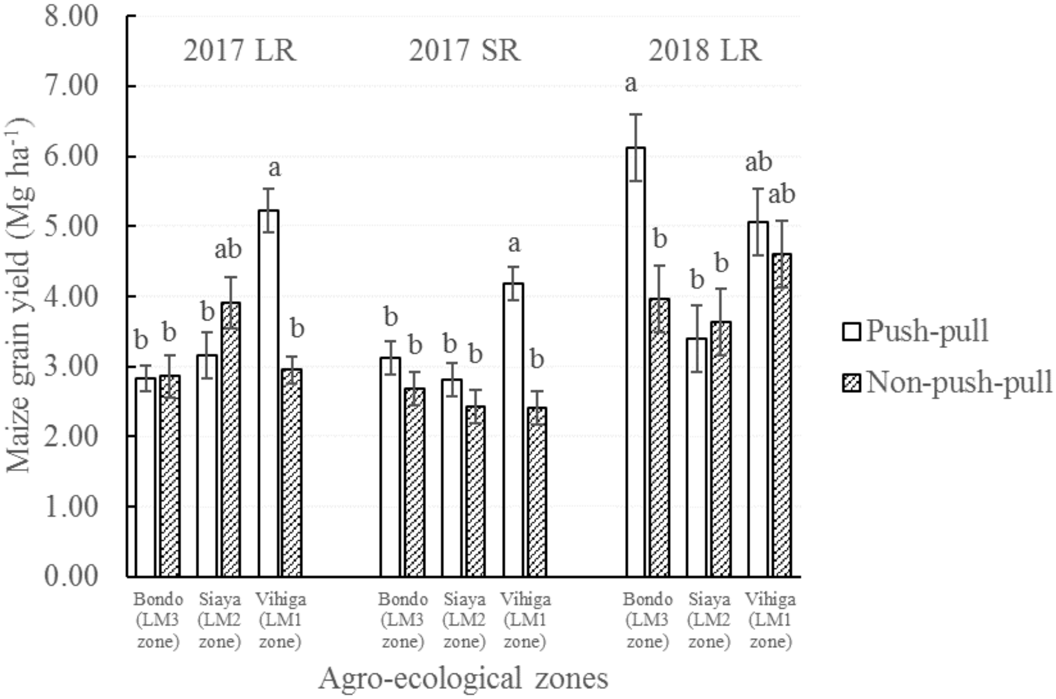

Figure 4.9. Maize grain yield in push-pull and non-push-pull farms in 2017 long rains, 2017 short rains and 2018 long rains in three agro-ecologicsl zones: Bondo (LM3 zone), Siaya (LM2 zone) and Vihiga (LM1 zone)

The interaction between cropping systems and the age of push-pull in the farm was significant only for 2018 LR (P = 0.044). In that season, farms where push-pull had been adopted for a period between 2 and 5 years had 5.41 Mg ha^{-1} [95% confidence interval (CI) = 4.39 to 6.44 Mg ha^{-1}] while non-push-pull farms had 3.67 Mg ha^{-1} (95% CI = 2.65 to 4.70 Mg ha^{-1}) (Figure 4.10). During the two other seasons (2017 LR and 2017 SR), maize grain yield did not depend on the period of time push-pull had been adopted in a farm.

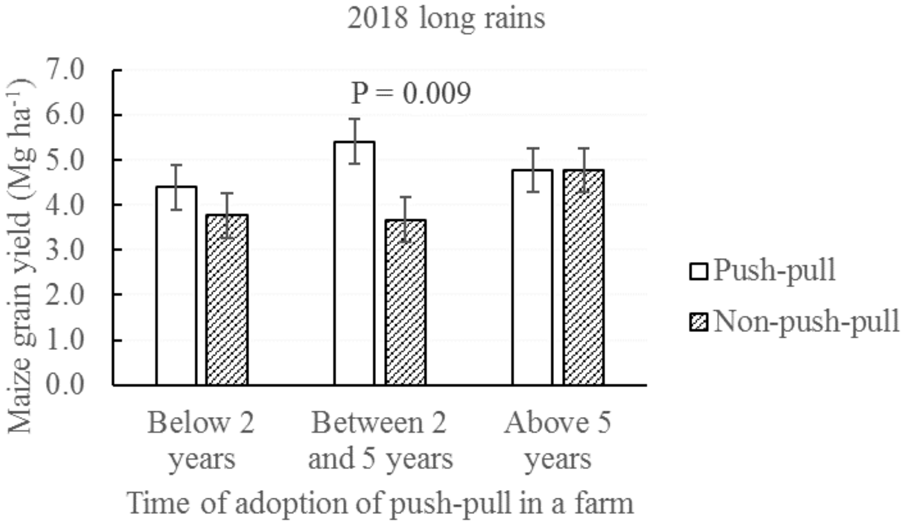

Figure 4.10. Maize grain yield in farms which had push-pull for less than 2 years, between 2 and 5 years, and above 5 years, and their respective non-push-pull farms in 2018 long rains

4.2.3.2. Total biomass

The amount of aboveground biomass depended on the interaction between site (agro-ecological zone), season and cropping systems (Table 4.2). The analysis per site showed a significant effect of seasons ($P = 0.010$) and cropping systems ($P < 0.001$), but not their interaction ($P = 0.900$) in Bondo (LM3) (Figure 4.11). The amount of aboveground biomass produced in both push-pull and non-push-pull farms was higher in 2018 LR than 2017 SR season.

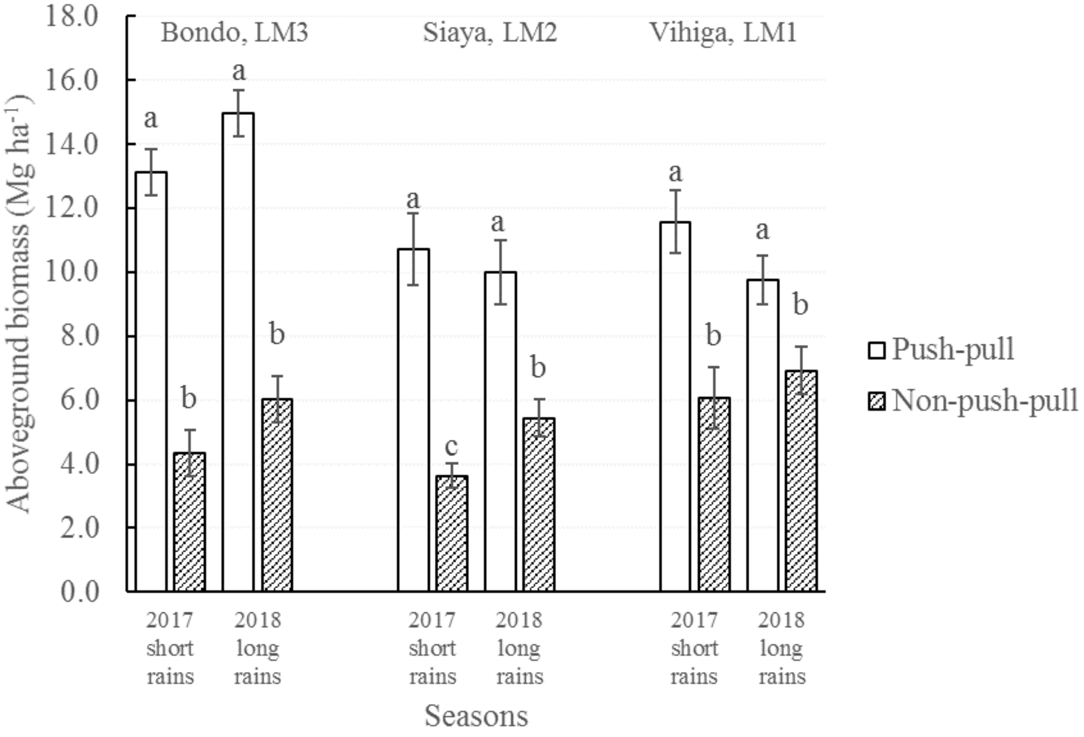

Figure 4.11. Aboveground biomass in push-pull and non-push-pull farms in 2017 short rains and 2018 long rains in three agro-ecological zones: Bondo, LM3, Siaya, LM2 and Vihiga, LM1

In 2017 SR, push-pull farms produced 13.1 Mg of biomass ha^{-1} (95% CI = 11.8 to 14.4 Mg ha^{-1}). In the same season, the biomass yield for non-push-pull farms (4.3 Mg ha^{-1}, 95% CI = 3.0 to 5.6 Mg ha^{-1}) was 33.1% the yield for push-pull farms and was significantly smaller ($P < 0.001$). During 2018 LR, the biomass yield for both push-pull (14.9 Mg ha^{-1}, 95% CI = 13.1 to 16.7 Mg ha^{-1}) and non-push-pull (6.02 Mg ha^{-1}, 95% CI = 4.2 to 7.8 Mg ha^{-1}) farms rose by 1.85 and 1.67 Mg ha^{-1}, respectively (14.1 and 38.3% increment) compared to that for the previous season (2017 short rains). Still, the yield for non-push-pull was 40.2% the yield for push-pull farms ($P < 0.001$) in that season (2018 LR).

