DESMODIUM EFFECT ON SOIL FERTILITY, STRIGA CONTROL AND MAIZE PRODUCTION IN BUSIA AND SIAYA COUNTIES, WESTERN KENYA.

BY

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AGR/D.PHIL/02/07

A THESIS SUBMITTED TO THE SCHOOL OF AGRICULTURE AND BIOTECHNOLOGY, UNIVERSITY OF ELDORET, IN PARTIAL FULFILMENT FOR THE REQUIREMENT OF THE AWARD OF DOCTOR OF PHILOSOPHY DEGREE IN SOIL SCIENCE.

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JULY, 2013

DECLARATION

Declaration by the candidate

This thesis is my original work and has not been presented for a degree in any other University. No part of this thesis may be reproduced without the prior written permission from the author and /or University of Eldoret.

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GENERAL ABSTRACT

Low soil fertility, stemborer and *Striga* weeds limit production of maize in western Kenya. *Desmodium* in the "Push-Pull" technology has been found to reduce *Striga* and stemborer but its contribution to soil fertility rehabilitation is not well understood. Field trials were conducted in Busia and Siaya counties, western Kenya, to test the hypotheses that (1) inorganic nitrogen, soil carbon, ^{13}C isotope discrimination ($\delta\ ^{13}C$) and biological nitrogen fixation (BNF) in maize-*Desmodium* intercropping system are affected by *Desmodium* species and sampling time and (2) maize yield, the degree of *Striga* suppression and economic benefits of intercropping maize with *Desmodium* are affected by different *Desmodium* species and the cutting regime of the *Desmodium*. Maize was intercropped with *Desmodium uncinatum* (Jacq.) DC., cv Silverleaf (*D. uncinatum*) or *Desmodium intortum* (Mill.) Urb. cv Greenleaf (*D. intortum*), and treatments with sole maize with or without urea were included for comparison. The first two *Desmodium* cutting events were fixed at every start of every season and 4 weeks later while the third cutting was varied and conducted at 9, 12 or 18 weeks after planting maize in each season. Maize biomass, mineral nitrogen, soil carbon, $\delta\ ^{13}C$ and biological nitrogen fixation parameters were determined over time in both maize-*Desmodium* intercrop with *Desmodium* cut at 18WAP and sole maize systems. To study the contribution of *Desmodium* to soil phosphorus (P) rehabilitation, a greenhouse experiment was conducted in two phases to assess the extent to which *Desmodium* spp fertilized with Busumbu phosphate rock (BPR) could increase soil available P, P uptake and biomass yield of maize crop planted after *Desmodium spp*. Treatments included sole maize and two *Desmodium spp* : (*D intortum* and *D.uncinatum*) with or without BPR grown in the first phase of the experiment followed by sole maize with no P application in the second phase of the experiment. Reference treatments with soluble P (KH_2PO_4) were included. Results showed that *D. intortum* was superior to *D. uncinatum* in producing the highest biomass, fixed N, soil carbon, mineral N and N concentration at different sampling times. However, despite these positive attributes, *D. intortum* resulted in somewhat lower cumulated (over four seasons) maize grain yields. Maize shoots $\delta^{13}C$ values in *Desmodium* intercropping and sole maize systems did not differ significantly, an indication of comparable environmental effect on both systems. Varying the time of cutting *Desmodium* had little effect on maize yield and net benefits. Average net benefits from *Desmodium* intercropping over the four seasons were increased by 1290 and 918 \$ ha^{-1} relative to the maize monocrop in Busia and Siaya respectively. *D. intortum* and *D. uncinatum* equally reduced *Striga* counts, an indication that the two species may demonstrate comparable phytochemical attributes. Greenhouse results showed that maize dry matter yields, plant P concentration and available P in soils were higher in maize following *Desmodium spp* compared to maize following maize wheather BPR was applied or not. *D. intortum* was however a more potent solubilizer of BPR than *D. uncinatum*. The present study extends the recommendation of the *Desmodium*-maize intercropping system to farmers who apply P fertilizers and can benefit from increased soil nitrogen, soil carbon and crop yield after the system becomes well established. Nevertheless, a further multi-locational and multi-seasonal evaluation of *Desmodium*-maize intercropping system would be required to investigate whether the system is also advantageous in terms of yield stability and sustainability, across locations and seasons.

DEDICATION

To my dear husband, baby Daisy, Allan and Ryan for their patience, encouragement and support during the study period.

To my late father, Kibuku Kamau, my dear mum Teresiah Wanjiku and my parents in law whose continuous encouragement gave me strength to move on.

To **Almighty God** for giving me life.

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SHORT FORMS AND ACRONYMS

BPR - Busumbu Phosphate Rock

CIAT - International Center for Tropical Agriculture

DI - *Desmodium intortum*

DMY - Dry Matter Yield

DU - *Desmodium uncinatum*

ICIPE - International Centre for Insect Physiology and Ecology

IFS - International Foundation for Science

IPM - Intergrated Pest Management

IPNI - International Plant Nutrition Institute

ISFM - Integrated Soil Fertility Management

LR - Long Rainy Season

MOP - Muriate of Potash

NAS - Neutral Ammonium Solubility

NCST - National Council for Science and Technology

PPT - Push -Pull Technology

PR - Phosphate Rock

SED - Standard Error of the Difference

SR - Short Rainy Season

TSBF - Tropical Soil Biology and Fertility Institute of CIAT

TSP - Triple Super Phosphate

WAP - Weeks after Planting

ACKNOWLEDGEMENT

I sincerely appreciate the financial support from the German Academic Exchange Service (DAAD) through the Afican Regional Postgraduate Programme in Insect Science under **International Centre of Insect Physiology and Ecology (*icipe*).** The scholarship award allowed me to start and complete my Ph. D. studies successfully.

This work could not have been possible without the encouragement of my university supervisors, **Prof J.R. Okalebo** and **Prof. C.O. Othieno**. They taught me science and made me feel competitive and well equipped to face the future science challenges with confidence. I must sincerely thank **Prof. Z. R. Khan, Prof.Pickett, Dr. B. Vanlauwe and Dr. P. Pypers** who co-supervised this work. They were a constant source of inspiration and introduced me to the world of publications. Many thanks to **Dr. Serrem** who contributed in a big way to the site characterization (soil classification) of the study areas.

I am very greatful to the laboratory technicians in University of Eldoret (Schola Mutua, Ann Njoki and Mary Emongore) and TSBF-CIAT (Evonne Oyugi and Wilson Ngului) who worked tirelessly on my very many soil and plant samples. I am particularly very grateful to all University of Eldoret greenhouse staff who worked without complaining. **Emi Kosgei**, thanks for the many days you told me “let stress not get you down because you will die and leave your children in problems”. This statement kept me going and gave me a reason to deal with emerging challenges.

My field work was conducted in Siaya and Busia Counties and I am indebted to Laban Nyabega, Dickens Nyagol, Nahashon Otieno and Richard Ouma who encouraged me even when things were not working out as anticipated. I appreciate all the farmers who allowed me to work on their farms and field technicians (TSBF and ICIPE) who took care of the trials.

My Ph.D. field work was partially financially supported by IFS, NCST, IPNI and Moi University. I want to sincerely acknowledge these organizations for the generous funding

I am sincerely grateful to Director Kenya Agricultural Research Institute (KARI) for granting me study leave and providing funds for me to attend international conferences.

I cannot forget to honestly express my gratitude to all the other post graduate students (Keziah Wairimu, Moses Thuita, Peris Mongare, Abigael Nekesa, Ruth Njoroge and the late Patrick Webo). The many ideas we shared helped in shaping this thesis.

I must sincerely thank my dear husband for his unlimited support, extended family and my house helper (mamababu) for taking care of our kids while I was away.

Above all I thank the Almighty God for the gift of life and good health which allowed me to do this work. **GLORY BE TO HIS NAME.**

CHAPTER ONE

1.0. GENERAL INTRODUCTION

1.1 Background

Crop production in most of the sub-Saharan Africa is on the decline as soils become increasingly depleted of nutrients, coupled with increased pest and disease infestation. Smaling *et al.*, (1993a) reported an average nutrient loss in sub-Saharan Africa of 22 kg N, 2.5 kg P and 15 kg K ha^{-1} yr^{-1}, although in Kisii district, Kenya, depletion of 112 kg N, 3 kg P and 70 kg K ha^{-1} yr^{-1} was specifically observed (Smaling *et al.*,1993b). In western Kenya, nitrogen (N) and phosphorus (P) are limiting nutrients and the major cause for poor yields of maize, the main staple food crop in the region (Lijzenga, 1998).

Striga weeds (specifically *Striga hermonthica* and *Striga asiatica*) (witchweed) and stem borers (particularly, *Chilo partellus*) are major biotic factors affecting cereal crop production, particularly maize in western Kenya (Murage *et al*., 2011; De Groote *et al*., 2010). In this region, *Striga hermonthica* is the most common and it is estimated to cause between 5-15% and 100% maize yield losses with sparse and heavy infestations respectively (ICRAF, 1995). Stem borers occur in all major agro-ecological zones of Kenya, and cause average maize crop losses of 13.5% countrywide and 16.6% in the moist Mid-Altitude zone (De Groote *et al*., 2010). Sustainable maize production will depend on how well soil fertility replenishment and pest control strategies are incorporated into the farming systems.

Over the last two decades, research has provided a sound knowledge base on cropping systems, crop and land management practices that increase food production while repressing the *Striga* spp. (Kanampiu *et al*., 2003). These practices consist use of herbicide resistant/tolerant maize varieties that include imazapyr resistant (IR) and Kakamega *Striga* Tolerant Population (KSTP). Other promising *Striga* control stratergies include rotation or intercropping with legumes that trigger suicidal *Striga* germination, application of N and P fertilizers, application of organic inputs, irrigation, hand pulling, and application of lime (Kanampiu, *et al*., 2003; Khan *et al*., 2002). Similarly, several options are available for replenishing soil N and P, and restore crop productivity in western Kenya, and these include the use of mineral fertilizers and farm-based organic residues or their combination, phosphate rocks, short duration fallows, or N-fixing grain and forage legumes (Dahlin and Stenberg, 2010; Ojiem *et al*., 2007; Kifuko *et al*., 2007; Ndung'u *et al*., 2006; Okalebo *et al*., 2006; Jama, *et al*., 1997). In some areas, the adoption of the proposed technologies has been high and positive impact has been reported but still in other areas adoption has been slow and uneven due to various socio-economic and environmental factors (Murage *et al*., 2011; Okalebo *et al*., 2006; Gachengo, *et al*., 2004; Showemimo, *et al*., 2002). The low adoption is reflected in the overall low (<1 t ha^{-1}) and declining maize yields in this region (Okalebo *et al*., 2006).

Given the multiple factors that limit cereal production, an integrated approach capable of addressing soil fertility, pest and disease problems is the key to sustainable cereal production in western Kenya. One promising integrated approach that accommodates principles of intergrated soil fertility management (ISFM) and intergrated pest management (IPM) is the "Push-Pull" technology (PPT) that uses a mixture of behavior-modifying stimuli to manipulate the distribution and abundance of insect, a strategy that was established in 1987 as an approach for integrated pest management for control of *Helicoverpa* in cotton crops in Australia (Duraimurugan and Regupathy, 2005). In Kenya, the PPT strategy was adopted by the International Centre for Insect Physiology and Ecology (ICIPE) in collaboration with other partners, and is defined as maize intercropped with a stem borer moth-repellent *Desmodium*, and surrounded with an attractant host plant, napier grass, planted as a trap plant for stem borers (Khan *et al*., 2000). Chemicals released by *Desmodium* roots induce abortive germination of the parasitic *Striga* weed seed, providing control of this noxious weed (Khan *et al*., 2002). Besides being nutritious for cows and repelling insects, *Desmodium* spp substantially reduce damage of maize by *Striga* by (i) producing chemicals that stimulate germination of *Striga* but do not support their growth (ii) shading effect, (ii) increased humidity as a result of abundant leaf fall that provides deep duff layer under the plants and, (iv) increased available nitrogen through biological nitrogen fixation (Khan *et al*., 2002; 2001). *Desmodium* spp and napier grass are highly nutritious perennial fodder that can be cut throughout the year to supplement the available animal feed.

In western Kenya however, widespread and severe phosphorus (P) deficiency caused mainly by P fixation and low P in parent soil material limit the growth of legumes given that they are poor competitors for P when intercropped with cereals, this being attributed to differences in root morphology. Studies show that, upon decomposition of legumes biomass, some organic acids whose carboxyl and hydroxyl functional groups ionize and release H^+ ions react with Al, Fe and Ca to form complexes, which increase P activity in the soil solution (Lindsay and Stephenson, 1956). Another promising strategy in replenishing P is the use of a low cost ground P-rich phosphate rocks (PR), which are widely distributed in eastern and southern Africa (van Straaten, 1997; Buresh *et al*., 1997). However, the use of PRs such as Busumbu PR (BPR) found in eastern Uganda is limited by their low solubility but legumes have been shown to increase the dissolution and utilization of PR because of their acidifying effect on the rhizosphere (Melenaghen *et al*., 2004). Information is however lacking on the effect of *Desmodium* spp on solubility of BPR.

1.2 Justification

Desmodium is a leguminous crop capable of adding soil nitrogen through biological nitrogen fixation and increasing soil organic matter as a result of abundant leaf fall, decomposition and mineralization. However, despite the well documented role of *Desmodium* in controlling *Striga* and stem borer (Khan *et al*., 2000; 2002) in western Kenya, contribution of *Desmodium* to soil nutrient replenishment in this system is not well understood.

In a crop-livestock integrated system, lack of animal feed is a major constraint which may force the farmers to cut *Desmodium* several times during the season. Subjecting *Desmodium* to different cutting strategies can have an impact on crop yield. Even though cutting *Desmodium* during the season is a common practice to reduce shading and provide fodder in the PPT, little is known on how this management practice affects the yield of the associated cereal crop and overall economic benefit of the PPT.

In western Kenya, there is widespread and severe P deficiency caused by P fixation and low soil inherent P (van Straaten, 2007; Buresh *et al*., 1997). Use of PR such as BPR and Mijingu PR (MPR) to replenish P in western Kenya is economical because they are widely distributed in eastern Africa. However, due to their low water solubility and slow P release, particularly BPR, they are rarely used as a direct P input (Pypers *et al*., 2007; Stamford *et al*., 2005). Because of its low solubility, use of BPR, particularly in western Kenya, is limited and alternatively MPR has vastly been promoted in this region (Kifuko *et al*., 2007 and Ndungu *et. al*., 2006).