In Siaya (LM2 zone), the interaction between season and cropping systems was significant ($P = 0.012$). Non-push-pull farms in 2017 SR had the lowest amount of aboveground biomass (3.6 Mg ha^{-1}, 95% CI = 2.8 to 4.6 Mg ha^{-1}). This amount was 33.9% of 10.7 Mg ha^{-1} (95% CI = 8.2 to 13.7 Mg ha^{-1}, $P < 0.001$) recorded in push-pull farms in that season (Figure 4.11b). It increased from 3.6 Mg ha^{-1} in 2017 SR to 5.4 Mg ha^{-1} (95% CI = 4.2 to 7.0 Mg ha^{-1}) in 2018 LR and was significantly lower ($P < 0.001$) than 9.9 Mg ha^{-1} (95% CI = 7.7 to 12.8 Mg ha^{-1}) harvested in push-pull farms in that season (54.3% the biomass in push-pull farms). The biomass produced in non-push-pull farms in 2018 LR increased by 1.7 Mg ha^{-1} compared to the amount produced in 2017 SR. This increment was equivalent to 49.1% ($P = 0.015$). Contrary to non-push-pull farms, the biomass yield for push-pull farms did not vary significantly between 2017 SR and 2018 LR (10.7 versus 9.9 Mg ha^{-1}, $P = 0.950$).

In Vihiga (LM1 zone), the biomass produced in push-pull farms in 2017 SR (11.5 Mg ha^{-1}, 95% CI = 9.2 to 13.8 Mg ha^{-1}) decreased by 1.8 Mg ha^{-1} (15.6%) to 9.7 Mg ha^{-1} (95% CI = 8.1 to 11.3 Mg ha^{-1}) in 2018 LR. On the other hand, the biomass yield for non-push-pull was 6.0 Mg ha^{-1} (95% CI = 3.7 to 8.3 Mg ha^{-1}) in 2017 SR and increased by 0.8 Mg ha^{-1} (14.0%) to 6.9 Mg ha^{-1} (95% CI = 5.31 to 8.54 Mg ha^{-1}) in 2018 LR (the P value for the interaction between cropping systems and season was 0.055). The increment of the biomass for push-pull farms compared to non-push-pull farms was 90.6% (5.5 Mg ha^{-1}, $P < 0.001$) in 2017 SR and narrowed to 41.0% (2.8 Mg ha^{-1}, $P = 0.013$) in 2018 LR (Figure 4.11).

4.2.3.3. Striga weed

Analysis of striga emergency in 2017 LR showed interaction between site (agro-ecological zone) and cropping systems (P = 0.044). The lowest number of striga was observed in push-pull farms in Vihiga (LM1 zone) and was significantly lower than the number of striga observed in Siaya (LM2 zone) (both push-pull and non-push-pull farms) and non-push-pull farms in Bondo (LM3 zone) and Vihiga (Table 4.3). The number of emerged striga in push-pull farms was significantly lower than the number observed in non-push-pull ones in Bondo and Vihiga by at least 10.0 shoots/m^2 (Table 4.3). Similar to 2017 LR, there was a significant interaction between cropping systems and site (agro-ecological zones) in 2017 SR (P < 0.001). This time, the number of striga emerged in push-pull compared to non-push-pull farms was significantly lower in Bondo (LM3) and Siaya (LM2), but not in Vihiga (LM1) (Table 4.3).

Table 4.3. Number of striga/m2 for push-pull and non-push-pull farms in Bondo (LM3 zone), Siaya (LM2 zone) and Vihiga (LM1 zone) in 2017 long rains and 2017 short rains

Treatment structure	Striga number/m^2 (95% CI)	P value of pairwise comparison of means				
		Bondo, PP	Bondo, NPP	Siaya, PP	Siaya, NPP	Vihiga, PP
2017 long rains						
Bondo, PP	2.7 (1.2 – 6.3)					
Bondo, NPP	14.2 (6.5 – 31.0)	**0.046**				
Siaya, PP	6.3 (2.8 – 13.9)	0.702	0.692			
Siaya, NPP	18.8 (8.6 – 41.0)	**0.009**	0.995	0.363		
Vihiga, PP	0.5 (0.1 – 1.5)	0.140	**< 0.001**	**0.002**	**< 0.001**	
Vihiga, NPP	13.2 (6.0 – 28.9)	0.065	1.000	0.767	0.988	**< 0.001**
2017 short rains						
Bondo, PP	0.6 (0.3 – 1.3)					
Bondo, NPP	1.0 (1.0 - 12.3)	**<0.001**				
Siaya, PP	0.0 (0.0 – 0.5)	0.257	**<0.001**			
Siaya, NPP	1.0 (1.0 – 14.9)	**<0.001**	0.976	**<0.001**		
Vihiga, PP	0.0 (0.0 – 0.0)	1.000	1.000	1.000	1.000	

Vihiga, NPP	1.0 (1.0 – 12.5)	**<0.001**	1.000	<0.001	0.983	0.999

Generally, the number of emerged striga was lower in 2017 SR than 2017 LR for both push-pull and non-push-pull farms (Table 4.3). In 2018 LR, the interaction between site (agro-ecological zone) and cropping systems was not significant ($P = 0.428$) contrary to the two previous seasons (2017 LR and 2017 SR). In this season, the separate effect of cropping systems and site (agro-ecological zone) was significant ($P < 0.001$ for both model terms). The mean number of striga/m^2 for Bondo (2.0, 95% CI = 1.0 – 3.7) was almost six times the mean for Siaya (0.3, 95% CI = 0.0 – 2.2, $P < 0.001$), and was similarly significantly ($P < 0.001$) higher than the mean for Vihiga which was almost zero (95% CI = 0.0 – 0.0). The mean for Siaya and the one for Vihiga were not significantly different from each other ($P = 0.370$). In all the three sites (agro-ecological zones), the number of emerged striga was less than one shoot/m^2 in push-pull versus one and above observed in non-push-pull farms. In fact, the mean number of striga/m^2 for push-pull farms in Bondo (LM3), Siaya (LM2) and Vihiga (LM1) was respectively, 0.2 (95% CI = 0.0 – 0.7), 0.0 (95% CI = 0.0 – 0.9), and 0.0 (95% CI = 0.0 – 0.0). This was significantly lower than 18.8 (95% CI = 13.5 – 26.2), 6.4 (95% CI = 2.9 – 14.0), and 1.0 (95% CI = 1.0 – 5.5) striga/m^2 observed in non-push-pull farms in Bondo, Siaya and Vihiga, respectively ($P < 0.001$ for all the three sites).

The effect of age of push-pull in a farm on striga emergence was observed in push-pull farms in 2017 LR (Table 4.4). Farms where push-pull had been practiced for more than five years had a mean number of striga/m^2 below one while it was above five shoots/m^2 in farms which had practiced push-pull for less than two years. Farms where push-pull had been practiced for a period of two to five years had intermediate number of striga between farms which had practiced push-pull for less than two years and those for more than five years (Table 4.4). The number of striga reduced in the three categories of push-pull farms (below 2 years, 2 to 5 years, and above 5 years of adoption in a farm) and was below one shoot/m^2 and not significantly different between each other in the two subsequent seasons (2017 SR and 2018 LR). On the other hand, there was no difference due to push-pull age categories among their respective non-push-pull farms in the three cropping seasons (Table 4.4). In these farms (non-push-pull), the number of striga/m^2 was at least four.

Table 4.4. Effect of time of adoption of push-pull on striga emergence in 2017 long rains, 2017 short rains and 2018 long rains

Age of push-pull	Push-pull fams			Non-push-pull farms		
	Striga/m^2	Below 2 years	Between 2 and 5 years	Striga/m^2	Below 2 years	Between 2 and 5 years
2017 long rains						
Below 2 years	5.42 (2.18 – 13.44)			17.39 (8.19 – 36.91)		
Between 2 and 5 years	3.41 (1.35 – 8.59)	0.750		19.04 (8.97 – 40.37)	0.984	
Above 5 years	0.79 (0.27 – 2.29)	**0.015**	0.091	9.98 (4.66 – 21.35)	0.547	0.442
P value	**0.026**			0.444		
2017 short rains						
Below 2 years	0.39 (0.13 – 1.13)			9.90 (6.59 – 14.87)		
Between 2 and 5 years	0.07 (0.00 – 0.56)	0.304		7.39 (4.86 – 11.23)	0.570	
Above 5 years	0.21 (0.05 – 0.79)	0.752	0.643	9.24 (6.14 – 13.92)	0.969	0.721
P value	0.265			0.579		
2018 long rains						
Below 2 years	0.05 (0.00 – 0.50)			8.62 (5.02 – 14.79)		
Between 2 and 5 years	0.11 (0.02 – 0.53)	0.855		11.28 (6.62 – 19.22)	0.754	
Above 5 years	0.05 (0.00 – 0.50)	1.000	0.855	9.44 (5.51 – 16.16)	0.968	0.883
P value	0.812			0.764		

4.3. Impact of cropping system on nitrogen and phosphorus availability

4.3.1. Effect of legumes on available nitrogen and phosphorus

Intercropping maize and desmodium significantly improved availability of N and P (Table 4.5 – 4.9). Total available N for maize-desmodium at 12 WAP for 2017 SR (15.7 kg ha^{-1}) and 2018 LR (17.8 kg ha^{-1}) was significantly higher than that found in maize monocrop for the same period (Table 4.8). Similarly, the total available N measured at 8 WAP in 2018 LR (23.5 kg ha^{-1}) was twice the amount found in maize monocrop (Table 4.7). Maize-desmodium intercrop had higher amounts of ammonium form of nitrogen, but not nitrate (Table 4.6 and 4.7). The level of ammonium for maize-desmodium was significantly higher than that for maize monocrop for all three sampling times (4, 8 and 12 WAP) during 2017 SR and 2018 LR (Table 4.6). Available P for maize-desmodium at 4, 8 and 12 WAP in 2017 SR was higher by 40.5, 48.9 and 54.2 kg ha^{-1} than what was found in maize monocrop for the same period of sampling (Table 4.9, P at 8 WAP = 0.072). In addition, available P measured in maize-desmodium at 4 WAP during the 2018 LR season was higher by 62.6 kg P ha^{-1} than that found in maize monocrop (Table 4.9).