Although compared to MPR, BPR is of lesser reactivity with low neutral ammonium solubility (NAS) of 2.3%, its close proximity to western Kenya (< than 20 km away) compared with MPR (>820 km away) makes it attractive in this region (van Straaten, 2002). Many grain legumes have been shown to increase solubility of PRs (Pypers *et al*., 2007) but information is lacking on the effect of perennial legumes particularly *Desmodium* spp on solubility of Busumbu PR (BPR). To understand the above mentioned concerns in an intercropping system involving *Desmodium* and maize, this study focused on the following objectives:

1.3 Study Objectives

1.3.1. Broad objective

To assess *Desmodium* effect on soil fertility rehabilitation, *Striga* control and maize yield in a maize–*Desmodium* intercropping system in Busia and Siaya counties in western Kenya.

1.3.2. Specific objectives

The specific objectives of this study were to:

(i) Monitor if changes in selected soil properties (inorganic mineral nitrogen, soil carbon and biological N_2 fixation) are affected by *Desmodium* spp and sampling time.

(ii) Assess changes in stable ^{13}C isotope discrimination of maize at different growth stages in *Desmodium*-maize intercropping system.

(iii) Monitor if maize yield, degree of *Striga* suppression and economic returns of PPT are influenced by the *Desmodium* spp and cutting regime of the *Desmodium*.

(iv) To assess if inclusion of *Desmodium* spp into maize cropping system will enhance BPR solubility and P availability.

1.4 Hypotheses

1) Changes in inorganic mineral nitrogen, soil carbon and biological N_2 fixation in maize-*Desmodium* intercropping system are influenced by *Desmodium* spp and sampling time.
2) Intercropping maize with *Desmodium* has an impact on maize stable ^{13}C isotope discrimination at different maize growth stages.
3) The maize yield, degree o*f Striga* suppression and economic returns of PPT are influenced by th*e Desmodium* spp and cutting regime of th*e Desmodium*.
4) Incorporating *Desmodium* spp into maize cropping system will enhance Busumbu phosphate rock solubility and P availability.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Soil fertility and productivity in cropping systems of Sub- saharan Africa

Soil fertility is defined as the capability of the soil to supply nutrients that enhance plant growth (Follet *et al*., (1987). Most often this term is confused with soil productivity, but soil productivity is the soil's ability to produce a crop. Productivity is a function of a soil's natural fertility status plus nutrients added as fertilizer, organic residues and other sources, soil physical and biological properties; climate, management and other non-inherent factors used to produce crops (Follet and Wilkinson, 1985). Sub-saharan Africa (SSA) has major challenges in increasing agricultural productivity to achieve food security and to raise rural incomes (Ngoze *et al*., 2008). Land degradation and declining soil fertility are critical problems affecting agricultural productivity and human welfare in tropical Africa. According to Sanchez *et al*., (1997), soil-fertility depletion in smallholder farms is the fundamental biophysical cause for declining *per capita* food production in sub-Saharan Africa. It is estimated that an average of 660 kg of nitrogen (N) ha^{-1}, 75 kg of phosphorus (P) ha^{-1} and 450 kg of potassium (K) ha^{-1} has been lost during the last 30 years from 1997 backwards in about 200 million ha of cultivated land in 37 African countries (Sanchez *et al*., 1997). The underlying socioeconomic causes of nutrient depletion, their consequences and the various strategies for tackling this constraint are fairly well known (Ranamukhaarachchi *et al.,* 2005; Buresh *et al*., 1997; Smaling *et al*., 1993b).

2.2 Soil fertility replenishment technologies

Improving soil fertility is a key entry point for achieving food security, reducing poverty and preserving the environment for smallhold farmers in SSA. In the past, long natural fallow periods regenerated soil fertility (Greenland, 1977; Cooke, 1967) but as a result of population pressures and increased poverty, land has been cultivated continuously with negligible to no nutrient returns (Smaling *et al.*, 1997). With the escalating inflation and lack of fertilizer subsidies, farmers no longer consider buying mineral fertilizers as a priority. In addition, there has been low fertilizer use (below the level of maintaining soil fertility) because of the high cost of mineral fertilizers, unavailability at the right time and the risks from erratic and limited rainfall (Okalebo *et al.*, 2006; Rao and Mathuva, 2000).

In most acidic soils, P has been reported as the second limiting nutrient to crop production after nitrogen (Jama and van Straaten, 2006; Jama *et al.*, 2000) because of the high P sorption capacity of these soils and high levels of H^{+} and Al^{+++} that interfere with crop growth. To replenish nitrogen, several organic matter technologies such as green manures (Jama *et al*., 2000), animal manures (Kifuko *et al*., 2007, Waigwa *et al*., 2003) and biological nitrogen fixation (BNF) (Ndung'u *et al*., 2006; Giller, 2001; Rao and Muthuva, 2000) have been tested and recommended for use in SSA countries but the reported adoption rate is none or limited (Okalebo *et al*., 2006). The greatest challenge in the use of organic matter technologies is that processing and application of organic wastes residues is labor intensive, organic materials differ widely in quantity and quality, release variable quantities of nutrients in soils at different times, resulting to differences in nutrient availability and crop yields (Gachengo, *et al.*, 2004; Shepherd and Soule 1998; Palm, *et al.*, 1997).

In exploiting the BNF process, it should be noted that P deficiency can prevent nodulation (Giller, 2001) and because of widespread P deficiency in western Kenya, legumes can only be important as a component of an integrated soil fertility management (ISFM) strategy since P has to be obtained from elsewhere (Ojiem *et al*., 2007). Options for P replenishment are organic materials, mineral P fertilizers, phosphate rocks (PR) and use of phosphorus solubilizing micro-organisms (PSM) and leguminous to enhance P availability from PR (Ndung'u-Magiroi *et al*., 2011; Okalebo *et al.*, 2006; Nekesa *et al.*, 1999; Sanchez *et al.*, 1997). Several PRs deposits of variable reactivity exist within east Africa (Van Straaten, 2002; Okalebo and Woomer, 1994) and their potential as a source of P for plants within the context of an integrated soil fertility management approach needs to be explored. Given the acute poverty and limited access to mineral fertilizers, a promising approach should target the efficient use of N through biological nitrogen fixation (BNF) and improved P availability through P inputs. However, for proper management and a full realization of the benefits of this plant-microbial association, it is necessary to estimate how much nitrogen is fixed under different field conditions using reliable and accurate BNF quantification methods. One such promising method for BNF quantification is the use of ^{15}N isotope techniques.

2.3 ^{15}N isotope techniques for BNF estimation

Most early estimates of N_2 fixation in legume based cropping systems were based simply on the total amounts of biomass N accumulated by the crops (Ledgard and Steele, 1992). This approach tends to overestimate the amounts of N_2 fixed as it erroneously assumes that the entire N present in the legume originates from N_2

fixation. Recent methods apply ^{15}N isotope based procedures in N fixation studies that permit determination of the proportions of legume N that was derived from atmosphere (Unkovisch *et al*., 1994).

2.3.1 Use of ^{15}N Isotope

The use of $^{15}N_2$ gas method provides direct evidence for N_2 fixation since the ^{15}N concentration in plants exposed to $^{15}N_2$ is greater than the 0.3663% natural abundance. This method involves the enclosure of plants in chambers filled with the enriched ^{15}N gas (Azam and Farooq, 2003). The extent to which $^{15}N_2$ is detected in the plant provides an estimate of the proportion of the plant N that was derived from fixation, and is thus a direct method for quantifying N_2 fixed. The use of ^{15}N-labelled gas however, is impracticable in the field as it would require a gas tight enclosure (chamber) of the entire root system. The environment within the chambers is, however, likely to be different from that in a field situation. Also, it is difficult to confine plants in these chambers for long periods without affecting the growth conditions as compared to the field environment. The isotope composition of the chamber can also change with time if the enclosure is not gas tight due to leakage of air. Results obtained from such studies therefore tend to be of short term (hours to days) and subject to errors associated with extrapolating data from short term studies to a growing season which involves diurnal, daily and seasonal variations (Boddey and Knowles, 1987).

2.3.2 ^{15}N isotope dilution method

The ^{15}N isotope dilution (ID) method involves the growth of N_2 fixing (F) and non-fixing reference (NF) plants in soil fertilized with ^{15}N enriched inorganic or organic fertilizers. It relies on the differential dilution in the plant of ^{15}N- labeled fertilizer by soil and fixed nitrogen. The uptake of ^{15}N enriched fertilizer added to soil will result in a $^{15}N/^{14}N$ ratio greater than 0.3663% within the plant. The atom%^{15}N excess of the fertilizer nitrogen within the plant is an indication of the extent to which the plant took up N from other unlabelled N sources (IAEA, 2001). Methods based on ID methods offer accurate estimates to quantify symbiotic nitrogen fixation. However, the use of ^{15}N dilution technique ideally requires that the soil N is labeled uniformly throughout the rooting zone, and preferably remains approximately stable with time over the period of the study which is extremely difficult to achieve in the field (Sanginga *et al.*, 1995). Variations are, however, often found depending on the non-fixing standard crop. This has been found to be mainly due to differences in N uptake patterns of the legume and reference plants, together with a decrease in the ^{15}N /^{14}N ratio of the substrate with time (Azam and Farooq, 2003).

2.3.3 Natural abundance method

The natural abundance (NA) method is based on the fact that the natural abundance of ^{15}N of the N_2 in the air is constant (0.3663 at % ^{15}N) (Junk and Syec, 1958) and does not show detectable difference between sites anywhere on the earth (Mariotti, 1983). However, as a result of isotope discrimination effects occurring during soil formation, most soils have slightly higher ^{15}N abundance than the atmosphere. As an outcome of this difference in ^{15}N abundance between soil and atmospheric N_2, nitrogen fixing plants have been found to have lower ^{15}N enrichment than non-fixing plants, and this has been used to measure BNF (Shearer and Kohl, 1986). Under field conditions, the ^{15}N natural abundance method has advantage over, for example, the ^{15}N enrichment method because no addition of ^{15}N labeled fertilizer is required, and can therefore be used on-farm, provided appropriate non-N_2-fixing reference plants are present. The choice of reference plants is a major factor that can influence the reliability of this method (IAEA, 2001). Another limitation in application of NA method is that this technique requires access to stable isotope ratio mass spectrometer capable of detecting small differences which is very expensive and not within reach in developing countries.

2.4 Estimates of nitrogen fixation in legume cropping systems

Nitrogen deficiency is a major constraint to the productivity of the African smallholder farming systems (Ojiem *et al.*, 2007). In some agricultural systems, legumes are used as a source of N for subsequent crops and for maintaining soil N levels through biological nitrogen fixation (BNF) (Glasener *et al.*, 2002). On average, close to 20 and 25 kg of shoot N are fixed for every tonne of legume herbage dry matter produced in temperate and tropical environments (Peoples and Baldock, 2001). Overall estimates are in the order of 25 to 100 kg N ha^{-1} yr^{-1} per crop for grain legumes and as much as 280 kg N ha^{-1} yr^{-1} for some herbaceous and woody perennials (Giller and Wilson, 1991). Unfortunately, grain legumes are widely grown in most cropping systems but their potential for net N inputs by BNF is quite limited. For instance, nitrogen fixation by peanut *(Arachis hypogea* L.) ranges from 68 to 206 N ha^{-1} yr^{-1} per crop, but most of it is removed at harvest (Giller and Wilson, 1991). Common bean is widely cultivated in east Africa, but it has such a low inherent capacity to fix N that it is likely to produce a negative N balance in the soil. Soybean *[Glycine max* (L.) Mem] has a high BNF capacity, but it concentrates N in the pods, adding little to the soil (Giller and Wilson, 1991). Therefore, the contribution of BNF by commonly grown grain legumes with high N harvest index does not necessarily translate to soil N replenishment. Short-term fallows of leguminous trees and herbaceous cover crops such as forage legumes, however, provide a practical means of N replenishment via BNF when grown in rotation with cereal crops. Herbaceous perennial forage legumes fix significant high amount of nitrogen compared to annual grain legumes. For instance, Nutman (1976) reported that *Stylosanthes gracilis* and *S. humilis* fixed 34-220 kg N ha $^{-1}$ year^{-1} in a seasonal environment while *Centrosema pubescens* fixed 80-280 kg N ha $^{-1}$ year^{-1} under grazing. Elsewhere in Australia, Whitney *et al*., (1967) found sole *Desmodium canum* and *Desmodium intortum* to fix 89 kg N ha $^{-1}$ year^{-1} and 382 kg N ha $^{-1}$ year^{-1}, respectively in a continuously moist climate. Suttie (1968) estimated that *D. uncinatum* contributed 160 kg fertilizer N in association with grasses in Kenya while in Malawi the estimate was 90 kg/ha where the legume comprised 30 percent of the sward. In Kenya, feed shortage is a major constraint in livestock production sector and inclusion of perennial fodder legumes in crop-livestock integration systems can ensure more stable income and food security.

2.5 Effect of legume pruning on soil nutrients

Competition for above and below-ground resources occurs in simultaneous cropping systems involving perennial and annual crops (Corlett *et al*., 1992). In such systems, pruning is a common management practice for mulching and reducing competition. Several authors have however reported that the dynamics of nutrients in the rhizosphere is affected by pruning. In an acacia hedgerow planting in northern Kenya, Peter and Lehmann (2000) observed that pruning effectively reduced root development which decreased potential below-ground competition with intercropped plants, but the reduction in subsoil roots increased the danger of nutrient losses by leaching. Elsewhere, in an *Albizia lebbeck* and *Leucaena leucocephala* cropping system, Kadiata and Mulongoy (1998) found that removal of plant shoots reduced nodule and root biomass by some 30–38% and halved nodule N. In addition, the unpruned plants of both species maintained greater levels of total N in their rhizosphere compared to those that were pruned. Ohyama and Harper (1991) reported that plant pruning, particularly when it is done low, limits the supply of photosynthate to the nodules. This affects N_2 fixation and results to nodule decay and shading of the nodules in the rhizosphere. In the PPT, it has been observed that pruning of *Desmodium* during early maize growth stages is a common practice to reduce competition and also provide high quality fodder during dry spell.

2.6 Role and dynamics of nitrogen and phosphorus in legume cropping systems

There are 16 elements that are known to be essential for crop growth. In western Kenya, N and P are the most commonly deficient in agricultural soils (Okalebo *et al*., 2006) and their role and dynamics are discussed below:

2.6.1 Role and dynamics of nitrogen in legume cropping systems

Nitrogen is a constituent of all proteins, all enzymes, many metabolic intermediates involved in synthesis and energy transfer, and even of the deoxyribonucleic acids making up the genetic code itself. Nitrogen is required for optimum crop quality as protein content of crops is directly related to N supply (Grant and Flaten, 1998). Plants can obtain N in several ways, the most obvious being uptake of inorganic N from the surrounding soil and N_2 fixation via the N_2 –fixing legume –Rhizobia symbiosis (Giller, 2001; Haynes and Goh, 1978). Accumulation of soil mineral N via rhizodeposition of N released from living roots and the return of foliage N ingested by grazing animals in urine and dung are additional pathways in pasture systems (Peoples and Baldock, 2001).

Nitrogen fixed by the intercrops may be available to the associated cereal crop in the current growing season (He *et al.*, 2003; Simard *et al.*, 2002) or as a residual N for the benefit of the succeeding cereal crops (Biajukya *et al*., 2006). The residual N effects from legumes through litter fall and biomass incorporation are well documented (Ojiem *et al*., 2007; Vanlauwe and Sanginga, 1998). However, the question of current or direct transfer of nitrogen to an associated crop is still a controversial issue and the reported data on the amount of N transferred have been variable. For instance, in some cases N transfer has been small (<5%) (Frey and Schuepp, 1992), but in others N transfer has accounted for as much as 10-48% of the N in the receiver plant or has not occurred at all (Moyer-Henry *et al.*, 2006; Bethlenfalvary *et al.*, 1991). Several authors have indicated that N transfer is subject to donor genotypic characteristics (King and Purcell, 2005), the extent of mycorrhizal colonization (Simard *et al.,* 2002) and relative competitiveness of the donor and receiver plant (Moyer-Henry *et al.*, 2006). There has been some evidence of direct N transfer from *Desmodium uncinatum* (*Khan pers. comm*) and *Desmodium heterocarpon* (*Rao. pers. comm*) to the accompanying maize which has emerged from observed increased growth and N yield of the associated maize.

Nitrogen is lost from cropping systems through harvested crop products, leaching and denitrification in which most of the denitrification products are volatilized (Cameron and Haynes, 1986, Cai *et al*., 1979). Loss of nitrogen through crop harvest depends on the species and the amounts of biomass produced. Crop uptake of N is relatively inefficient and often results in average losses of 50% because of leaching, denitrification and volatilization (Barker and Zublena, 1995). In a recent study, Chirwa *et al*., (2006) reported that removal of woody leguminous crop resulted in a loss of 20-30 kg N ha^{-1} in the gliricidia+maize and gliricidia+maize+pigeonpea sytems. Harvesting maize in this system removed 80-95 kg N ha^{-1}.

Nitrate leaching is often the most important channel of N loss from field soils (Chikowo, *et al.,* 2003). Nitrate is very susceptible to leaching in tropics because apart from some acid soils in the tropics, there is no significant adsorption of nitrate on to the soil surfaces, and there are no common insoluble nitrates (King *et al*., 1993). Studies done with ^{15}N techniques (for 5-6 years) showed that over the years only 3.8% of the labelled nitrogen appeared in the leachate in the sandy loam lysimeters and 5% in that of the clay lysimeter (Vinten and Smith, 1993). Tinker (1991) while using ^{15}N- labelled fertilizers, demonstrated that only a few kg ha^{-1} of the labeled material was left in the soil as nitrate after harvest, and was thus vulnerable to leaching. Accurate assessment of gaseous N losses has been limited by the variations which occur with environmental conditions under field conditions (Vlek *et al*., 1981) whereas nitrous oxide emissions in most studies have been shown to be small, and are probably not the key N loss pathway in most legume cropping systems (Chikowo, 2004). Estimates of the quantities of nitrogen lost by denitrification from agricultural land differ widely. A review produced by Colbourn and Dowdell (1984) gave figures of 0-20% of the applied N fertilizers from arable land and 0.7% from grassland. However, a survey by De Datta *et al***,** (1991) indicated losses of 20-40% from applied N fertilizer. High denitrification rates have been associated with soil nitrate contents exceeding 5 mg kg^{-1}. Various factors that affect denitrification include; nitrate concentration, soil pH, water content, temperatures and land use. Nitrogen can also be lost from agricultural soils through the release of gaseous ammonia- NH_3. In a study of the NO, N_2O emissions from savannah soils following the first simulated rains of the season, Scholes *et al*., (1997) reported that N_2O emissions averaged 8% of the total N emissions. The amounts of ammonia lost are influenced by a number of factors which include, factors affecting the transfer of NH_3 from the soil surface to the atmosphere, the amount of urea applied, the rate of urea hydrolysis, the initial soil pH and the buffer capacity of the soil, the soil moisture level, and the depth of application (Rachhpal-Singh and Nye, 1986).

It is important to note that nitrogen is also of major concern with regards to environmental sustainability because nitrate leaching can reduce ground water quality and N_2O emissions can contribute to the greenhouse gas effect and global warming (Campbell *et al.,* 1995). Therefore, an efficient cropping system will attempt to balance crop demands for N with timing and rate of N supply so that crop yield is optimized while N is neither over-depleted from the soil nor accumulated in quantities that result in the contamination of ground waters or surface waters.

2.6.2 The role and dynamics of phosphorus in legume cropping systems

Phosphorus (P) is involved in energy dynamics of plants (Barker and Zublena, 1995) and without it plants cannot convert solar energy into the chemical energy needed for the synthesis of sugars, starches and proteins. In eastern Africa, soil phosphorus deficiency has been widely recognized as one of the crucial and limiting factors to agricultural development especially in the densely populated highlands (Jama *et al*., 1997; Buresh *et al*., 1997; Sanchez and Palm, 1996). In western Kenya, it is estimated that P deficiency affects around 80% of the acid soils (Jama and van Straaten, 2006).The deficiency is attributed to low native P and high fixation by aluminium and iron oxides (Buresh *et al*., 1997; Warren, 1992). Insufficient use of P fertilizers to either replace P exported with plant products or correct the inherent low P levels has further contributed to depletion of soil phosphorus stocks (Okalebo *et al*., 2006).

In exploiting the BNF process in western Kenya, it should be noted that P deficiency can prevent nodulation (Giller, 2001) and legumes can only be important as a component of an integrated soil fertility management (ISFM) strategy since P has to be obtained from elsewhere (Ojiem *et al*., 2007). Improvements in N_2 fixation following phosphorus applications to legumes have been observed (Peoples *et al*., 1995). Elsewhere, legumes have been shown to increase the dissolution and utilization of PR phosphorus and reduce P sorption because of their acidifying effect on the rhizosphere (Melenaghen *et al*., 2004; Horst *et al*., 2001; Vanlauwe *et al*., 2000). In addition, legume crops with extensive deep rooting have been known to increase P pools in the cropping system because of their potential ability to access sparingly soluble P sources. In a greenhouse experiment, Nuruzzaman *et al*., (2005) observed that wheat shoot P concentration was 30–50% higher when grown after legumes than when grown after wheat. In contrast, when working with three pigeon pea (*Cajanus cajan* L. Millspp.) varieties intercropped with maize in Tanzania and Malawi, Adu-Gyamfi *et al*., (2007) found that the P budget was negative irrespective of whether the aboveground biomass of maize and pigeonpea was incorporated or exported out of the fields.

2.7 *Striga* weed control strategies

One of the most important biotic constraints of maize and sorghum production in western Kenya is parasitic weeds in the genus *Striga* (Scrophulariaceae) (Oswald and Ransom, 2001). *Striga hermonthica* which is also referred to as witchweed, is the most important, infesting an estimated 158 000 ha of maize and sorghum in the Lake Victoria basin alone (Hassan *et al*., 1994).

Striga problem is intimately associated with changes in land use intensity leading to declining soil fertility, mono cropping with host crops, and use of contaminated seeds (Berner *et al.*, 1995a; 1995b). In addition to draining photosynthates, minerals and water (Tenebe and Kamara, 2002; Press and Graves, 1995), the parasitic weed does most of its damage to its host, partly through phytotoxins, before the weed emerges from the soil (Gurney *et al*., 2006; Gurney *et al*., 1995). These effects result in a large reduction in host plant height, biomass, and eventual grain yield (Gurney *et al*., 1999). Several *Striga* control strategies have been tried, some with partial or local success, but all have limitations and none has provided a complete solution (Oswald, 2005). Fallow and fertilizer application have been found to suppress *Striga* (Kureh *et al*., 2000; Kim and Adetimirin, 1997; Ransom, 1996). However, increasing human population has resulted in intensive land use comprising intensive cultivation of small pieces of land, with shortened or no fallow (Webb *et al*., 1993), and in most cases high rates of fertilizers are required to achieve a significant impact on *Striga*, the rates which most small-scale farmers cannot afford (Pieterse *et al*., 1996). Resistant/tolerant maize varieties to witchweed have been used successfully (Showemimo, *et al*., 2002) but durability and stability of vertical resistance, based on a single or a few genes is challenged by allogamy of the *Striga* and the existence of geographical strains. In addition, using tolerant varieties permits increase in witch weed seed production which could be a risk to other, non tolerant varieties. The most recent technology for controlling *Striga* through imazapyr herbicides-resistant mutant maize (IR maize) has shown significant increase in maize yields (De Groote *et al.,* 2007; Kanampiu, *et al*., 2003) but adoption of this technology by poor small scale farmers remains limited (Khan *et al*., 2006a) because the seeds are expensive and not readily available in the market. Trap cropping which involves rotation or intercropping with a crop that produces germination stimulants, but is not parasitized by the witchweed, is another potential control method (Khan *et al.*, 2002). It has been shown in various studies that intercropping cereals with legumes can reduce the number of *Striga* plants that mature in an infested field (De Groote *et al*., 2010; Khan *et al*., 2006a, 2006b, Tenebe and Kamara, 2002). In western Kenya, *Desmodium* spp, which is a fodder legume, has been shown to uniformly control *Striga* (Khan *et al.*, 2007, Khan *et al*., 2006a, 2006b). Khan *et al* .,(2007) noted that overall, cowpea, crotalaria, and greenleaf *Desmodium* significantly enhanced maize grain yields relative to mono maize control by 58.3, 54.2, and 125%, respectively in western Kenya. All the legumes reduced *Striga* count but it was only in the greenleaf *Desmodium* intercrop where the seasonal differences in *Striga* counts were significant throughout the study period.

2.8 *Desmodium* species

Desmodium, which belongs to Fabaceae family, is a widespread legume genus of more than 350 species occurring throughout tropical and sub-tropical regions in open woodland and forest clearings (Imrie *et al*., 1983). The genus includes mostly perennial herbaceous plants or subshrubs. A number of species are successful or have shown potential as pasture/forage plants and cover crops. The agronomic value of several *Desmodium* spp is well documented (Imrie *et al*., 1983). Greenleaf (*D. intortum*) is a large trailing and scrambling perennial plant. It has a strong taproot and the long trailing stems can root at the nodes if in contact with moist soil (http://www.fao.org/ag/AGP/AGPC/doc/Gbase/data/pf000026.htm). Silver leaf (*D. uncinatum*) is a large rambling perennial, cylindrical or angular stems densely covered with short, hooked hairs with a shallow rooting system. *D. uncinatum* is adapted to a wide range of soils ranging from sands to clay loams (http://www.fao.org/ag/agp/AGPC/doc/Gbase/data/pf000030.htm) but it is not as successful on sands as *D. intortum*. *D. uncinatum* does well on acid to neutral (pH 5.0-7.0) soils with an open texture and not so well on compact heavy clays. It is fairly tolerant to soil acidity but does not tolerate salinity (Andrew and Robins, 1969; Anderson and Naveh, 1968). Average yields range from 4-7 t/ha/year depending on soil factors and management practices (Anderson and Naveh, 1968). *D. intortum grows* on a wider range of soils than *D. uncinatum*. It grows in a range of soils from light to clay loams and requires a soil with a pH in excess of 5.0 (Jones, 1983). *D. intortum* has no tolerance to salinity, and is depressed by high chloride levels (Andrew and Robins, 1969). *D. intortum* is a higher yielder compared to *D. uncinatum* and a yield of 19 t/ha/year has been recorded in temperate countries (Kanehiro and Sherman, 1967). Greenleaf and Silverleaf are widely adapted, highly productive legumes which associate well with stoloniferous grasses (Cameron 1984; Imrie *et al*., 1983). Both species require adequate levels of phosphorus, sulphur, potash and molybdenum for growth. Despite well documented role of *Desmodium* in *Striga* and stemborer control, little information exists on its potential to replenish N in the context of PPT. Environmental facrors such as rainfall, light and temperature affect the growth of *Desmodium* spp. For instance, while both *D. intortum* and *D. uncinatum* requires rainfall in excess of 900 mm, the latter does not thrive well when rainfall is above 3000mm. *D. intortum* is fairly tolerant of flooding and poor drainage compared to *D. uncinatum*. Although *D. intortum* has low seeding vigour compared to *D. uncinatum*, the former has good shade tolerance (http://www.fao.org/ag/agp/AGPC/doc/Gbase/data/pf000030.htm, http://www.fao.org/ag/AGP/AGPC/doc/Gbase/data/pf000026.htm)

CHAPTER THREE

3.0 GENERAL MATERIALS AND METHODS

3.1 The study area

The study was conducted for a duration of two years (Year 2009 and 2010) in two fields of smallholder farmers at Nyabeda site, Siaya County (0° 39.5' N, 34° 1.5' E, 1273 m above sea level), and at Matayos site, Busia County (0° 26.1' N, 34° 52.2' E, 1182 m above sea level) located in western Kenya. (Appendix 1, Jaetzold and Schmidt, 2006). The study area is densely populated with about 360 inhabitants km^{-2}, land holdings <0.2 ha (De Groote *et al*., 2008). Most households predominantly grow maize on small land holdings and obtain average yields of about 1 t ha^{-1} (Odendo *et al*., 2001). Rainfall in the study area is bimodal with the long rainy (LR) season from March to August and the short rainy (SR) season from September to December. Rainfall during the study period was measured using two rain gauges installed in the field in Nyabenda site while rainfall data for Matayos were obtained from Ministry of agriculture meteorological station (<5 km) located at Matayos shopping centre. The soils are low in natural fertility and classified as an Orthic Ferralsol in Busia and a Humic Acrisol in Siaya (FAO/UNESCO, 1990). The soils are ideal for the growth of maize and *Desmodium*.