Table 4.5. Summary of analysis of effect of cropping systems (treatments), growth stage and season on availability of N and P, performance of maize and intercropped legumes, and striga emergence. NA means ‘not applicable’

Observed variables	**Unit**	**Treatment**	**Growth stage**	**Season**	**Treatment: Growth stage**	**Treatment: Season**	**Growth stage: Season**	**Treatment: Growth stage: Season**
Ammonium	kg ha^{-1}	0.012^{*}	0.229	0.295	0.661	0.214	0.143	**0.376**
Nitrate	kg ha^{-1}	0.053**.**	$< 0.001^{***}$	0.012^{*}	0.704	0.918	$< 0.001^{***}$	**0.763**
Total N	kg ha^{-1}	0.001^{**}	0.552	0.594	0.568	0.256	0.067**.**	**0.340**
Available P	kg ha^{-1}	< 0.001	0.549	0.010^{*}	0.737	0.047^{*}	0.002^{**}	**0.872**
Maize shoot weight	g per shoot	$< 0.001^{***}$	$< 0.001^{***}$	0.314	$< 0.001^{***}$	$< 0.001^{***}$	$< 0.001^{***}$	**$< 0.001^{***}$**
Maize stover yield	Mg ha^{-1}	$< 0.001^{***}$	NA	$< 0.001^{***}$	NA	$< 0.001^{***}$	NA	**NA**
Maize grain yield	Mg ha^{-1}	$< 0.001^{***}$	NA	$< 0.001^{***}$	NA	0.002^{**}	NA	**NA**
Biomass yield of legumes	Mg ha^{-1}	$< 0.001^{***}$	NA	$< 0.001^{***}$	NA	$< 0.001^{***}$	NA	**NA**
Grain yield of legumes	Mg ha^{-1}	$< 0.001^{***}$	NA	$< 0.001^{***}$	NA	0.002^{**}	NA	**NA**
Striga counts	number	$< 0.001^{***}$	NA	$< 0.001^{***}$	NA	$< 0.001^{***}$	NA	**NA**

Table 4.6. Effect of legumes on availability of N (ammonium) at Mbita, *icipe* research station

Season	**Sampling date**	**Maize – monocrop**	**Maize – desmodium**	**Maize – crotalaria**	**Maize – bean**	**Maize – groundnut**	**Maize – green gram**	**Maize – cowpea**
		kg ha^{-1}						
2017 LR	8	11.1 (8.4 – 14.4)a	10.1 (7.7 – 13.3)a	7.0 (5.4 – 9.2)a	7.6 (5.8 – 9.9)a	8.1 (6.2 – 10.6)a	7.5 (5.8 – 9.8)a	**8.4 (6.4 – 11.0)a**
	12	9.0 (6.6 – 11.4)ab	12.8 (10.5 – 15.2)a	10.0 (7.6 – 12.4)ab	8.6 (6.3 – 11.0)ab	7.9 (5.5 – 10.3)b	9.7 (7.4 – 12.2)ab	**9.5 (7.1 – 11.9)ab**
2017 SR	4	6.3 (4.7 – 8.0)a	9.5 (7.8 – 11.1)a	8.5 (6.8 – 10.1)a	7.6 (5.9 – 9.2)a	6.9 (5.3 – 8.6)a	8.1 (6.4 – 9.8)a	**7.5 (5.8 – 9.1)a**
	8	7.1 (5.8 – 8.4)b	11.1 (9.8 – 12.4)a	9.0 (7.7 – 10.3)ab	8.6 (7.3 – 9.9)b	7.1 (5.8 – 8.4)b	7.9 (6.6 – 9.2)b	**8.7 (7.4 – 10.0)ab**
	12	6.6 (5.6 – 7.8)b	11.5 (9.8 – 13.5)a	8.6 (7.3 – 10.1)b	8.1 (6.9 – 9.5)b	7.6 (6.4 – 9.0)b	8.4 (7.1 – 9.9)b	**8.0 (6.8 – 9.5)b**
2018 LR	4	6.7 (4.2 – 9.3)b	11.0 (8.4 – 13.6)a	8.3 (5.8 – 10.9)ab	8.5 (6.0 – 11.1)ab	8.1 (5.5 – 10.6)ab	8.2 (5.6 – 10.7)ab	**8.3 (5.7 – 10.9)ab**
	8	8.5 (6.1 – 11.9)b	15.4 (11.1 – 21.5)a	10.4 (7.5 – 14.5)ab	9.8 (7.0 – 13.7)b	9.7 (7.0 – 13.5)b	10.5 (7.6 – 14.7)ab	**11.1 (8.0 – 15.3)ab**
	12	7.4 (4.8 – 9.9)b	12.4 (9.8 – 15.0)a	9.3 (6.7 – 11.9)ab	8.3 (5.7 – 10.8)ab	7.9 (5.3 – 10.5)b	9.4 (6.8 – 12.0)ab	**9.7 (7.1 – 12.2)ab**

Table 4.7. Effect of legumes on availability of N (nitrate) at Mbita, *icipe* research station

Season	**Sampling date**	**Maize – monocrop**	**Maize – desmodium**	**Maize – crotalaria**	**Maize – bean**	**Maize – groundnut**	**Maize – green gram**	**Maize – cowpea**
		kg ha^{-1}						
2017 LR	8	4.5 (3.2 – 5.8)ab	5.1 (3.8 – 6.4)a	4.4 (3.1 - 5.7)ab	2.4 (1.1 – 3.7)b	3.3 (2.0 – 4.6)ab	3.3 (2.0 – 4.6)ab	**4.5 (3.2 – 5.8)ab**
	12	1.4 (0.5 – 2.9)a	2.6 (1.2 – 4.8)a	4.9 (2.6 – 8.1)a	2.0 (0.8 – 3.8)a	3.9 (2.0 – 6.7)a	2.8 (1.3 – 5.1)a	**2.4 (1.0 – 4.4)a**
2017 SR	4	4.9 (1.4 – 12.0)a	7.5 (2.6 – 16.3)a	6.8 (2.2 – 15.2)a	4.4 (1.2 – 11.0)a	6.6 (2.1 – 14.8)a	10.3 (4.0 – 21.0)a	**8.3 (3.0 – 17.7)a**
	8	2.8 (1.1 – 4.5)a	2.1 (0.4 – 3.9)a	2.5 (0.8 – 4.2)a	3.0 (1.3 – 4.8)a	2.1 (0.4 – 3.8)a	2.7 (0.9 – 4.4)a	**2.0 (0.3 – 3.7)a**
	12	3.0 (1.5 – 5.2)a	4.1 (2.2 – 6.8)a	3.5 (1.8 – 5.9)a	2.4 (1.1 – 4.3)a	2.9 (1.4 – 5.0)a	3.7 (1.9 – 6.2)a	**1.7 (0.7 – 3.3)a**
2018 LR	4	2.2 (0.1 – 10.6)a	3.1 (0.2 – 13.1)a	5.8 (0.7 – 19.4)a	1.4 (0.1 – 8.1)a	1.8 (0.1 – 9.5)a	2.4 (0.1 – 11.0)a	**4.3 (0.4 – 15.8)a**
	8	2.0 (0.4 – 5.2)a	7.7 (3.4 – 14.8)a	2.9 (0.9 – 7.0)a	0.9 (0.1 – 3.1)a	2.1 (0.5 – 5.5)a	3.2 (1.0 – 7.4)a	**3.5 (1.1 – 8.0)a**
	12	3.7 (1.8 – 6.7)ab	6.3 (3.5 – 10.3)a	3.0 (1.4 – 5.6)ab	1.5 (0.5 – 3.3)b	1.5 (0.5 – 3.3)b	3.4 (1.6 – 6.2)ab	**4.2 (2.1 – 7.4)ab**

Table 4.8. Effect of legumes on availability of N (total nitrogen) at Mbita, *icipe* research station

Season	Sampling date	Maize – monocrop	Maize – desmodium	Maize – crotalaria	Maize – bean	Maize – groundnut	Maize – green gram	Maize – cowpea
		kg ha-1						
2017 LR	8	15.4 (12.8 – 18.9)a	15.3 (12.5 – 18.5)a	11.4 (9.4 – 14.0)a	10.0 (8.2 – 12.1)a	11.8 (9.7 – 14.4)a	10.9 (9.0 – 13.3)a	**13.0 (10.6 – 15.7)a**
	12	9.9 (8.0 – 12.4)a	15.3 (12.3 – 19.1)a	15.0 (12.0 – 18.7)a	10.6 (8.6 – 13.3)a	11.9 (9.6 – 14.8)a	13.0 (10.4 – 16.2)a	**12.5 (10.0 – 15.6)a**
2017 SR	4	11.5 (6.8 – 17.8)a	17.3 (11.1 – 26.7)a	16.4 (10.1 – 24.7)a	12.2 (7.5 – 19.4)a	14.6 (8.9 – 22.2)a	19.4 (12.2 – 28.9)a	**15.9 (9.8 – 24.1)a**
	8	10.0 (7.5 – 12.5)ab	13.3 (10.8 – 15.9)a	11.6 (9.1 – 14.2)ab	11.6 (9.1 – 14.2)ab	9.3 (6.8 – 11.8)b	10.6 (8.1 – 13.2)b	**10.7 (8.2 – 13.3)ab**
	12	9.6 (8.6 – 10.9)b	15.7 (14.1 – 17.8)a	12.1 (10.9 – 13.7)b	10.8 (9.6 – 12.0)b	10.9 (9.7 – 12.3)b	12.4 (11.1 – 13.8)ab	**10.5 (9.4 – 11.8)b**
2018 LR	4	11.6 (6.6 – 16.5)a	15.0 (10.0 – 19.9)a	15.0 (10.0 – 19.9)a	11.2 (6.2 – 16.1)a	11.2 (6.2 – 16.1)a	13.2 (8.3 – 18.1)a	**15.3 (10.4 – 20.2)a**
	8	10.8 (7.8 – 14.7)b	23.5 (17.1 – 32.1)a	13.7 (9.9 – 18.9)b	11.3 (8.2 – 15.6)b	13.0 (9.4 – 17.9)b	14.4 (10.4 – 19.8)ab	**15.1 (11.0 – 20.9)ab**
	12	11.5 (9.2 – 13.7)b	17.8 (15.6 – 20.0)a	12.1 (9.8 – 14.3)b	10.0 (7.8 – 12.2)b	10.4 (8.1 – 12.6)b	13.4 (11.1 – 15.6)ab	**14.0 (11.8 – 16.2)ab**