3.2 Experimental design and field layouts

The experiments were started in April 2009 during the long rainy season of 2009 (LR2009) at both sites. Treatments consisted of three cropping systems, namely: (i) *D. uncinatum* intercropped with maize, (ii) *D. intortum* intercropped with maize, (iii) a sole maize crop. Maize and *Desmodium* were planted at the same time. During the first season, *Desmodium* was allowed to establish, and no cutting of biomass was done. In the subsequent seasons, cutting regimes were imposed in the intercropping systems: the *Desmodium* was cut at land preparation (at the start of every season), and again at 4 weeks after planting (WAP) maize, which is recommended for good maize establishment (Khan, *pers. comm.).* The third cutting was varied according to the treatment, and done at 9, 12 or 18 WAP. In the maize monocropping system, two treatments were imposed after, starting in the short rainy season of 2009 (SR2009): a control without urea, and a treatment with urea application. The treatments were arranged in a randomized complete block design (RCBD) taking into consideration PPT requirements, replicated three times in plot sizes of 10 m x 10 m (Appendix 2 and 3).

3.3 Field experiment management

During the first season (LR 2009), basal P and K were applied before planting as triple super phosphate (TSP) and muriate of potash (MOP) at rates of 60 kg P ha^{-1} and 60 kg K ha^{-1}, the recommended rates for the PPT. Maize (*Zea mays* L., IR variety) and *Desmodium* spp. were sown in alternating rows at the same time. Maize seeds were sown and thinned to a final plant population of 44,444 plants ha^{-1} (0.75 m between rows x 0.3 m within the row), and *Desmodium* seeds were sown in drills in between the maize lines at a seed rate of 2.5 kg ha^{-1} , the recommended seeding rate in the PPT (CTA, 2007).. Plots were kept weed free by hand weeding, and termites and stemborer were controlled by applying commercial insecticides namely, Gladiator (active ingredients, Bromethalin 0.01%, manufacturer Nova Industries) and dilute dust formulated stemborer dust (active ingredients, pirimiphos methyl 1.62% and pyrethrin

0.31%, manufacturer Dow Agrosciences), respectively. In the subsequent seasons, all operations were repeated, apart from planting the *Desmodium* spp., which were instead cut at the ground level using a cutlass at the prescribed cutting times, and allowed to regrow. Urea was split-applied to the sole maize crop at a rate of 90 kg N ha^{-1}. At 6WAP when maize had reached knee-height urea was applied at a rate of 45 kg N ha^{-1}, and at 3-4 weeks later, after a rain event, a subsequent application was done at a rate of 45 kg N ha^{-1}.

3.4 Laboratory Analysis

Soil pH,organic carbon, particle size analysis, exchangeable bases and acidity, Olsen extractable P, total nitrogen and phosphorus in soils and plants were analyzed following the procedures given in Okalebo *et al*., (2002).

3.4.1 Determination of soil pH (1:2.5 H_2O)

Fifty (50) ml of distilled water was added to 20 air- dry (2mm) soil. The mixture was stirred for two minutes and allowed to stand for 30 minutes after which the soil suspension was stirred for two minutes and pH measured using the pH meter.

3.4.2 Total organic carbon content of soils

Soil organic carbon was determined using the Walkely and Black (1934) oxidation method using procedure described by Okalebo *et al*., (2002). This method involved complete oxidation of soil organic carbon using acid (H_2SO_4) dichromate solution. The excess or unreacted dichromate was determined by titrating using ferrous ammonium sulphate. The end point was noted through a colour change from greenish to brown and the titre used was recorded which was used to calculate organic carbon after making the blank correction.

3.4.3 Soil particle size analysis

Soil particle size analysis was done using the hydrometer procedure (of sedimentation) as described by Okalebo *et al*., (2002). This involved the dispersion of soil particles into different constituents using sodium hexametaphosphate (calgon) solution and the subsequent sedimentation of the particles. Sedimentation allowed the particles to settle into the bottom of the cylinder according to the size, density and the viscosity of the liquid. Sand settled first (after 40 seconds) followed by silt (2 hours) and the clay being the lighetest settled last. The hydrometer (H_2) and the thermometer (T_2) readings were recorded which were used to calculate the percentage sand, clay and silt contents in the soil.The textural class was read off from the textural triangle.

3.4.4 Available soil phosphorus

Extractable soil phosphorus (P) was determined using the phosphomolybdate method (Olsen *et al*., 1954). In this method phosphate and ammonium molybdate formed a complex, which was reduced with ascorbic acid to produce a blue colour complex in solution whose intensity (the absorbance) was measured using spectrophotometer at a wavelenth setting of 880 nm. Phosphorus concentartion (ppm) in solution was obtained by plotting absorbance versus concentarion from which sample concentartion was read off from the graph and ppmP in solution calculated.

3.4.5 Total phosphorus in plant samples

The plant samples were digested with concentrated sulphuric acid in presence of a catalyst. The principle involved in digestion of plant materials is oxidation of orgaic materials to inorganic soluble P components (phosphate). Phosphate was measured using the phosphomolybdate colorimetric method in which the absorbance (blue colour intensity) was measured at 880 nm wavelength setting in a spectrophotometer. Blank correction was made by subtracting the mean blank reading from the sample reading. A graph of absorbance against standard P concentration was plotted from which solution P concentrations for the samples were determined.

CHAPTER FOUR

4.0 NITROGEN DYNAMICS, BIOLOGICAL N_2 FIXATION AND NITROGEN CONCENTRATION IN DESMODIUM-MAIZE INTERCROPPING SYSTEM

In the "Push-Pull technology" (PPT) *Desmodium* is subjected to early two cutting regimes (before planting and at 4WAP) to minimize competition for light, nutrients and water between *Desmodium* and maize. The third cutting regime is left at the discretion of farmers but in most cases it is conducted at maize harvesting time (18WAP). In this study, the third cutting of *Desmodium* was varied and done at 9, 12 or 18 WAP. This chapter assessed changes over time of selected soil properties, nitrogen concentration and ^{13}C isotope discrimination of maize shoot in maize *Desmodium* intercropping system with *Desmodium spp* cut at 18WAP. This was done for two consecutive seasons when the system was well established i.e. during long rainy season, 2010 (LR2010) and short rainy season, 2010 (SR2010). In addition, biological nitrogen fixation (BNF) of *Desmodium* was assessed for all the *Desmodium* cutting regimes during short rainy season 2009 (SR2009), LR2010 and SR2010.

Abstract

Low soil fertility in western Kenya region is a major limitation to maize production. *Desmodium* in PPT is capable of addresiing this constraint. Field trials were conducted in Nyabeda and Matayo sites located in Busia and Siaya counties in western Kenya region respectively during LR2010 and SR2010 to test the hypothesis that, changes in maize biomass, soil mineral nitrogen, soil carbon, ^{13}C isotope values ($\delta^{13}C$) of maize shoot and maize nitrogen concentration over time in maize-*Desmodium* intercropping system with *Desmodium* cut at 18WAP is affected by *Desmodium* spp and sampling time. In addition, effect of *Desmodium* spp and cutting regime on BNF was assessed for three consecutive seasons (SR2009, LR2010 and SR2010). Maize was intercropped with *D. uncinatum* or *D. intortum* and treatments with sole maize (with and without urea) were included for comparison. All treatments received basal P and N. The first two *Desmodium* cutting events were fixed while the third cutting was varied and conducted at 9, 12 or 18 weeks after planting maize. N_2-fixation was estimated using the ^{15}N natural abundance method. Results showed that mineral N was higher in *Desmodium* intercropping system with *D. intortum* relative to *D. uncinatum*. Nitrogen leaching in *Desmodium* intercropping with *D. intortum* was lower than in sole maize system as evidenced by the low total mineral nitrogen in *D. intortum* intercrop beyond 60 cm soil depth. *D. intortum* was superior to *D. uncinatum* producing the highest biomass, fixed N, soil carbon and total mineral N for two consecutive seasons. $\delta^{13}C$ contents in maize shoot did not differ significantly between *Desmodium* intercropping and sole maize systems, an indication of comparable environmental effect in both systems. The proportion of N_2-fixed in both sites ranged between 49-71, 50-63 and 44-64% during SR2009, LR2010 and SR2010 respectively irrespective of *Desmodium* species and cutting regime.

4.1 Introduction

Nitrogen and phosphorus are limiting nutrients to production of maize in sub-Saharan Africa (Smaling *et al.*, 1993a). Smaling *et al*., (2002) reported nitrogen (N) balances for SSA of -26 kg N ha^{-1} in 2000, compared with -20 kg N ha^{-1} in 1983. In western Kenya, there is a strong evidence of widespread N and P deficiencies that has contributed to low and declining crop yields in this region (Okalebo *et al*., 2006; Woomer *et al*., 2003). Nitrogen inputs to most cropping systems in Africa consist mainly of inorganic fertilizers and practices such as biomass transfer, biological nitrogen fixation (BNF), animal manures, farm residues or composts (Giller, 2001; Haynes and Goh, 1978). Inorganic N fertilizers are expensive and the value of manure and compost as a source of N ranges from high-quality manure that increases crop yields to low-quality manure that does not improve crop yields due to N immobilization (Mugwira and Mukurumbira, 1986). However, it is worth noting that organic resources can have multiple benefits besides the short –term supply of available N such as improved P and organic matter, improved soil moisture or less pest and disease pressure (Vanlauwe *et al*., 2001). Due to resource limitations, it is therefore evident that, appropriate nitrogen replenishment strategies are sustainable low input agricultural systems that provide biologically fixed nitrogen and at the same time slowly rebuild N stocks.

Considering the inconsistent use of N fertilizers, very limited returns of crop residues to the soil and low N inputs from grain legumes, incorporating N-fixing trees and herbaceous legumes into the farming system enhances nutrient cycling and also provides the organic carbon (C) and N necessary for maintaining N capital (Kwesiga and Beniest, 1998, Palm, 1995). In sub Saharan Africa, the main species used as herbaceous legumes are of the genus *Mucuna, Crotolaria, Pueraria, Dolichos,* and *Desmodium* (Balasubramanian and Blaise, 1993; Wortmann *et al*., 1994; Khan *et al*., 2006a). The use of *Desmodium* species for control of *Striga* weed and stemborer in the context of PPT is expanding in western Kenya (Murage *et al*., 2011) and its use in nitrogen replenishment cannot be underestimated. However, despite the well documented role of *Desmodium* spp in control of *Striga* and stemborer (Chamberlain *et al.*, 2006; Khan *et al*. 2006a), scanty information exists on its contribution to overall improvement of soil N and carbon.

A major problem in the PPT is the competition for light, nutrients and water between *Desmodium* and maize which causes crop yields decline (Khan *et al*., 2008b). The relationship between the ^{13}C isotopic discrimination and environmental factors during the growth period are well documented for C_3 and C_4 plants (Darcon *et al*., 2006, Zhao *et al*., 2004). The carbon stable isotope ratio ($^{13}C/^{12}C$) of plant biomass is a widely used indicator because of the integrative response of the isotopic ratio to multiple eco-physiological constraints during the time of biomass development (Dawson *et al*., 2002). Cabon dioxide (CO_3) in the atmosphere is composed of molecules with a light atom of C (^{12}C, 98.89%) and molecules with heavy atom of C (^{13}C, 1.11%). There is an isotope discrimination against carbon dioxide with ^{13}C during carbon dioxide fixation in photosynthesis, resulting in depletion of ^{13}C in plant biomass (Píšová *et al*., 2008). The rate of discrimination is affected by environmental conditions such as temperature, water availability, atmospheric pollution, nutrient availability etc., which affects stomatal conductance and photosynthesis rate (McCarroll and Loader, 2004; Helle and Schleser 2004). The ratio of $^{13}C/^{12}C$ (Δ) reflects the relative magnitude of net assimilation and stomatal conductance that relate to demand and supply of CO_2 (Píšová *et al*., 2008). Carbon -13 data are thus a useful index of assessing intrinsic water use efficiency. When, for instance, soil moisture level decreases, plants close the stomata to reduce water loss and the CO_2 diffusion from the air outside to the air inside the leaf will be reduced. The reduction of CO_2 concentration inside the leaf causes a higher ^{13}C abundance of the fixed CO_2 (Dercon *et al*., 2006) and the crop becomes depleted of ^{13}C relative to the air due to isotope discrimination against ^{13}C and preferred uptake of ^{12}C during photosynthesis (Píšová *et al*., 2008). Although carbon isotope discrimination values have been used successfuly to assess water stress in the crops in developed countries, data on the effect of short water stress effects on the isotopic discrimination in developing countries are scarce and the information is rare about how Δ values measured at different stages of plant growth can be used as a historic account on how water availability varied during the entire cropping cycle. The objectives of this study were therefore (i) to assess the mineral N dynamics and soil carbon in *Desmodium*-maize intercropping system with *Desmodium* cut at 18WAP, (ii) assess if varying the time of cutting *two Desmodium spp* impact on BNF, (iii) assess nitrogen concentration in maize at harvest in *Desmodium*-maize intercropping system and iv) to use stable ^{13}C isotope discrimination to assess water stress in maize at different growth stages in *Desmodium*-maize intercropping system.

4.2 Materials and methods

4.2.1 The study area

The experiments were installed in two fields of smallholder farms at Nyabeda site, Siaya County and Matayos site, Busia County, located in western Kenya. Detailed description of sites is given in chapter 3, section 3.1.

4.2.2 Experimental design and field layout

Experimental design and treatments are described in chapter 3, section 3.2 and trial layouts are presented in Appendix 2 and 3.

4.2.3 Experiment management

Details of how the trials were managed are presented in chapter 3, section 3.3.

4.2.4 Biomass sampling

Maize biomass sampling was conducted from a net plot of $3.75m^2$ from *Desmodium* intercroping systems with two *Desmodium* spp cut at 18WAP. The sampling was done at 10 13, 15 and 18WAP which corresponded to time from maize tasseling, silking and full maturity (18WAP) during long and short rainy seasons of 2010 when the system had fully established. Sampling from sole maize control and sole maize with urea was included for comparison. *Desmodium* biomass sampling was done from a net plot of $81m^2$. The first two *Desmodium* cutting events were fixed at land preparation i.e. at the start of every season, and 4 weeks later, following the recommended practice, while the third cutting was varied and conducted at 9, 12 or 18 weeks after planting maize.

Desmodium samples were oven dried (65^{0}C), ground for analysis of N and N^{15} isotope and the maize biomass samples were oven dried (65^{0}C) for determination of % C and ^{13}C isotope (δ^{13}C) contents.

4.2.5 Sampling for mineral N analysis

In *Desmodium* intercroping system, soil sampling for ammonium and nitrate N analysis was conducted in treatments where the cutting regime of *Desmodium* was conducted at 18WAP during LR2010 and SR2010 in Busia and Siaya respectively. These seasons were selected because they resulted to significant maize grain yield increase in *Desmodium*- intercroping system relative to sole maize system. Soil sampling for mineral N analysis was conducted at 4, 9, 10 and 12WAP from (i) *D. uncinatum* intercropped with maize, (ii) *D. intortum* intercropped with maize, (iii) sole maize control and (iv) sole maize without urea. Following depths were sampled: 0-15, 15-30, 30-60, 60-90 and 90-120. Sampling was done twice per subplot and one composite sample per plot and per depth was collected for analysis of NO_3-N and NH_4-N. Soil cores of known volume sampled from the vertical faces of soil pits were dried at 105^{o}C for 24 h to determine their dry weight and hence bulk density. Bulk densities for the various soil horizons were used to convert the values for NO_3-N and NH_4-N from mg kg $^{-1}$ to kg N ha^{-1}.

4.2.6 Measurement of extractable soil NO_3-N and NH_4-N

Nitrate-N (NO_3-N) and NH_4-N were extracted by shaking 20g soil samples in 2M KCl for 1 hour before filtering the extract. To determine NO_3-N, a modified Griess – IIosvay method (Keeny and Nelson 1982) was used to reduce nitrate to nitrite (NO_2-N). This was treated with sulphanilic acid (4-aminobenzene sulphonic acid) in 2.4 N HCl to produce the NO_2^-diazonium salt, and then with 1.5 g of 5-amino-2-naphthalene sulphonic acid (5-2 ANSA) dissolved in 1500 ml of 15% acetic acid to form a reddish-purple azo compound. Absorbance was determined at 525 nm (wavelength) using a spectrophotometer. A standard curve drawn using the standards was used to convert the absorbance to concentation.

NH_4-N concentration was determined using the Indophenol blue method (Keeny and Nelson 1982), in which ammonium reacted with phenol in the presence of an oxidising agent (5.25% hypochlorite) to form a blue complex under alkaline pH conditions. The sensitivity of the reaction was improved by adding sodium nitroprusside as a catalyst. The intensity of the colour developed is proportional to the concentration of ammonium present. Absorbance was determined at 655nm (wavelength) using a spectrophotometer.

4.2.7 N_2- fixation assessment

The proportion of legume N derived from N_2-fixation was determined using the ^{15}N natural abundance method (Peoples *et al.*, 1989). A subsample of fresh shoots was weighed, air dried, subsampled for moisture determination, oven dried at 65^o ,reweighed and ground to 1mm. The oven dried and ground plant sub-samples were thoroughly mixed in a twin-shell blender, and 5g subsample was ground to a fine powder in a dental amalgam bull mill model. Finally, plant subsamples were analysed for total N and ^{15}N contents using an automated flash-combustion analyzer coupled to an isotope ratio mass spectrometer in Leuven University, Belgium. The %N from N_2-fixation was calculated using the equation of Shearer and Kohl (1986) as follows:

%N from N_2 –fixation

$$\%Nfixed = 100\left(\frac{\delta^{15}N_{ref} - \delta^{15}N_{legume}}{\delta^{15}N_{ref} - \beta}\right) \text{………………. } \textit{Equation 4.1}$$

where δ^{15}Nref is the ^{15}N natural abundance of the shoots of a non-N_2-fixing reference plant deriving its entire N from the soil N (in this study maize was used as a reference plant), $\delta^{15}N$ legume is the ^{15}N natural abundance of the shoots of the N_2-fixing legume plant growing in the same soil and β is the $\delta^{15}N$ of the test legume fully dependent on N_2-fixation for growth, and a correction for isotopic fractionation during N_2-fixation. The β value (-1.55) in this study was obtained from the literature (Peoples *et al.*, 1989).

4.2.8 Plant sampling and determination of $\delta^{13}C$ signatures

Maize shoots were first air dried and afterwards oven dried at 65 ^{0}C until constant weight. After drying, the plant material was homogenized by grinding in a ball mill. The samples were analyzed for % C content and $\delta^{13}C$ signatures using stable isotope mass spectrometer (Leuven University, Belgium). $\delta^{13}C$ signatures were expressed into $\delta^{13}C$ ‰ units using the International Pee Dee Belemnite (PDB) standard (Dercon *et al.* 2006; O'Leary, 1988).

$$\delta^{13}C = (\frac{Rsample}{R.s\tan dard} - 1)x1000 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textit{Equation 4.2}$$

$$R = \frac{^{13}C}{^{12}C}$$

The $\delta^{13}C$ is a relative value where the $^{13}C/^{12}C$ ratio (*R*) of the sample is compared with the ratio of an international PDB standard (i.e. limestone from the Pee Dee formation in South Carolina)

$\delta^{13}C$ content of the plant material is related to ^{13}C isotope discrimination (Δ)
by the following equation:

$$\Delta = \frac{(\delta^{13}C_{air} - \delta^{13}C_{plant}}{(1 + \frac{\delta^{13}C_{plant}}{1000})} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textit{Equation 4.3.}$$

Where $\delta^{13}C_{air}$ is the $\delta^{13}C$ value of air (-8‰) and $\delta^{13}C_{plant}$ is the measured value of the plant material.

4.2.9 Statistical analysis

The data was subjected to analysis of variance (ANOVA) using a mixed procedure (SAS Institute Inc., 2003). Treatments were considered as fixed factors, and replicate as a random factor. A one-way ANOVA was conducted to evaluate differences between the four treatments (2 *Desmodium*-maize intercropping systems and 2 sole maize systems). To determine the interaction effect, a factorial procedure was used in processing the data and a two-way ANOVA employed for evaluating the interactions between *Desmodium* spp/treatments with either cutting regimes ,sampling times or soil depths. The one and two way ANOVA models are as described below. Treatment differences were evaluated by computing least square means and the standard errors of difference (SED). Standard errors of difference is the difference between means of two samples randomly drawn from the same normally distributed source population. Significance of difference was evaluated at $P \leq 0.05$ and $P \leq 0.001$ levels. The mathematical model used for one and two way ANOVA were:

One way ANOVA model:

$Y_{ij} = \mu + \alpha_i + E_{ij}$..*Equation 4.4.*

Y_{ij}- any observation for which i is the treatment factor

j- the blocking factor

μ - treatments (2 *Desmodium*-maize intercropping systems and 2 sole maize systems) overall mean

α_i- treatment effect

E_{ij}- error term

a) **Two way ANOVA model**

$Y_{ij}=\mu+\alpha_i+\beta_j+(\alpha\beta)_{ij}+E_{ij}$……………………………..*Equation 4.5.*

Y_{ij}- any observation for which i is the treatment factor

μ - Overall (grand) mean

α_i - *Desmodium* spp effect

β_j- cutting regime/sampling time/depth effect

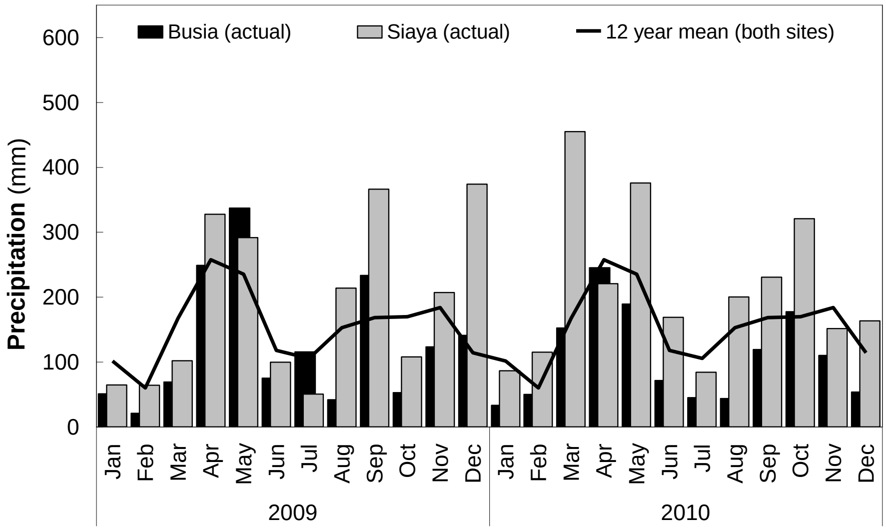
$(\alpha\beta)_{ij}$- the interaction effects of *Desmodium* spp and cutting regime, treatments (2 *Desmodium*-maize intercropping systems and 2 sole maize systems) and Sampling time or soil depth

$Ɇ_{ij}$- error term (independent random variable)

4.3 Results

4.3.1 Rainfall amount and soil characteristics

During the study period, Busia received 1,682 and 1,978 mm during year 2009 and 2010, respectively. The corresponding values for Siaya were 1,676 and 2,114 mm, respectively (Fig. 4.1.). Generally rainfall amount in Busia and Siaya sites during the study period was below and above respectively, the 12 years mean rainfall amount in most months of the year.



(Source: Author, 2013).

Fig 4.1: Monthly rainfall during the study period and twelve year mean rainfall from Matayos (Busia) and Nyabeda (Siaya) sites

The initial characterization of the study sites (Fig 4.1.) showed that the soil in Busia was slightly more acidic (pH 5.0) compared with the soil in Siaya (pH 5.6). The soil in Siaya had a deep profile, higher contents of organic matter, exhangeable bases and clay, compared to the soil in Busia. Both soils were howerver very low in available (Olsen) P which amounted to 1.94 and 0.70 and mg P kg^{-1} in Busia and Siaya respectively.

Table 4.1: Selected physico-chemical topsoil (0-20cm) properties of Nyabeda (Siaya) and Matayos (Busia) sites.

Properties	**Matayos (Busia)**	**Nyabeda (Siaya)**
pH (1:2.5 in water)	5.03	5.59
Organic C (%)	1.44	2.51
Total N (%)	0.16	0.24
Olsen P (mg P kg^{-1})	1.94	0.70
Exchangeable K ($cmol_c$ kg^{-1})	0.22	0.40
Exchangeable Mg ($cmol_c$ kg^{-1})	0.65	1.68
Exchangeable Ca ($cmol_c$ kg^{-1})	2.28	4.93
CEC ($cmol_c$ kg^{-1})	6.67	10.0
Clay (%)	28	38
Silt (%)	10	14
Sand (%)	62	48
Textural class	Sandy clay loam	Sandy clay

4.3.2 Ammonium levels in Busia soil during long rainy season, 2010

Table 4.2 outlines the ammonium (NH_4-N) levels in Busia site during long rainy season of 2010. During this season, higher NH_4-N concentrations ranging from 1.56 - 35.62 kg N ha^{-1} were observed in *Desmodium* intercropping system compared to sole maize control which ranged from 7.35 - 24.62 kg N ha^{-1} between 4th and 12th WAP. Significant differences among the treatments in NH_4-N concentration were observed only at 4WAP whereby NH_4-N concentration in the intercropping system with *D.*

intortum (13.94 kg N ha^{-1}) was significantly higher than with *D. uncinatum* (6.98 kg N ha^{-1}). However, at this time, NH_4-N concentration in sole maize control was significantly higher relative to intercropping system with both *Desmodium* spp irrespective of sampling depth. Sampling depth had a positive significant effect on NH_4-N concentration only at 10WAP. At this time, NH_4-N concentration significantly increased in 0-15 cm depth compared to 60-120 cm depth. NH_4-N concentration in the intercropping system with *D. intortum* was higher than with *D. uncinatum* from 4th to 9th WAP in most of the sampling times. Urea application in the sole maize system had no significant effect on NH_4-N concentration at all sampling times.

Table 4.2: Ammonium levels (kg N ha^{-1}) in *Desmodium*-maize intercropping systems with *D. uncinatum* and *D. intortum* relative to a sole maize system with or without urea application in Matayos (Busia) during long rainy season 2010.

	4 weeks after planting					**9 weeks after planting**				
	Treatments					**Treatments**				
Depth	Maize -urea	Maize +urea	*D. uncinatum*	*D. intortum*	**Mean**	Maize-urea	Maize +urea	*D. uncinatum.*	*D. intortum*	**Mean**
0-15	22.38	14.17	1.56	11.47	**11.47**	16.01	18.13	17.79	17.56	**17.37**
15-30	12.38	11.11	12.69	12.19	**12.19**	18.21	13.11	11.89	35.62	**19.71**
30-60	15.99	12.80	7.90	17.33	**17.33**	21.56	21.39	7.56	31.47	**20.50**
60-90	13.25	14.10	5.78	12.61	**12.61**	17.54	16.14	7.10	17.37	**14.54**
90-120	17.54	9.33	nd	3.37	**3.37**	10.10	8.50	11.19	11.09	**10.22**
Mean	**16.31**	**12.30**	**6.98**	**11.39**	**11.90**	**16.68**	**15.45**	**11.11**	**22.62**	**16.47**
SED $_{treatment (T)}$	2.57					4.56				
SED $_{depth (D)}$	3.29					5.70				
SED$_{T*D}$	7.35					13.03				
	10 weeks after planting					**12 weeks after planting**				
Depth	Maize -urea	maize +urea	*D. uncinatum*	*D. intortum*	**Mean**	Maize - urea	maize +urea	*D. uncinatum*	*D. intortum*	**Mean**
0-15	24.62	36.60	29.30	28.11	**29.66**	8.77	17.11	8.73	5.47	**10.02**
15-30	11.66	35.39	24.09	23.51	**23.66**	7.37	13.56	10.60	12.44	**10.99**
30-60	23.56	22.99	28.25	18.06	**23.22**	10.92	10.69	11.43	15.95	**12.25**
60-90	7.35	17.80	7.06	13.89	**11.53**	8.08	10.37	6.06	14.89	**9.85**
90-120	nd	6.67	8.76	6.82	**7.42**	nd	6.44	3.67	nd	**5.06**
Mean	**16.80**	**23.89**	**19.49**	**18.08**	**19.10**	**8.79**	**11.63**	**8.10**	**12.19**	**9.63**
SED $_{treatment (T)}$	7.37					2.90				
SED $_{depth (D)}$	9.67					2.89				
SED$_{T*D}$	23.24					6.49				

[1]

[1] ***SED** - standard errors of difference, **D**-Desmodium, **Nd**-not done*

4.3.3 Nitrate levels in Matayos (Busia) soil during long rainy season, 2010

Nitrate in sole maize control and *Desmodium* intercropping system amounted to 2.84 - 29.61 and 0.32-48.8 kg N ha^{-1} respectively between 4^{th} and 9^{th} WAP during LR2010 in Busia (Table 4.3.). Treatments differences on NO_3^- concentration were observed at 4^{th}, 9^{th}, and 12^{th} WAP. At 4 WAP, NO_3^- concentration in sole maize systems was significantly higher than in *Desmodium* intercropping systems. Nevertheless, at 9^{th} and 12^{th} WAP, significant higher levels of NO_3^- were observed in *Desmodium* intercropping system with *D. intortum* relative to sole maize. Significant higher NO_3^- was recorded in *Desmodium* intercropping system with *D. intortum* than *D. uncinatum* at 9^{th} and 12^{th} WAP. Sampling depth had a significant positive effect on NO_3^- only at 10 WAP. During this time, significant higher amounts of NO_3^- occurred in 0-15 cm soil depth relative to all the other depths. A buildup of NO_3^- in *Desmodium* intercropping with *D. intortum* was observed from 9 to 12 WAP in the top 30 cm layer. Below 60 cm depth, NO_3^- concentration was slightly higher in sole maize system relative to *Desmodium* intercropping system with *D. intortum* in most sampling times.