Table 4.9. Effect of legumes on availability of P at Mbita, *icipe* research station

Season	Sampling date	Maize – monocrop	Maize – desmodium	Maize – crotalaria	Maize – bean	Maize – groundnut	Maize – green gram	Maize – cowpea
		kg ha^{-1}						
2017 LR	8	66.9 (36.2 – 111.2)a	49.0 (24.6 – 85.7)a	64.4 (34.3 – 107.8)a	48.2 (24.1 – 84.6)a	40.7 (19.4 – 73.5)a	59.7 (31.5 – 101.8)a	**58.8 (30.9 – 99.8)a**
	12	41.9 (23.2 – 60.6)a	64.5 (45.8 – 83.2)a	42.0 (23.3 – 60.7)a	46.4 (27.7 – 65.1)a	40.8 (22.1 – 59.5)a	38.9 (20.1 – 57.6)a	**38.6 (19.8 – 57.3)a**
2017 SR	4	29.6 (12.8 – 46.3)b	70.1 (53.4 – 86.9)a	32.8 (16.0 – 49.5)ab	40.3 (23.5 – 57.0)ab	20.9 (4.1 – 37.6)b	34.9 (18.2 – 51.7)ab	**34.8 (18.0 – 51.5)ab**
	8	42.0 (18.9 – 65.1)a	90.9 (67.8 – 114.0)a	40.4 (17.3 – 63.5)a	47.8 (24.7 – 70.9)a	35.5 (12.4 – 58.6)a	37.8 (14.7 – 60.9)a	**42.9 (19.8 – 66.0)a**
	12	38.9 (19.1 – 58.7)b	93.1 (73.3 – 112.8)a	37.8 (18.0 – 57.5)b	44.9 (25.1 – 64.6)b	35.6 (15.8 – 55.4)b	34.1 (14.3 – 53.9)b	**44.7 (24.9 – 64.5)b**
2018 LR	4	27.0 (6.0 – 48.0)b	89.8 (68.8 – 110.7)a	28.4 (7.4 – 49.4)b	42.0 (20.9 – 62.9)b	53.3 (32.3 – 74.3)b	49.9 (28.9 – 70.9)b	**27.8 (6.8 – 48.8)b**
	8	40.0 (22.4 – 64.9)a	54.0 (32.1 – 84.6)a	22.4 (10.9 – 40.0)a	34.9 (19.0 – 58.4)a	20.7 (9.9 – 37.5)a	31.8 (16.7 – 53.5)a	**24.3 (12.0 – 42.8)a**
	12	43.5 (26.2 – 60.7)ab	73.3 (56.1 – 90.1)a	23.9 (6.6 – 41.1)b	46.3 (29.0 – 63.5)ab	29.5 (12.2 – 46.7)b	37.9 (20.7 – 55.2)ab	**37.4 (20.1 – 54.6)ab**

Other legumes (crotalaria and green gram) also increased availability of N, but not P (Table 4.6 – 4.9). In 2017 LR and 2017 SR, total available N in maize-crotalaria at 12 WAP was higher than in maize monocrop; however, the difference was not significant (P = 0.085 and 0.089). Ammonium measured at 12 WAP in 2017 SR was higher in maize-crotalaria (8.6 kg ha^{-1}) than in maize monocrop (6.6 kg ha^{-1}) (P = 0.075). Compared to maize monocrop, total available N was higher in maize-green gram only at 12 WAP in 2017 SR (Table 4.8, P = 0.062). On the contrary, the level of total available N in maize-bean intercrop was lower than that found in maize monocrop at 8 WAP in 2017 LR (Table 4.8, P = 0.054).Desmodium increased available N than other legumes. The level of available N was consistently higher in maize-desmodium than in maize-bean and maize-groundnut (all the three cropping seasons) and other cropping systems in 2017 SR and 2018 LR (Table 4.6 – 4.8). Moreover, the level of available P in maize-desmodium was higher than that found in other maize-legume intercrops especially in 2017 SR and 2018 LR (Table 4.9). Available quantities of P in maize-desmodium were almost twice the quantity found in other maize-legume intercrops (Table 4.9).

4.3.2. Effect of legumes on maize shoot weight

Intercropping desmodium with maize improved the growth of the latter. Maize shoot weight observed at 8 and 12 WAP in 2017 LR in maize-desmodium intercrop was about ten times the weight for maize grown in monocrop (Table 4.10). Similarly, in the following season (2017 SR), the shoot weight for maize grown with desmodium tripled that for maize grown in monocrop at 4 and 8 WAP, and was 7 times that for maize grown in monocrop at 12 WAP in the same cropping season (2017 SR). In the third season (2018 LR), the shoot weight for maize grown with desmodium was 1.8 times the weight for maize grown in monocrop at 4 and 8 WAP (Table 4.10). In the same season (2018 LR) at 12 WAP, the heavier maize grown in monocrop was 100.4 g (upper limit of the 95% confidence interval) while the lighter maize grown with desmodium was 95.6 g (lower limit of the 95% confidence interval, Table 4.10).

Table 4.10. Effect of legumes on maize shoot weight (g per maize plant shoot) measured at 4, 8 and 12 weeks after planting (WAP) at Mbita, *icipe* research station in 2017 long rain (LR), 2017 short rain (SR) and 2018 LR. Measurements were not taken at 4 WAP in 2017 LR

Season	**Sampling date**	**Maize – monocrop**	**Maize – desmodium**	**Maize – crotalaria**	**Maize – bean**	**Maize – groundnut**	**Maize – green gram**	**Maize – cowpea**
		g per maize plant shoot						
2017 LR	8	11.5 (7.2 – 18.5)c	103.5 (64.7 – 165.6)a	42.5 (26.8 – 68.0)ab	16.6 (10.3 – 26.5)bc	21.9 (13.7 – 34.8)bc	24.7 (15.4 – 39.2)bc	**21.3 (13.3 – 34.1)bc**
	12	18.7 (10.3 – 33.7)b	202.3 (112.1 – 365.0)a	69.4 (38.4 – 125.2)ab	33.1 (18.3 – 59.1)b	28.5 (15.7 – 51.4)b	21.1 (11.7 – 38.0)b	**27.1 (15.0 – 48.9)b**
2017 SR	4	2.8 (1.8 – 4.3)c	8.9 (5.7 – 13.8)a	7.7 (5.0 – 11.9)ab	2.6 (1.7 – 4.1)c	3.7 (2.4 – 5.7)bc	3.4 (2.2 – 5.4)bc	**5.4 (3.4 – 8.3)bc**
	8	10.5 (6.6 – 17.1)b	36.2 (22.4 – 57.9)a	14.4 (8.9 – 23.3)ab	6.6 (4.1 – 10.6)b	10.6 (6.6 – 17.1)b	8.6 (5.3 – 14.0)b	**10.8 (6.6 – 17.2)b**
	12	47.4 (20.4 – 108.8)b	336.9 (146.9 – 772.7)a	50.9 (22.1 – 117.9)b	38.4 (16.7 – 88.2)b	57.9 (25.2 – 132.9)b	17.6 (7.6 – 40.4)b	**29.0 (12.6 – 66.6)b**
2018 LR	4	3.8 (3.0 – 4.9)b	7.1 (5.6 – 9.0)a	4.5 (3.5 – 5.7)ab	3.9 (3.1 – 5.0)b	4.6 (3.3 – 5.8)ab	4.2 (3.3 – 5.3)b	**4.7 (3.7 – 5.9)ab**
	8	14.0 (10.1 – 19.1)bc	26.5 (19.2 – 36.2)a	20.0 (14.5 – 27.6)ab	14.5 (10.5 – 20.0)bc	15.3 (11.1 – 21.1)bc	8.0 (5.8 – 11.1)c	**16.2 (11.8 – 22.4)bc**
	12	59.7 (35.8 – 100.4)ab	162.3 (96.5 – 270.4)a	46.0 (27.6 – 77.4)b	54.5 (32.7 – 91.8)ab	58.5 (35.1 – 98.4)ab	43.8 (26.3 – 73.6)b	**63.4 (37.7 – 105.6)ab**

For legumes other than desmodium, the highest significant increase in the growth of maize relative to maize monocrop was only found in maize-crotalaria at 8 and 12 WAP in 2017 LR, and at 4 and 8 WAP in 2017 SR and 2018 LR (Table 4.10). In 2017 LR, maize grown with crotalaria was 3.7 times the weight for maize grown in monocrop at 8 and 12 WAP. At 4 WAP in the following season (2017 SR), the weight for maize grown with crotalaria was 2.7 times that for maize grown in monocrop (Table 4.10).

Experiments with desmodium consistently showed better growth of maize compared to other legumes. In 2017 LR and 2017 SR, maize shoot weight for maize-desmodium intercrop was higher than that for other intercrops (Table 4.10). In 2018 LR, the shoot weight for maize grown with desmodium measured at 4, 8 and 12 WAP was 1.6, 3.3 and 3.7 times the shoot weight for maize grown with green gram, respectively (Table 4.10). The shoot weight for maize grown with desmodium was 1.8 times the weight for shoots of maize grown with bean at 4 WAP (2018 LR), while its recorded weight at 12 WAP (maize grown with desmodium) was 3.5 times the weight for shoots for maize grown with crotalaria (Table 4.10).

The comparison between legumes (other than desmodium) revealed that the least growth of maize was from maize-green gram in 2017 LR and 2018 LR, and maize-bean in 2017 SR. On the other hand, better growth of maize was observed in plots with crotalaria compared to these cropping systems (maize-green gram and maize-bean) in the three cropping seasons. In 2018 LR, plots with cowpea and groundnut also had better growth of maize than maize-green gram (Table 4.10).

4.3.3. Effect of legumes on maize stover and grain yield

Intercropping maize with desmodium increased maize stover and grain yield relative to the monocrop and other legumes. The stover yield for maize-desmodium was 5.7, 4.0 and 3.7 Mg ha^{-1} in 2017 LR, 2017 SR and 2018 LR versus 1.2, 0.8 and 1.9 Mg ha^{-1}

observed in maize monocrop in these respective seasons (Figure 4.12). Similarly, the maize grain yield for maize-desmodium was 5.0, 3.1 and 4.3 Mg ha^{-1} in 2017 LR, 2017 SR and 2018 LR against 0.5, 0.4 and 1.8 Mg ha^{-1} observed in maize monocrop in these respective seasons (Figure 4.12). Other legumes did not affect maize stover and grain yield. Grain yield for maize monocrop, maize-bean, maize-cowpea, maize-crotalaria, maize-green gram and maize-groundnut for 2018 LR was at least twice compared to their yield in 2017 LR, and at least four times their yield observed in 2017 SR (Figure 4.12).

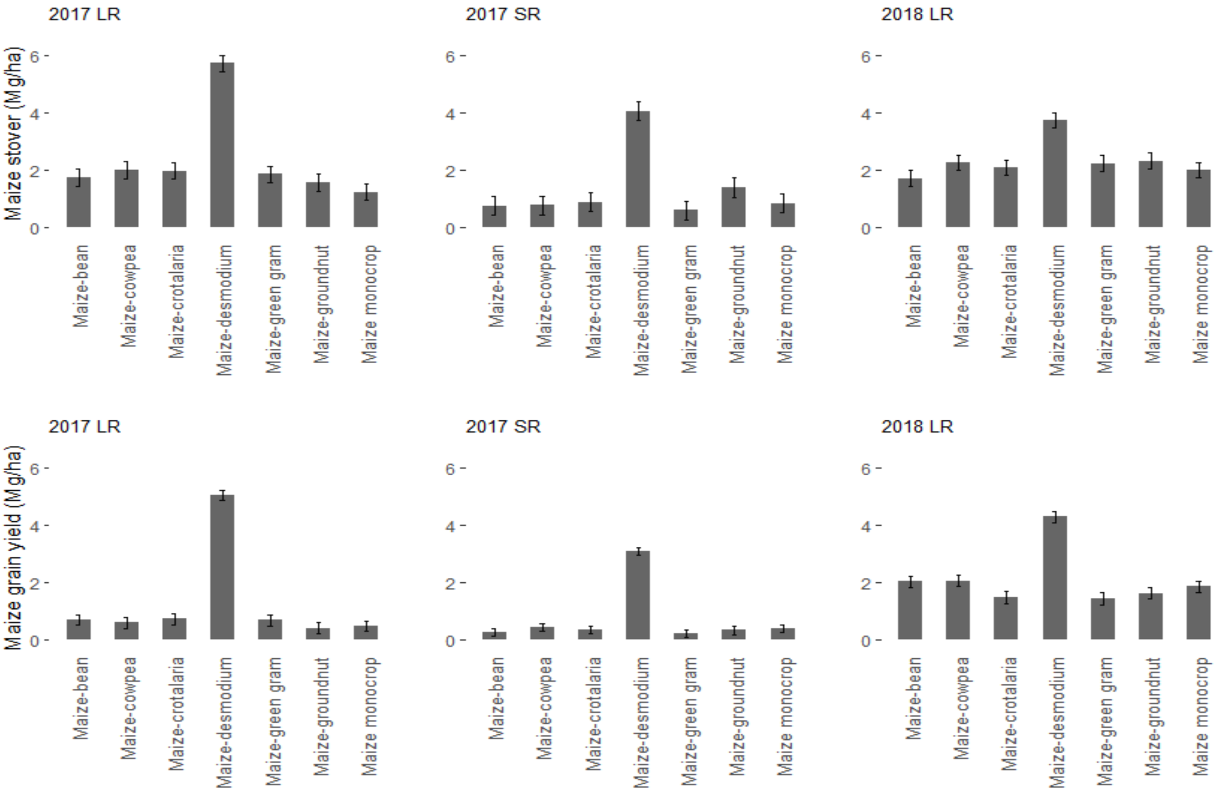

Figure 4.12. Effect of legumes on maize stover and grain yield in Mbita, *icipe* research station in 2017 long rains, 2017 short rains and 2018 long rains

The stover yield for maize-desmodium was three-times the yield for maize-bean, maize-cowpea, maize-crotalaria, maize-green gram and maize-groundnut in 2017 long and short rains. Grain yield for the same cropping system was at least six times that for these maize-legume intercrops in the two respective seasons (Figure 4.12). In 2018 LR, stover yield for maize-desmodium was higher by between 61 and 119.6 % compared to maize-bean, maize-cowpea, maize-crotalaria, maize-green gram and maize-groundnut (Figure 4.12). In the same season, grain yield for maize-desmodium was twice that for maize-bean, maize-cowpea, maize-crotalaria, maize-green gram and maize-groundnut (Figure 4.12).

4.3.4. Biomass and grain yield of legumes

Desmodium, crotalaria and groundnut produced relatively higher amount of biomass compared to bean, cowpea and green gram, but this depended on seasons (Figure 4.13). In 2017 LR, desmodium produced 1.6 Mg ha^{-1} while other legumes had less than 1.0 Mg ha^{-1}. In 2017 SR, the biomass yield for desmodium rose from 1.6 in 2017 LR to 2.4 Mg ha^{-1}, an increment of 0.8 Mg ha^{-1}, and increased further by almost 2.0 Mg ha^{-1} to 4.3 Mg ha^{-1} in 2018 LR. Biomass yield for crotalaria was 0.4, 3.3 and 1.4 Mg ha^{-1} in 2017 long and short rains and 2018 LR, respectively. The amount of biomass in these respective seasons for groundnut was 0.2, 1.7 and 1.8 Mg ha^{-1}. Biomass yield for beans, cowpea and green gram was consistently below 1.0 Mg ha^{-1} (Figure 4.13).

Grain yield for common bean, crotalaria and groundnut was relatively higher in 2017 LR compared to the two following seasons (2017 SR and 2018 LR). Grain yield for common bean was 0.9, 0.2 and 0.1 Mg ha^{-1} in 2017 LR, 2017 SR and 2018 LR, respectively (Figure 4.13). For crotalaria, it was 0.2, 0.1 and 0.3 while that for groundnut was 0.9, 0.2 and 0.3 Mg ha^{-1} in the three respective cropping seasons (Figure 4.13).