Table 4.3: Nitrate levels N (kg N ha^{-1}) in *Desmodium*-maize intercropping systems with *D. uncinatum and D. intortum* species relative to a sole maize system with or without urea application in Matayos (Busia) during long rainy season, 2010.

	4 weeks after planting					**9 weeks after planting**				
	Treatments					**Treatments**				
Depth	Maize -urea	Maize +urea	*D. uncinatum*	*D. intortum*	**Mean**	Maize-urea	Maize +urea	*D. uncinatum.*	*D. intortum*	**Mean**
0-15	22.49	16.26	8.3	12.25	**14.83**	8.91	14.12	12.76	24.82	**15.15**
15-30	9.42	15.53	4.91	9.96	**9.96**	5.54	13.32	12.46	17.63	**12.24**
30-60	29.61	18.92	7.58	13.03	**17.29**	5.87	22.83	7.62	20.65	**14.24**
60-90	19.96	13.78	7.81	11.32	**13.22**	9.5	14.81	17.22	10.89	**13.11**
90-120	11.24	21.05	nd	3.36	**11.88**	5.69	6.9	10.84	18.05	**10.37**
Mean	**18.54**	**17.11**	**7.15**	**9.98**	**13.43**	**7.10**	**14.40**	**12.18**	**18.41**	**13.02**
SED $_{\text{treatments (T)}}$			**3.67**					**3.34**		
SED $_{\text{depth (D)}}$			**4.71**					**4.18**		
SED$_{T*D}$			**10.48**					**9.04**		
	10 weeks after planting					**12 weeks after planting**				
Depth	Maize -urea	Maize +urea	*D. uncinatum*	*D. intortum*	**Mean**	Maize - urea	Maize +urea	*D. uncinatum*	*D. intortum*	**Mean**
0-15	6	8.57	48.05	33.49	**24.03**	5.67	11.69	9.63	31.69	**14.67**
15-30	2.84	8.95	14.8	15.76	**10.59**	3.68	10.93	4.46	17.49	**9.14**
30-60	7.2	9.24	8.81	9.45	**8.68**	14.53	19.45	7.4	16.86	**14.56**
60-90	15.22	5.42	5.33	8.56	**8.63**	18.09	22.43	7.71	13.57	**15.45**
90-120	nd	1.99	0.32	6.45	**2.92**	nd	18.14	6.97	nd	**12.56**
Mean	**7.82**	**6.83**	**15.46**	**14.74**	**10.97**	**10.49**	**16.53**	**7.23**	**19.90**	**13.28**
SED $_{\text{treatments (T)}}$			**5.22**					**5.12**		
SED $_{\text{depth (D)}}$			**6.87**					**5.12**		
SED$_{T*D}$			**16.47**					**11.5**		

Note*:SED - standard error of difference,* ***D****- Desmodium,* ***Nd****-not done*

4.3.4 Ammonium levels in Nyabeda (Siaya) soil during short rainy season, 2010

During SR2010, NH_4-N concentration was relatively higher in *Desmodium* intercropping system and ranged from 1.35-53.31 kg N ha^{-1} compared to a range of 0.93-29.88 kg N ha^{-1} obtained in sole maize system (Table 4.4). Significant treatments differences occurred at 9th and 10th WAP. At 9 WAP, NH_4-N concentration in *Desmodium* intercropping systems with *D. intortum* and *D. uncinatum* were comparable and only urea application in the sole maize system significantly increased NH_4-N concentration above all the other treatments. At 10 WAP, intercropping system with *D. intortum* significantly increased NH_4-N concentration above intercropping with *D. uncinatum*. Sole maize systems significantly increased NH_4-N concentration above intercropping system with *D. uncinatum*. Again, like in Busia, *Desmodium* intercropping system with *D. intortum* had higher amounts of NH_4-N compared to *D. uncinatum* in most sampling depths. Sampling depth had a significant effect on NH_4-N in all sampling times with the highest concentration occurring in 30-60 cm depth.

Table 4.4: Ammonium levels (kg N ha^{-1}) in *Desmodium*-maize intercropping systems with *D.uncinatum* and *D. intortum* relative to a sole maize system with or without urea application in Nyabeda (Siaya) during short rainy season, 2010.

	4 weeks after planting					9 weeks after planting				
	Treatments					Treatments				
Depth	Maize -urea	Maize +urea	*D. uncinatum*	*D. intortum*	**Mean**	Maize -urea	Maize +urea	*D. uncinatum.*	*D. intortum*	**Mean**
0-15	3.82	11.98	4.4	12.18	**8.10**	5.32	28.65	8.3	18.8	**15.27**
15-30	22.66	13.5	15.76	9.34	**15.32**	5.93	133.24	9.98	53.31	**50.62**
30-60	29.88	27.51	16.85	33.26	**26.88**	14.03	72.52	20.13	33	**34.92**
60-90	9.73	13.68	9.15	17.65	**12.55**	7.99	13.51	7.08	15.7	**11.07**
90-120	5.61	2.97	5.04	6.53	**5.04**	3.4	7.37	5.52	8.06	**6.09**
Mean	**14.34**	**13.93**	**10.24**	**15.79**	**13.58**	**7.33**	**51.06**	**10.20**	**25.77**	**23.59**
SED $_{treatment (T)}$			**3.03**					**12.03**		
SED $_{depth (D)}$			**3.39**					**13.11**		
SED$_{T*D}$			**6.78**					**26.43**		
	10 weeks after planting					**12 weeks after planting**				
Depth	Maize -urea	Maize +urea	*D. uncinatum*	*D. intortum*	**Mean**	Maize -urea	Maize +urea	*D. uncinatum*	*D. intortum*	**Mean**
0-15	0.93	1.11	1.35	1.54	**1.23**	6.28	6.09	1.78	6.89	**5.26**
15-30	11.67	11.17	3.56	3.19	**7.40**	11.31	7.44	5.18	6.52	**7.61**
30-60	25.01	22.97	13.53	21.84	**20.84**	18.63	15.48	12.81	6.95	**13.47**
60-90	8.86	8.63	4.12	8.29	**7.48**	5.31	7.71	12.54	2.78	**7.09**
90-120	4.41	3.54	3.69	5.07	**4.18**	4.12	3.35	2.84	3.31	**3.41**
Mean	**10.18**	**9.48**	**5.25**	**7.99**	**8.22**	**9.13**	**8.01**	**7.03**	**5.29**	**7.37**
SED $_{treatment (T)}$			**1.55**					**1.86**		
SED $_{depth (D)}$			**1.73**					**2.08**		
SED$_{T*D}$			**3.46**					**4.16**		

***Note**: **SED** - standard error of difference, **D**- Desmodium, **Nd**-not done*

4.3.5 Nitrate levels in Nyabeda (Siaya) soil during short rainy season, 2010

Table 4.5 presents nitrate (NO_3^-) levels in Nyabeda during SR2010. During this season, *Desmodium* intercropping system had significant higher NO_3^- concentration (16.84 – 128.41 kg N ha^{-1}) compared to sole maize control (19.28- 53.19 kg N ha^{-1}) in the profile. Significant treatments differences in NO_3^- concentrations were observed at 9th, 10th and 12th WAP whereby intercropping with *D. intortum* consistently gave significant higher concentration of NO_3^- compared to *D. uncinatum* and sole maize control. NO_3^- concentration in the intercropping system with *D. intortum* was comparable to the NO_3^- concentration of the sole maize with urea applied in most sampling times. Urea application significantly increased NO_3^- concentration in the sole maize system at 9th, 10th and 12th WAP. Sampling depth significantly affected NO_3-N concentration at 9th, 10th and 12th WAP with the highest NO_3^- accumulation occurring in the top 0-15 cm soil depth. There was an evidence of NO_3^-movement in the soil profile. Averaged over all the sampling times, the sole maize system had the highest concentration of nitrate amounting to 50.9 kg N ha^{-1} followed by *Desmodium* intercropping system with *D. intortum* (32.7 kg N ha^{-1}) and *D. uncinatum* (20.93 kg N ha^{-1}) in100-120 cm depth.

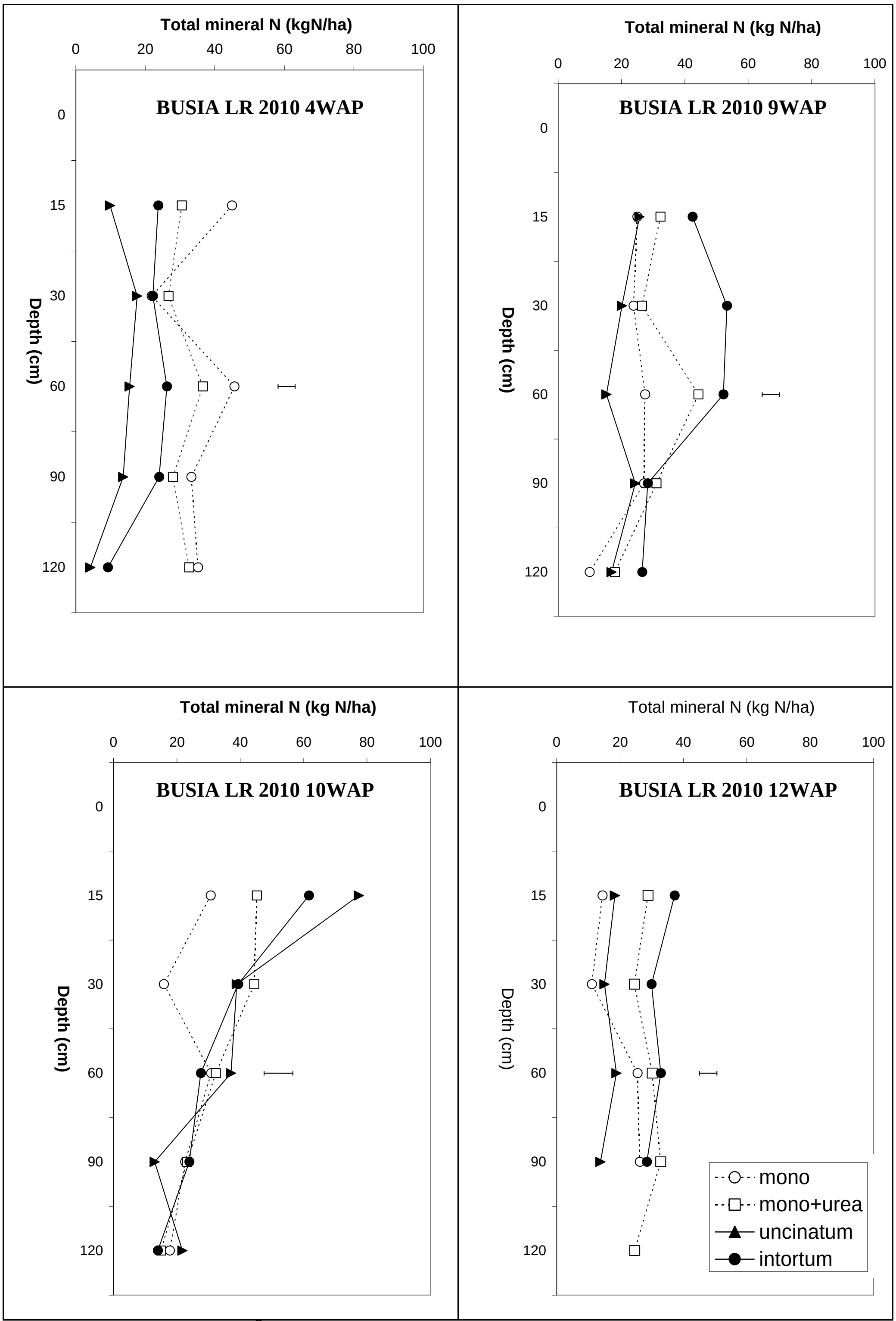
Table 4.5: Nitrate levels (kg N ha^{-1}) from *Desmodium*-maize intercropping systems with *D. uncinatum* and *D. intortum* relative to a sole maize system with or without urea application in Nyabeda (Siaya) during short rainy season, 2010.

	4 weeks after planting					**9 weeks after planting**				
	Treatments					**Treatments**				
Depth	Maize -urea	Maize +urea	*D. uncinatum*	*D. intortum*	**Mean**	Maize -urea	Maize +urea	*D. uncinatum.*	*D. intortum*	**Mean**
0-15	53.19	65.54	58.37	57.2	**58.58**	43.8	100.11	82.55	87.97	**78.61**
15-30	35.25	53.41	40.12	45.38	**43.54**	37.54	75.46	54.81	84.4	**63.05**
30-60	34.77	47.34	57.63	41.07	**45.20**	46.15	97.44	38.09	90.59	**68.07**
60-90	40.33	55.4	40.49	32.9	**42.28**	41.78	60.98	24.81	36.4	**40.99**
90-120	33.98	45.95	29.24	32.23	**35.35**	44.49	91.49	16.84	26.65	**44.87**
Mean	**39.50**	**53.53**	**45.17**	**41.76**	**44.99**	**42.75**	**85.10**	**43.42**	**65.20**	**59.12**
SED $_{treatment (T)}$			6.96					11.07		
SED $_{depth (D)}$			7.78					12.45		
SED$_{T*D}$			15.56					24.13		
	10 weeks after planting					**12 weeks after planting**				
	Treatments					**Treatments**				
Depth	Maize-urea	Maize +urea	*D. uncinatum*	*D. intortum*	**Mean**	Maize-urea	Maize +urea	*D. uncinatum*	*D. intortum*	**Mean**
0-15	43.77	86.33	70.45	128.41	**82.24**	30.22	75.66	47.9	52.2	**51.50**
15-30	23.55	78.2	57.29	81.57	**60.15**	22.54	69.92	38.95	37.41	**42.21**
30-60	27.36	60.03	46.32	57.71	**47.86**	19.28	79.59	48.57	46.44	**48.47**
60-90	35.56	58.42	36.58	40.46	**42.76**	19.35	54.86	30.16	30.99	**33.84**
90-120	47.47	59.73	20.43	40.12	**41.94**	30.48	53.91	17.21	31.83	**33.36**
Mean	**35.54**	**68.54**	**46.21**	**69.65**	**54.99**	**24.37**	**66.79**	**36.56**	**39.77**	**41.87**
SED $_{treatment (T)}$			6.72					6.98		
SED $_{depth (D)}$			7.51					7.86		
SED$_{T*D}$			15.02					15.61		

***Note**: **SED** - Standard errors of difference, **D**- Desmodium, **Nd**-not done.*

4.3.6 Total soil mineral N in Matayos (Busia) during long rainy season, 2010

Total mineral N in Matayos during long rainy season of 2010 is presented in Fig 4.2. During this season, higher levels of total N (NH_4-N+NO_3-N) were observed in *Desmodium* intercropping system which ranged between 4.14 to 77.36 kg N ha^{-1} relative to sole maize control which ranged between 9.87 to 45.6 kg N ha^{-1}. Significant treatments differences on total mineral N in Busia were observed in all sampling times with exception of 10 WAP. At 4WAP, significant higher amounts of total N were observed in sole maize control which amounted to 34.79 kg N ha^{-1} relative to intercropping system with either *D. intortum* (34.79 kg N ha^{-1}) or *D. uncinatum* (11.07 kg N ha^{-1}) irrespective of sampling depth. However, at 9WAP, total N concentration in *Desmodium*-maize intercropping system with *D. intortum* was significantly higher than with *D. uncinatum* in 0-60 cm soil depths. *Desmodium*-maize intercropping system with *D. intortum* significantly increased total N compared to sole maize control at 9th and 12th WAP at 0-60 cm soil depth. No significant treatment differences on total N concentration were observed beyond 90 cm soil depth. Sampling depth had no significant effect on total N concentration in all sampling times.