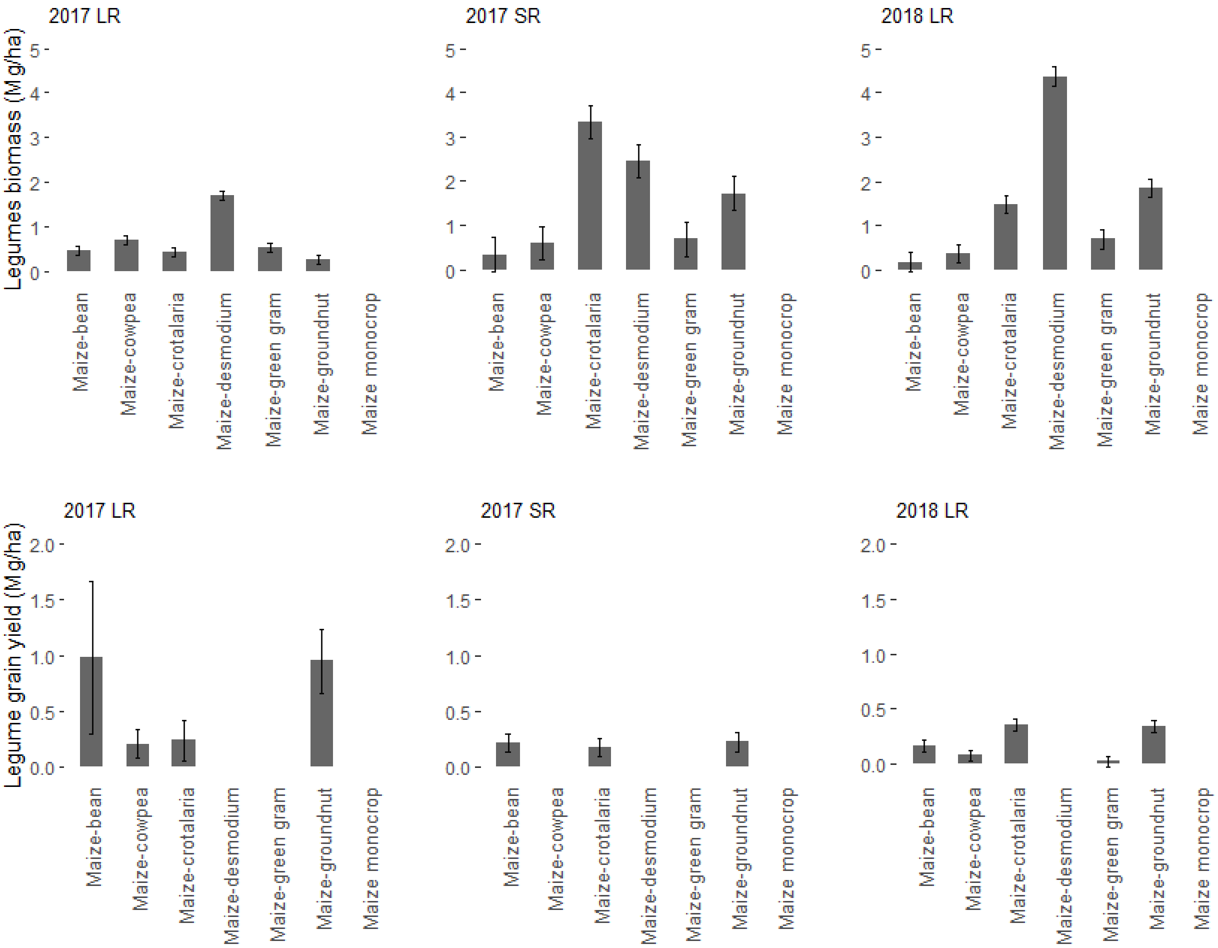

Figure 4.13. Biomass and grain yield for legumes in Mbita, *icipe* research station in 2017 LR, 2017 SR and 2018 LR

4.3.5. Striga weed

The effect of intercropped legumes on the number of striga emerged per plant depended on seasons (Table 4.11). In 2017 LR, plots having desmodium had 4 less striga per maize plant compared to monocrop plots, and 5 to 12 less striga compared to plots having food legumes (common bean, cowpea, crotalaria, green gram and groundnut). Plot having crotalaria recorded the highest number of striga, followed by those with common bean and cowpea, and had 5 to 8 more striga per maize plant than that observed in maize monocrop (Table 4.11).

Table 4.11. Effect of intercropped legume on striga emergence per maize plant in Mbita, *icipe* research station in 2017 LR, 2017 SR and 2018 LR

Treatment	Striga emergence		
	2017 LR	2017 SR	2018 LR
Maize-beans	14.5±3.3b	2.2±0.7a	5.0±2.4c
Maize-cowpea	14.0±5.8b	3.0±1.0a	6.7±2.7b
Maize-crotalaria	16.5±3.7a	4.2±1.6a	3.2±0.8d
Maize-desmodium	4.7±2.0d	0.2±0.2b	0.0±0.0e
Maize-green gram	9.7±3.5c	4.0±0.5a	10.0±4.3a
Maize-groundnut	10.2±3.4c	3.7±0.9a	10.0±4.5a
Maize monocrop	8.7±1.4c	3.0±0.9a	8.0±3.8b

In 2017 SR, the number of striga reduced in all plots and was below 5 striga per maize plant. It was almost zero in plots having desmodium and was significantly lower compared to the number recorded in maize monocrop and intercrops of maize with food legumes. The number of striga per maize plant in plots having food legumes was statistically similar to the one for maize monocrop. In 2018 LR, the number of striga emerged in plots having desmodium was zero and was significantly lower than the number observed in maize monocrop and intercrops of maize and food legumes (Table 4.11). Contrary to what was observed in 2017 LR and 2017 SR, plots having common bean and those having crotalaria had 3 and 5 less striga per maize plant than plots for maize monocrop, respectively. The number of emerged striga tended to decrease from 2017 LR to 2018 LR in plots having crotalaria and those having desmodium and fluctuated for plots having other food legumes and those having maize monocrop, the lower number being for 2017 SR.

4.4. Summary of results

Cropping systems with push-pull technology stock between 1.8 to 2.4 Mg ha^{-1} more carbon in aboveground biomass than cropping systems without push-pull maize. This was consistent in all seasons and sites (agro-ecological zones) and period of time push-pull had been practiced in a farm. Similarly, cropping systems with push-pull stored between 3.8 to 9.4 Mg ha^{-1} more carbon in the soil than those without. Soil organic carbon was higher in Bondo (LM3 zone) and Vihiga (LM1 zone) than Siaya (SM2 zone), and higher in farms that practiced push-pull longer than those that had practiced it for less than two years. Maize grain yield was higher in push-pull than non-push-pull farms in Vihiga by 2.33 and 1.77 Mg ha^{-1} in 2017 LR and 2017 SR, respectively, and in Bondo by 2.15 Mg ha^{-1} in 2018 LR. Push-pull and non-push-pull farms had similar maize grain yield in Siaya throughout the study period. Total biomass across seasons and sites (agro-ecological zones) varied between 9.7 and 14.9 Mg ha^{-1} for push-pull farms and between 3.6 and 6.9 Mg ha^{-1} for non-push-pull cropping systems. The number of striga per maize plant was significantly lower in push-pull farms than non-push-pull, and the efficacy of push-pull increased with time it was practiced in a farm. Total available N, ammonium and available P were higher in maize-desmodium than maize monocrop and intercrops of maize-common bean, maize-cowpea, maize-crotalaria, maize-green gram and maize-groundnut. Similarly, the performance of maize and control of striga was better in maize-desmodium intercrop than maize monocrop and maize intercropped with either common bean, cowpea, crotalaria, green gram or groundnut.

CHAPTER FIVE

DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

5.1. Introduction

This chapter gives a discussion of major finding on carbon stocks, availability of N and P and productivity in the first section, major conclusions and recommendations in the second and third sections, respectively.

5.2. Discussion

5.2.1. Aboveground and soil carbon stocks

5.2.1.1. Aboveground biomass carbon

Push-pull farms had higher biomass carbon. This is attributed to higher biomass produced in farms with push-pull compared to those without push-pull (Figure 4.11). High biomass production in push-pull is due to its relatively high level of intensification of crops as maize was grown with desmodium in additive intercrop and brachiaria in the surrounding of the push-pull farm. The combined biomass for maize, desmodium and brachiaria outperformed that for maize alone or maize intercropped with legumes other than desmodium in non-push-pull farms. Observed increase in biomass carbon in push-pull farms compared to non-push-pull farms suggests that adoption of push-pull can increase carbon inputs into soils relative to non-push-pull cropping systems and help to attain the 2050 global target of 55 Mg C ha^{-1} in the 30 cm topsoil (FAO, 2014; Lal, 2016; Luo *et al.,* 2016; Minasny *et al.,* 2017). However, this can only be achieved, when plant residues are retained in the farm or returned as livestock manure.

5.2.1.2. Soil organic carbon concentration

The concentration of SOC was higher in push-pull than non-push-pull farms when push-pull was practiced for more than five years (Figure 4.2). Moreover, the SOC concentration for non-push-pull tended to be higher than that for farms where push-pull had been practiced for less than 2 years, and yet, no difference was observed between non-push-pull and farms where push-pull had been practiced for 2 years and above (Figure 4.3). Even though push-pull systems had higher SOC concentration than non-push-pull systems, there was no clear positive trend of SOC concentration based on the period of time push-pull had been practiced in a farm. This is possibly because time was not enough to detect changes in SOC concentration. In a long-term study (19 years), (Barbera *et al.,* 2012) observed no significant difference in SOC concentration between no till and conventional till in a semi-arid environment in Italy. In addition, soils were not assessed for SOC concentration before they were turned into push-pull farms (this study) because the focus was initially on control of stem borers and striga and not on SOC stocks. Assessment of the initial SOC concentration could have made it possible to monitor changes overtime in push-pull and non-push-pull farms alike. Therefore, it is necessary to monitor changes that happen in push-pull and non-push-pull farms overtime to substantiate the claim that push-pull builds SOC concentration with time than non-push-pull maize based cropping systems. This claim is based on the fact that when soils are less disturbed and covered, soil particles bind together in micro and macro-aggregates and protect SOC from losses (Fuentes *et al.,* 2012). Similarly, push-pull technology is a combination of reduced tillage and permanent live mulch (desmodium). In fact, soil tillage in push-pull happens in strips between desmodium rows to plant maize, leaving around 60% of soils undisturbed (Khan *et al.*, 2011). The combination of these conditions would increase SOC concentration (Minasny *et al.,* 2017).

Differences between push-pull and non-push-pull farms were not significant in all the three sites (agro-ecological zones) in the three study seasons. These results concur with those from a five seasons study in Siaya and Vihiga where no change in SOC over time in push-pull plots compared to other maize-based cropping systems was found (Vanlauwe *et al.*, 2008) suggesting that changes might take long time to happen. This is because in cropping systems with low levels of inputs, plants depend much on mineralization of SOC for their nutrition *(*Zech *et al.*, 1997). In such conditions, maintaining current levels of SOC needs addition of organic matter at a rate ranging between 1.0 and 3.0 Mg ha^{-1} $year^{-1}$ or more especially in tropical conditions (Romanenkov *et al.,* 2019). This shows that for push-pull technology to be able to increase SOC significantly, it (push-pull technology) needs to contribute organic matter enough to maintain current levels of SOC and trigger improvement. This might call for the use of plant residues through direct application or recycling (composting and manuring) (Goyal *et al.*, 1999; Romanenkov *et al.*, 2019).

5.2.1.3. Soil bulk density

Soils with high soil bulk density are likely to limit growth of roots for crops due to compaction thus reducing the growth of shoots and yield (Koureh *et al.*, 2020). Contrary, bulk density values in push-pull were lower than critical values associated with compaction (Brown and Wherrett, 2014). Furthermore, push-pull promotes better crop growth and yields than conventional cropping systems (this study). Observed improvement in soil bulk density in push-pull farms implies a better soil aggregation and stability of aggregates than in non-push-pull farms. This would contribute to better infiltration of water and roots of plants, better aeration and respiration of roots under push-pull than non-push-pull farms, hence, better growth and yield of maize.

5.2.1.4. Soil carbon stocks

There was more carbon stocks in push-pull farms than in non-push-pull farms in all the three sites (agro-ecological zones). This is attributed to relatively higher soil bulk density observed in push-pull than non-push-pull farms (Figure 4.5) as well as organic inputs indicated by higher biomass production (Figure 4.11) and higher root turnover belowground. Higher bulk density suggests there was better soil aggregation and aggregate stability in push-pull than non-push-pull farms. Better soil aggregates physically protect SOC and reduce the rate of decomposition and release of stored carbon (Post and Kwon, 2000). From other studies, changing land use from native forest or pasture to crops leads to the loss of SOC by 42 and 59%, respectively (Guo and Gifford, 2002; Sommer *et al.,* 2018). Conservation tillage, reduced tillage, and cover cropping practices, which also characterize push-pull technology, reduce the rate of SOC mineralization and loss (Scharlemann *et al.,* 2014). Such practices are known to reverse the negative trend of SOC overtime in crop lands to positive trends (Scharlemann *et al.,* 2014). Soil organic carbon stocks observed in this study are in the range reported in central highlands of Kenya (Kapkiyai *et al.,* 1999). This study (Kapkiyai *et al.,* 1999) reported accumulation of 23.6 Mg C ha^{-1} in upper 15 cm soil when 120 kg N and 52 kg P ha^{-1} mineral fertilizer was applied, and 28.7 Mg C ha^{-1} when maize stover were retained and 10 Mg manure ha^{-1} were applied in addition to application of mineral fertilizer at 120 kg N and 52 kg P ha^{-1}. This was observed after 18 years of experimentation (Kapkiyai *et al.,* 1999). From findings of this study, adoption of push-pull helps to achieve improvement observed by Kapkiyai *et al.* (1999) with application of moderate quantities of mineral fertilizers (27 kg N, 12 kg P and 4.8 kg Ca ha^{-1}) and not necessarily retaining crop residues which can be used to feed livestock.

No till and reduced till have been reported to alter the distribution of SOC in the soil profile with high SOC accumulation in 10 cm uppermost soil layer and reduced SOC as you go downward. In addition to this, the overall SOC stock for no till and reduced till in the profile remains similar to that for conventional practices of tillage (Baker *et al.,* 2007; Blanco-Canqui and Lal, 2008; Luo *et al.,* 2010). Even though push-pull technology is a reduced till technology, it might be an exception in conserving SOC and insuring its (SOC) good distribution in the profile. This is because organic matter in push-pull technology is buried deep in the profile through tilling the maize strips between rows of desmodium. The soil cover in push-pull is desmodium, a perennial with deep roots (Van Saun, 2014), whose exudates and turnover increase SOC input into the soil. This might lead to higher SOC in push-pull farms than non-push-pull ones along the soil profile.

Soil organic carbon was higher in Bondo, cotton zone (LM3) (Figure 4.4 and 4.7), the drier climate than in Siaya (marginal sugarcane zone, LM2) and Vihiga (sugarcane zone, LM1) (wetter climate than in Bondo). This is because microbial activity on SOC is lower in dry environments than in wet ones making the turnover time of SOC to be shorter in wet areas than drier ones (Fekete *et al.,* 2021).

5.2.2. Impact of cropping system on nitrogen and phosphorus availability

Growing maize in combination with desmodium increased available N compared to growing maize alone or main in combination with other legumes. This could have been due to increased soil organic matter and its rate of mineralization, and/ or release of biologically fixed N to the soil (Birch and Dougall, 1967; Wu *et al.,* 2008; Urbatzka *et al.,* 2009). Nitrogen from legumes mineralizes slowly with relatively low loss and high synchrony with crops needs (Crews and Peoples, 2005). This implies that N mineralized from legumes would result in relatively higher N in intercrop with a legume than in maize monocrop. Maize-desmodium supported higher amount of biomass (maize stover and legume biomass) than other cropping systems, implying that there was more organic matter from fallen leaves and roots in this cropping system than maize monocrop. Other maize-legume intercrops had lower available N than maize-desmodium because desmodium might have fixed and released in soils more N than these legumes (Peoples and Crasswell, 1992; Ojiem *et al.*, 2007; Hoffman *et al.,* 2014). This is highly possible as the amount of biologically fixed N depends on the amount of biomass of the legume, N content of the biomass and the ability of the legume to derive N from the atmosphere helped by the bacteria (Unkovich *et al.,* 2008). In this study, the biomass yield for desmodium was higher than that for other legumes (Figure 4.13, except crotalaria in 2017 SR), highlighting the possibility of relatively higher amount of biologically fixed N by desmodium. Another possible mechanism might have been related to the regulation of nutrients in the soil solution so to maintain an equilibrium between plants and soil (Nieder *et al.,* 2011). Available N was largely in ammonium than nitrate form probably because ammonium is the primary form released from mineralization of organic matter (Heil *et al.,* 2016) and biological N fixation by legumes (Hoffman *et al.,* 2014). It is also less mobile and less susceptible to losses from the profile than nitrate (Randall and Mulla, 2001; Nieder *et al.,* 2011).

Desmodium increased available P than other maize-based cropping systems. This is because roots of legumes like desmodium release protons and carboxylates, organic acids, or phosphatase enzymes that facilitate the release of P from its otherwise unavailable forms (Neumann and Römheld, 1999; Miyasaka and Habte, 2001; Li *et al.,* 2007; 2018; Sharma *et al.,* 2013). Other legumes could not increase the availability of P showing the comparative advantage of intercropping maize with desmodium than with these legumes (common bean, cowpea, crotalaria, green gram and groundnut). Maize-bean, maize-cowpea, maize-crotalaria, maize-green gram and maize-groundnut had comparable available P with maize monocrop. Available P was expected to be higher in plots that had legumes than those that had monocrop of maize (Vanlauwe *et al.,* 2000; Li *et al.,* 2003; 2007). The lack of effect of legumes (other than desmodium) on availability of P compared to monocrop of maize was possibly due to low rate of N fixation or competitive use of availed P by both legumes and maize. The increase in available P implies that desmodium could be used to alleviate P deficiency in farms to improve P plant nutrition, a trait common in herbaceous legumes (Vanlauwe *et al.,* 2000). This ability is not compromised by acidity or alkalinity of soils as Vanlauwe *et al.* (2008)

observed improvement in Olsen P due to desmodium in acidic soils (pH of 5.4) in Vihiga, Western Kenya and was observed in Mbita, Homabay (this study) in alkaline soils with a pH of 7.2 to 8.1 (Table 3.2).

5.2.3. Maize grain yield, total biomass and striga

5.2.3.1. Maize grain yield

Push-pull produced more maize grain yield than non-push-pull in two over three seasons in Vihiga and one over three seasons in Bondo and produced similar maize grain yield in the rest of seasons in these two sites (Vihiga and Bondo), and in Siaya for all the three seasons. In Mbita, *icipe* research station, maize grown with desmodium produced more maize grain yield than maize grown in monocrop and maize intercropped with common bean, cowpea, crotalaria, green gram and groundnut. Maize grown with desmodium also had better growth than maize grown as monocrop or intercropped with common bean, cowpea, crotalaria, green gram and groundnut (Table 4.7). This means that adoption of push-pull does not bring about a loss in maize grain yield compared to commonly practiced maize-based cropping systems in western Kenya. Rather, it (push-pull) produces more maize grain.

This improvement in maize growth and grain yield was partially due to better N and P nutrition (Table 4.6 – 4.9) and better control of striga weed by desmodium compared to other legumes and monocrop of maize (Table 4.3, 4.4 and 4.11). In western Kenya, N and P are major limiting factors for maize production (Kihara and Njoroge, 2013; Nziguheba *et al.*, 2016). Typically, not applying N can mean a loss of 43% of maize grain yield, while not applying P would mean a loss of 50% of maize yield (Nziguheba *et al.*, 2016). Desmodium seemed to have the solution to that as it increased availability for both N and P. Besides, desmodium increased ammonium, which is an added advantage as plants prefer ammonium to nitrate for their N nutrition (Padgett and Leonard, 1996; Robinson *et al.*, 2011). On the other hand, when striga is not controlled, it attaches to maize roots, sucks its nutrients, causes phytotoxic effects on maize (Khan *et al.,* 2002), and impairs its photosynthesis (Rodenburg *et al.,* 2008). The effect of striga on colonized plant is felt even 4 days after attachment and results in shorter plants with smaller leaves (Frost *et al.*, 1997) and alarming loss in grain yields (Kim *et al.*, 2002).

There was no improvement in maize yield in Siaya (maize grain yield in push-pull were similar to that for non-push-pull throughout the study period). This was probably due to soil fertility related constraints. For example, Vanlauwe *et al.* (2008) reported improvement in Olsen-P in Vihiga due to push-pull contrary to no improvement in Siaya, and no improvement in maize grain yield in five over six seasons of their study in this site. Similar results were reported in Siaya by Kifuko-Koech *et al.* (2012) from on farm experiment in Siaya and Busia in 2009 and 2010. From this study, soil organic carbon in Siaya was lower than that for Bondo and that for Vihiga (Figure 4.4 and 4.8). This implies that the level of soil fertility is low in Siaya than in Bondo and Vihiga and might need more interventions than push-pull technology. Seasonal variation in comparative performance of push-pull in a site are due to seasonal variation in rainfall amount and distribution.