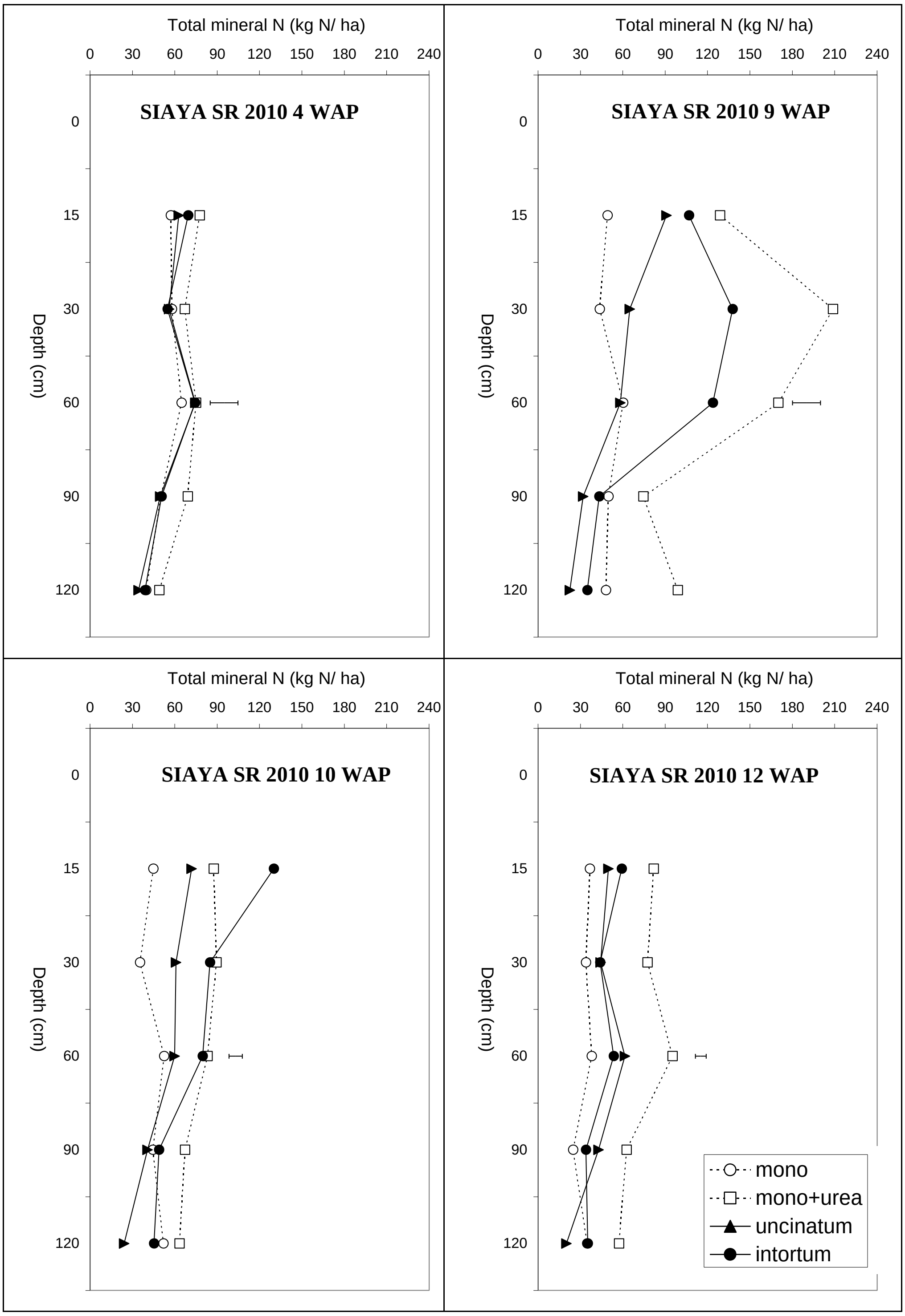
(Source: Author, 2013).[2]

Fig 4.2: Total mineral N (kg N ha^{-1}) from *Desmodium* intercropping systems with *D. uncinatum* and *D. intortum* relative to a sole maize system with and without urea application in Matayos (Busia) during LR2010

[2] *Error bar represents standard error of diference for comparisons of treatments*.

4.3.7 Total soil mineral N in Nyabeda (Siaya) during short rainy season, 2010

Fig 4.3 shows that in Siaya during SR2010, total N in *Desmodium*-maize intercropping ranged between 20.05 to 137.71 kg N ha^{-1} while significant lower amounts of total N were recorded in sole maize control which ranged between 24.65 to 64.65 kg N ha^{-1} during the sampling period. Significant treatments differences in total N were observed at 9th, 10th and 12th WAP in 0-60 cm soil depth. At 9th and 10th WAP, *Desmodium*-maize intercropping system with *D. intortum* gave significant higher amounts of total N relative to sole maize control and intercropping with *D. uncinatum*. Sole maize systems with urea applied significantly increased total N above all the other treatments from 9th to 12th WAP. Sampling depth had a significant effect on total N in all sampling times with the highest total N occurring in 0-60 cm soil depth. Urea application significantly increased total N in the sole maize system at all sampling times irrespective of the depth. Significant interaction effect between treatments and sampling depth was observed only at 10WAP, a time that recorded the highest total N amounting to 83.5 kg N ha^{-1} irrespective of treatments in Siaya during SR2010.



(Source: Author, 2013).

Fig 4.3: Total mineral N (kg N ha^{-1}) from *Desmodium* intercropping systems with *D. uncinatum* and *D. intortum* relative to a sole maize system with and without urea application in Nyabeda (Siaya) during SR2010 [3]

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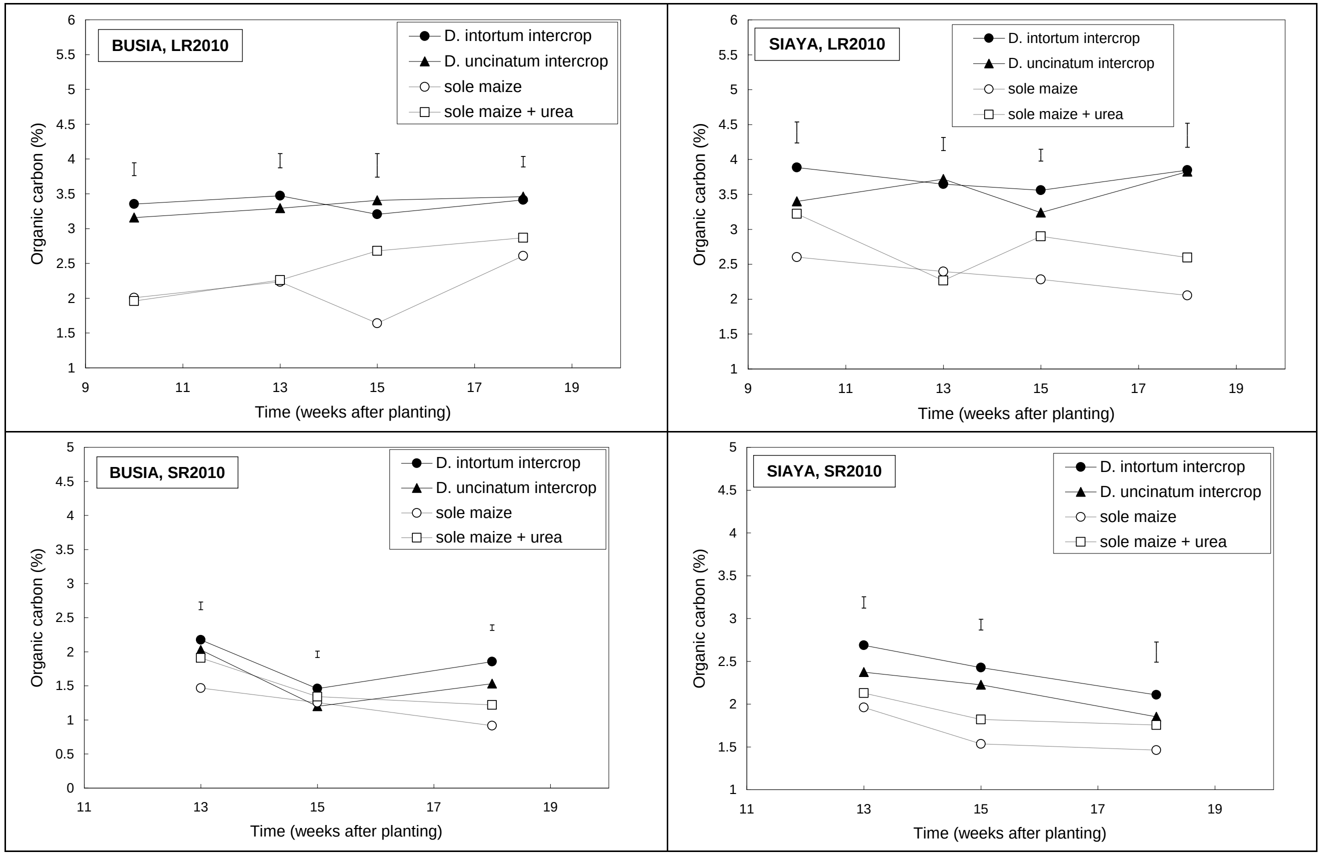
[3] *Error bar represents standard error of diference for comparisons of treatments.*

4.3.8 Organic carbon in soils

Fig 4.4. highlights the soil organic carbon in Busia and Siaya sites during LR2010 and SR2010 seasons. In both seasons, soil organic carbon was significantly higher in the Siaya than in Busia soils, irrespective of the treatments and sampling time. During LR2010, *Desmodium* intercropping with both *D.intortum* and *D. uncinatum* significantly increased organic carbon above sole maize control in all the sampling times in both Busia and Siaya sites. The soil organic carbon from *Desmodium* intercropping with *D. intortum* and *D. uncinatum* were comparable and ranged from 3.21 to 3.47 and 3.16 to 3.46 %C respectively in Busia. The corresponding values were from 3.56 to 3.89 and 3.24 to 3.83 %C respectively in Siaya. Sole maize control had the lowest organic carbon which ranged between 1.64 and 2.61 %C in Busia and 2.28 and 2.60 %C in Siaya. Significant interaction effect between treatments and sampling time was observed during LR2010 at both sites. During SR2010, similar trends were observed and significant higher amounts of organic carbon were obtained in *Desmodium* intercropping system relative to sole maize systems in both sites irrespective of sampling time. There was however a general decline in the levels of organic carbon in both sites compared to the previous season. Organic carbon in *D. intortum* and *D. uncinatum* ranged from 1.46 to 2.17 %C and 1.2 to 2.03 %C in Busia and Siaya respectively. Sole maize control recorded the lowest organic carbon during SR2010 in both sites.



(Source: Author, 2013).

Fig 4.4: Organic carbon (%) from *Desmodium* intercropping systems with *D. uncinatum* and *D. intortum* relative to a sole maize system with and without urea application in Matayos (Busia) and Nyabeda (Siaya) during LR2010 and SR 2010 respectively[4]

[4] Error bar represents standard error of difference for comparisons of treatments.

4.3.9 *Desmodium* nitrogen concentration and N_2 fixation

Desmodium nitrogen concentration and biological nitrogen fixation (BNF) values in Busia and Siaya sites during SR2009, LR2010 and SR2010 seasons are presented in Table 4.6 and 4.7. During these seasons, *Desmodium* biomass and N concentration were significantly higher in Siaya than in Busia irrespective of the *Desmodium* spp and cutting regime. In both sites, *D. intortum* had significantly higher biomass and N concentration irrespective of cutting regimes during SR2009 and LR2010. In Busia, *Desmodium* biomass and N concentration were significantly higher when cutting regimes were imposed at 12WAP relative to either 9 or 18WAP during SR2009. In Siaya, cutting regime had a significant effect on *Desmodium* biomass accumulation and N yield in all the seasons. During SR2009, higher *Desmodium* biomass accumulation and N concentration were observed when cutting was imposed at either 12 or 18WAP compared to 9WAP while during LR2010, cutting *Desmodium* at either 9 or 12WAP resulted to higher biomass accumulation and N concentration. Nonetheless, during SR2010, higher *Desmodium* biomass accumulation and N concentration were observed when cutting was delayed up to 18WAP relative to early cutting imposed at either 9 or 12WAP. Significant interaction effect between *Desmodium* spp and cutting regimes on *Desmodium* biomass yield occurred only in Busia during SR2009.

The two *Desmodium* spp had significantly lower $\delta^{15}N$ values than the non- fixing controls. The proportion of nitrogen derived from atmosphere (Ndfa) was higher in Siaya than in Busia irrespective of the *Desmodium* spp and cutting regime and ranged between 44-65% and 48-71% in Busia and Siaya, respectively (Table 4.6) across the seasons. In both Busia and Siaya sites, *D. intortum* and *D. uncinatum* gave comparable proportions of N fixed in all the seasons.