5.2.3.2. Total biomass

Push-pull doubled or more than doubled aboveground biomass produced in commonly practiced maize-based cropping systems in western Kenya. The biomass from push-pull is more diversified than that for maize monocrop, maize-bean, maize-cowpea, maize-crotalaria, maize-green gram and maize-groundnut intercrops. It includes brachiaria, desmodium and maize stalks. In terms of diversity, maize monocrop is the least as it provides only maize stalks while its intercrops with food legumes adds their stalks as well. However, stalks of these legumes might not be as good as desmodium biomass due to translocation of nutrients from leaves to grains (harvested) and loss of leaves as they shade before harvesting. Though they fix N as desmodium (Sanginga *et al.,* 2000; Ojiem *et al.,* 2007; Mathu *et al.,* 2012; Rurangwa *et al.,* 2018), their N harvest index is high (Vanlauwe and Giller, 2006) and might not be good quality fodder as desmodium (evergreen and no grains harvesting). Therefore, the mix from push-pull would make a better fodder than that from maize monocrop and intercrops of maize with common bean, cowpea, green gram and groundnut. For farmers who do not have livestock units, push-pull is still better than maize monocrop and intercrops of maize and common bean, cowpea, crotalaria, green gram and groundnut. This is because contrary to maize, common bean, cowpea, crotalaria, green gram and groundnut stalks, brachiaria and desmodium have a market value (De Groote *et al.,* 2010; Midega *et al.,* 2014). Currently, adopters of push-pull in western Kenya bale and sell a mix of brachiaria and desmodium as hay. In terms of soil fertility management, the biomass from push-pull would recycle more nutrients than commonly practiced maize-based cropping systems in western Kenya through direct application of residues or livestock feeding and manure making (Rufino *et al.,* 2006; Vanlauwe and Zingore, 2011; Vanlauwe *et al.,* 2014). This would lead to sustainable soil fertility management (Birch and Dougall, 1967; Drinkwater *et al.,* 1998; Gnanavelrajah *et al.,* 2008).

5.2.3.3. Striga weed

The performance of push-pull compared to commonly practiced maize-based cropping systems in western Kenya in controlling striga varied with sites and seasons. This is attributed to variations in rainfall amount and distribution that affect the growth of desmodium in push-pull farms and germination and growth of striga in other maize-based cropping systems' farms. However, the number of striga was almost zero in farms with push-pull in all sites and seasons while it was one and above in control cropping systems, similar to what was observed by Khan *et al.* (2008a,c). Lower number of striga was observed as well in maize-desmodium intercrop compared to other maize-legume intercrops in Mbita, *icipe* research station in the three study seasons. Mechanisms by which desmodium controls striga involve suicidal germination, shading, addition of nitrogen through biological fixation, and allelopathy (Khan *et al.,* 2002). Like desmodium, common beans, cowpea, crotalaria, green gram and groundnut stimulate striga germination through releasing strigolactones (Jamil *et al.,* 2011). But contrary to desmodium, these legumes do not have mechanisms to inhibit striga radical growth to prevent it from attaching to maize roots (Khan *et al.,* 2010). This renders them less efficient than desmodium in controlling striga (Khan *et al.,* 2007; Vanlauwe *et al.,* 2008; Midega *et al.,* 2014; Hailu *et al.,* 2018).

The efficacy of push-pull in controlling striga increased with time. Farms where push-pull had been practiced for a longer time had lower striga counts than those where push-pull had been practiced for less than two years. This phenomenon was observed in the first season of the study. During the second and third seasons, (2017 short rains and 2018 long rains), the number of striga in farms that had adopted push-pull for less than two years became similar to the number observed in older push-pull farms (more than two years of adoption of push-pull, Table 6). This is because desmodium (intercropped with maize in push-pull farms) controls striga and progressively depletes its soil seedbank since the second season of its growth (Vanlauwe *et al.,* 2008; Kifuko-Koech *et al.,* 2012).

5.2.4. Study limitations

In Mbita, *icipe* research station, this study was conducted on plots that were infected with striga seeds in 2003 (Khan *et al.,* 2007). Though infestation was done uniformly for all the treatments, the legumes studied have differing ability to control the effect of striga on maize (Khan *et al.,* 2007; Midega *et al.,* 2014). This is important because the performance of maize reported by this study was due not only to availability of N and P, but also to the presence of striga. Yet, striga is a serious threat for maize production in Africa affecting more than 40 million households, considerable land for crop production, and causing huge losses of income every season (Adesina and Baidu-forson, 1995; Emechebe *et al.*, 2004; Badu-Apraku and Fakorede, 2017; Mudereri *et al.*, 2020). Therefore, this study shows comparative benefits of adopting push-pull, a maize cropping system in areas affected by striga in SSA and similar environments. The presence of striga did not affect the performance of legumes in availing N and P as the growth and production of legumes are not affected by the presence of striga. Therefore, the veracity of relatively higher performance of desmodium in availing N and P for maize production observed in this study is guaranteed.

5.3. Conclusions

5.3.1. Organic carbon socks

Farms with push-pull store higher amount of carbon in biomass and soils than farms without push-pull, due to relatively higher level of crop intensification in push-pull farms and lower level of soil disturbance in push-pull farms compared to non-push-pull. The amount of carbon in the soil increased with time push-pull is practiced in a farm, but this was site specific. Push-pull increased bulk density within critical values associated with compaction. Differences in soil conditions are responsible for variations in the amount of biomass and soil carbon found in the three sites; Bondo, Siaya and Vihiga. Soil organic carbon (SOC) was higher in drier environment (Bondo) that in wetter environments (Siaya and Vihiga) because microbial activity on SOC is low when it is dry than when it wet. Adoption of push-pull offers opportunity to store more carbon both above and belowground in different climatic conditions.

5.3.2. Availability of nitrogen and phosphorus

Desmodium, a component crop for push-pull, improved availability of N and P hence performance of the main crop; maize and the desmodium itself. This suggests that desmodium has high biological N fixation capacity than common bean, cowpea, crotalaria, green gram and groundnut. The high biomass of desmodium means higher soil organic matter and subsequent effects in the soil. Common bean, cowpea, crotalaria, green gram and groundnut did not increase the availability of N and P probably due to their low rate of biological N fixation or simply due to competitive uptake with associated maize. Desmodium improved the growth and grain yield of maize because of N and P nutrition. The growth of desmodium did not limit the growth and yield of maize.

Push-pull improved the growth of maize and its grain yield due to improved nutrition in N and P facilitated by desmodium, striga control and other soil conditions including soil organic matter. Push-pull also improved biomass productivity, and drastically reduced striga infestation relative to maize monocrop, maize-bean, maize-cowpea, maize-crotalaria, maize-green gram, and maize-groundnut. The performance of push-pull varied across study sites and seasons but was consistently higher or similar to other maize-based cropping systems. The efficacy of striga control increased over time while maize grain yield and biomass productivity did not change due to the period of time the farm had been under push-pull.

5.4. Recommendations

5.4.1. Recommendations for improvement

It is recommendable to farmers from western Kenya and those from similar environments to adopt push-pull technology for maize production. Doing so does not negatively affect maize grain yield. Rather, adoption of push-pull provides higher yield of biomass that is more diversified than common maize-based cropping systems. In addition to this, adoption of push-pull will contribute to storing more carbon in plant biomass and soil leading to soil health improvement. Furthermore, adoption of push-pull will help farmers to produce more maize grain yield at low investment in mineral fertilizers as desmodium contributes to N and P nutrition of the maize. It is worth to note that intercropping desmodium in maize plantation does not affect the population of maize because desmodium is planted in the mid-distance between two rows of maize planted at 75 cm spacing.

It is recommendable to farmers who adopt push-pull to recycle the biomass produced in push-pull farms. This is because as push-pull produces high amount of biomass, it likely removes a good amount of nutrients from the soil system. Additionally, the amount of nutrients applied in the form of mineral fertilizers by push-pull farmers is little. Therefore, recycling the biomass might reduce the risk of depletion of nutrients in push-pull farms. Recycling can be done through direct application of crop residues or feeding residues to livestock units and returning the manure that is produced. In the case residues are sold as hay, farmers are encouraged to return the removed nutrients through increasing the amount of mineral fertilizers they apply.

It is recommended to *icipe* and agriculture extension agents that promote push-pull technology to have a strategic method of assessing the ability of push-pull technology to sequester carbon in soils. This would be done through establishing the baseline information on soil organic carbon content or concentration and its stock at a certain soil depth. Then after, regular assessments would be done to establish the trend; loss or gain of soil organic carbon overtime. This will shade light on how push-pull sequesters carbon overtime.

5.4.2. Recommendations for further studies, application of findings and/or commercialization

It is recommendable to researchers/scientists to assess emissions of greenhouse gases such as carbon dioxide, methane and nitrogen oxides from push-pull and non-push-pull farms, especially due to changes in wet or dry conditions and temperatures. From this study, push-pull stores more carbon and increases nitrogen in soils. There is need to know whether carbon and nitrogen in push-pull does not contribute to oxides of carbon, methane and oxides of nitrogen released into the atmosphere.

It is also recommended to undertake studies on distribution and stock of carbon; organic and inorganic in a soil profile of at least 60 cm, comparing push-pull and other maize based cropping systems. This is because this study focused on upper 15 cm soil layer. There is need to know whether the superiority of push-pull in storing carbon in upper 15 cm soil layer is not altered as you move down the soil profile.

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