Table 4.6: Shoot biomass, N yield, proportion of N derived from atmospheric N_2 –fixation and amounts of N_2 fixed by *D. uncinatum* and *D. intortum* for three consecutive seasons in Matayos (Busia County).

	Shoot biomass (kg ha^{-1}season^{-1})				Shoot N yield (kg ha^{-1}season^{-1})				Ndfa (%)				N_2 fixed (kg ha^{-1}season^{-1})			
Short rainy season,2009																
	Cutting regimes (cr)															
	9	**12**	**18**	**Mean**	**9**	**12**	**18**	**Mean**	**9**	**12**	**18**	**Mean**	**9**	**12**	**18**	**Mean**
Desmodium																
D. intortum intercrop	2817	4695	4238	**3917**	67	106	95	**89**	61	49	62	**57**	40	46	59	**48**
D. uncinatum intercrop	2554	3079	1651	**2428**	49	71	31	**50**	61	58	52	**57**	29	31	19	**26**
Mean	**2686**	**3887**	**2945**	**3172**	**58**	**89**	**63**	**70**	**74**	**69**	**71**	**71**	**35**	**39**	**39**	**37**
SED *Desmodium* spp(d)	**346.9**				**6.8**				**1.94**				**4.5**			
SED cutting regime (cr)	**424.8**				**8.3**				**2.38**				**5.5**			
SED$_{dxcr}$	**600.8**				**11.8**				**3.36**				**7.8**			
Long rainy season, 2010																
D. intortum intercrop	6886	6375	6159	**6473**	130	135	126	**130**	63	51	50	**55**	81	73	73	**76**
D. uncinatum intercrop	4258	4641	4595	**4498**	84	94	94	**91**	65	53	50	**56**	54	56	53	**54**
Mean	**5572**	**5508**	**5377**	**5486**	**107**	**115**	**110**	**111**	64	**52**	50	**55**	**68**	**65**	**63**	**65**
SED *Desmodium* spp(d)	**494.2**				**8.4**				**1.8**				**5.7**			
SED cutting regime (cr)	**605.3**				**10.3**				**2.21**				**7.0**			
SED$_{dxcr}$	**856.0**				**14.5**				**3.1**				**9.9**			
Short rainy season, 2010																
D. intortum intercrop	1683	1983	2548	**2071**	32	41	41	**38**	45	45	53	**48**	15	11	20	**15**
D. uncinatum intercrop	1010	2180	1733	**1641**	22	47	40	**36**	44	45	48	**46**	9	17	21	**16**
Mean	**1347**	**2082**	**2141**	**1856**	**27**	**44**	**41**	**37**	**45**	**45**	51	**47**	**12**	**14**	**21**	**16**
SED *Desmodium* spp(d)	**361.9**				**6.1**				**2.6**				**3.2**			
SED cutting regime (cr)	**443.2**				**7.5**				**3.2**				**3.9**			
SED$_{dxcr}$	**626.8**				**10.6**				**4.5**				**5.5**			

SED- standard errors of difference, %ndfa- proportion of N derived from atmosphere

Table 4.7: Shoot biomass, N yield, proportion of N derived from atmospheric N_2 –fixation and amount of N_2 fixed by *D. uncinatum* and *D. intortum* for three consecutive seasons in Nyabeda (Siaya County).

	Short rainy season,2009															
	Shoot biomass (kg $ha^{-1}season^{-1}$)				**Shoot N yield (kg $ha^{-1}season^{-1}$)**				**Ndfa (%)**				**N_2 fixed (kg $ha^{-1}season^{-1}$)**			
	Cutting regimes (cr)															
Cutting regimes	**9**	**12**	**18**	**Mean**	**9**	**12**	**18**	**Mean**	**9**	**12**	**18**	**Mean**	**9**	**12**	**18**	**Mean**
Desmodium																
D. intortum intercrop	2979	7186	7574	**5913**	61	159	155	**125**	70	50	58	**59**	37	75	97	**70**
D. uncinatum intercrop	3055	5057	5101	**4404**	66	119	105	**97**	71	50	60	**60**	47	48	61	**52**
Mean	**3017**	**6122**	**6338**	**5159**	**64**	**139**	**130**	**111**	**127**	**122**	**120**	**123**	**42**	**62**	**79**	**61**
SED $_{Desmodium\ (d)}$		**489.5**				**13.2**				**1.8**				**8.0**		
SED $_{cutting\ regime\ (cr)}$		**599.5**				**16.2**				**2.2**				**9.8**		
SED_{dxcr}		**847.8**				**22.9**				**3.1**				**13.9**		
	Long rainy season, 2010															
D. intortum intercrop	8306	9376	6079	**7920**	176	194	105	**158**	58	50	63	**57**	104	109	68	**94**
D. uncinatum intercrop	7037	6167	5296	**6167**	153	123	109	**128**	58	51	58	**55.7**	93	68	63	**75**
Mean	**7672**	**7772**	**5688**	**7044**	**164.5**	**159**	**107**	**143**	58	**51**	60.5	**56**	**98.5**	**89**	**66**	**84**
SED $_{Desmodium\ (d)}$		**519.3**				**12.8**				**1.7**				**7.9**		
SED $_{cutting\ regime\ (cr)}$		**636.1**				**15.7**				**2.0**				**9.7**		
SED_{dxcr}		**899.5**				**22.2**				**2.9**				**13.7**		
	Short rainy season, 2010															
D. intortum intercrop	3572	3458	5444	**4158**	74	76	101	83.67	62	48	51	**54**	47	39	55	**47**
D. uncinatum intercrop	2274	2897	4758	**3310**	44	59	86	63	64	60	47	**57**	29	30	49	**36**
Mean	**2923**	**3178**	**5101**	**3734**	**59**	**68**	**94**	**73**	**63**	**54**	49	**55**	**38**	**34.5**	**52**	**42**
SED $_{Desmodium\ (d)}$		**501.5**				**8.2**				**2.4**						
SED $_{cutting\ regime\ (cr)}$		**614.3**				**10.0**				**3.0**						
SED_{dxcr}		**868.7**				**14.2**				**4.2**						

Note: SED- standard errors of difference, %ndfa- proportion of N derived from atmosphere, **D**- *Desmodium*, **CR**- cutting regime,.

In Busia, cutting regime significantly affected the proportion of N fixed (%ndfa) during SR2009 and LR2010 while in Siaya cutting regime had a significant effect on %ndfa in all the seasons. Significant higher proportions of N fixed were observed when cutting was imposed at 9WAP relative to cutting at either 12 or 18 WAP in Busia whereas in Siaya cutting *Desmodium* at either 9 or 18WAP significantly increased %ndfa relative to cutting at 12WAP irrespective of *Desmodium* spp. Significant interaction effect between *Desmodium* spp and cutting regime on proportion of %ndfa occurred only in Busia during SR 2009.

Total fixed N (approximated using maize as reference crop) was larger in Siaya than in Busia irrespective of the *Desmodium* spp and cutting regime in all the seasons (Table 4.6, 4.7). In both sites, *D. intortum* fixed significantly larger amount of N compared to *D. uncinatum* in all seasons except during SR2010 in Busia. During SR2009 when *Desmodium* cutting regimes were first imposed, total N fixed ranged between 19-59 and 47-97 kg N ha^{-1} in Busia and Siaya, respectively irrespective of *Desmodium* spp. Significant higher amounts of N fixed were observed when *Desmodium* was cut at either 12 or 18WAP relative to when cut at 9WAP irrespective of *Desmodium* spp in Siaya site. Cutting regime interacted significantly with *Desmodium* spp during SR2009 in Busia site. The highest amount of N fixed was observed during LR2010 in both Busia and Siaya, possibly because the soil moisture was not limiting and biomass yields were greatly improved. Total N fixed ranged between 53-81 and 63-109 kg N ha^{-1} in Busia and Siaya, respectively. Significant higher amounts of N fixed occurred only when *Desmodium* was cut at either 9 or 12 WAP relative to when cut at 18WAP, irrespective of *Desmodium* spp in Siaya. No significant interaction effect between *Desmodium* spp and cutting regime was observed during SR2010 in both sites. During the last season (SR2010), the amount of N fixed remarkably reduced in both sites possibly due to reduced biomass yield and ranged between 9.3-21 and 29-55 kg N ha^{-1} in Busia and Siaya respectively. Cutting *Desmodium* spp at 18WAP significantly increased amount of N fixed relative to when cutting was imposed at either 9 or 12 WAP in Siaya. No significant interaction effect between *Desmodium* spp and cutting regime was observed during SR2010 in both sites.

4.3.10 Maize biomass

Maize biomass from sampling done between 10 and 18WAP ranged from 2.17 to 7.80 and 3.01 to 9.09 t ha^{-1} in Busia and Siaya, respectively during LR2010 irrespective of the treatments (Table 4.8). Howerver, in Siaya site intercropping with *D.uncinatum* significantly increased maize biomass above sole maize irrespective of sampling time. Application of urea increased maize biomass yield in the sole maize cropping system in both sites during LR2010 irrespective of sampling time. Biomass significantly increased with sampling time with an exception of 18WAP in Busia that recorded a significant reduction in biomass production.

Table 4.8: Maize biomass (t/ha) at different sampling times from *Desmodium* intercropping systems with *D.* uncinatum and *D. intortum* relative to sole maize system with and without urea application during 2010 long rainy season in Matayos (Busia County) and Nyabeda (Siaya County).

Site		Sampling Time				
		10WAP	13WAP	15WAP	18WAP	Mean
Busia	*D. intortum* intercrop	2.45	5.40	7.17	3.26	**4.57**
	D. uncinatum intercrop	2.45	6.38	5.01	3.44	**4.32**
	sole maize	2.17	5.42	5.76	3.11	**4.11**
	sole maize + urea	2.97	6.79	7.80	4.55	**5.52**
	Mean	**2.51**	**6.00**	**6.43**	**3.59**	**4.63**
	SED $_{Treatments}$			**0.54**		
	SED $_{Sampling\ time}$			**0.56**		
	SED$_{treatments*sampling\ time}$			**1.12**		
Siaya	*D. intortum* intercrop	3.87	7.11	6.28	5.18	**5.61**
	D. uncinatum intercrop	3.44	6.71	9.09	6.03	**6.32**
	sole maize	3.01	4.83	5.37	5.55	**4.69**
	sole maize + urea	3.81	6.74	8.73	5.83	**6.28**
	Mean	**3.53**	**6.35**	**7.37**	**5.65**	**5.72**
	SED $_{Treatments}$			**0.59**		
	SED $_{Sampling\ time}$			**0.61**		
	SED$_{treatments*sampling\ time}$			**1.22**		

Note: SED*- Standard error of the difference,* ***D****- Desmodium, WAP- weeks after planting*

During SR2010, generally lower maize biomass yield were obtained relative to LR2010. Maize biomass yield from sampling done between 10th to 18WAP ranged from 0.82 to 4.15 and 1.37 to 7.61 t ha^{-1} in Busia and Siaya, respectively (Table 4.9). In both Busia and Siaya sites, *Desmodium*-maize intercropping system with both *D. intortum* and *D. uncinatum* significantly increased maize biomass above sole maize control. Application of urea in the sole maize system significantly increased maize biomass in both sites in all the sampling times during SR2010. Biomass significantly increased with sampling time in both sites.

Table 4.9: Maize biomass (t ha^{-1}) at different sampling times from *Desmodium* intercropping systems with *D.* uncinatum and *D. intortum* relative to sole maize system with and without urea application during 2010 short rainy season in Matayos (Busia County) and Nyabeda (Siaya County).

		Sampling Time				
Sites	**Treatments**	**10 WAP**	**13 WAP**	**15 WAP**	**18 WAP**	**Mean**
Busia						
	D. intortum intercrop	1.02	2.31	3.32	2.97	**2.41**
	D. uncinatum intercrop	0.86	2.38	2.61	3.14	**2.25**
	sole maize	0.82	1.44	1.94	2.73	**1.73**
	sole maize + urea	1.31	3.76	3.58	4.15	**3.20**
	Mean	**1.00**	**2.47**	**2.87**	**3.25**	**2.40**
	SED $_{Treatments}$			**0.23**		
	SED $_{Sampling\ time}$			**0.24**		
	SED$_{treatments*sampling\ time}$			**0.48**		
Siaya	*D. intortum* intercrop	1.37	3.04	6.19	7.32	**4.48**
	D. uncinatum intercrop	1.50	2.20	5.25	7.61	**2.99**
	sole maize	1.54	2.02	3.09	5.29	**4.38**
	sole maize + urea	1.57	3.01	5.88	7.08	**4.14**
	Mean	**1.49**	**2.57**	**5.10**	**6.83**	**4.00**
	SED $_{Treatments}$			**0.43**		
	SED $_{Sampling\ time}$			**0.45**		
	SED$_{treatments*sampling\ time}$			**0.90**		

SED- Standard error of the difference, ***D*-** *Desmodium*, WAP- Weeks after planting

4.3.11 Variation in maize shoot $\delta\ ^{13}C$ contents

During LR 2010, no significant treatment differences in shoot $\delta\ ^{13}C$ values were observed irrespective of sampling time. Maize shoot $\delta\ ^{13}C$ values in *Desmodium* intercropping and sole maize system were similar and ranged from -12.85 to -11.8$^{0}/_{00}$ and -12.77 to -11.84 $^{0}/_{00}$ respectively in Busia. The corresponding values in Siaya were -12.77 to -11.84$^{0}/_{00}$ and -12.65 to -11.85$^{0}/_{00}$ respectively during LR2010 (Table 4.10). Age of the crop had a significant effect on $\delta\ ^{13}C$ values irrespective of treatments in both sites. Maize shoot samples collected at 10WAP had significant higher $\delta\ ^{13}C$ while the lowest $\delta\ ^{13}C$ were observed at 18 WAP in both sites. Low $\delta\ ^{13}C$ were observed at 4WAP (-12.15$^{0}/_{00}$), followed by an increase at 10WAP (-11.88$^{0}/_{00}$) and gradual and significant decline up to 18WAP (-12.71$^{0}/_{00}$) at both sites.

During SR2010, no significant treatment differences in shoot $\delta\ ^{13}C$ were observed and only the age of the maize biomass that had a significant effect on $\delta\ ^{13}C$ values. Maize shoot $\delta\ ^{13}C$ ranged from -12.84 to -11.59 $^{0}/_{00}$ in Busia and -12.80 to -11.63 in Siaya in all the treatments (Table 4.9). The $\delta\ ^{13}C$ values of maize shoot significantly decreased with age of the crop i.e from 4WAP (-11.73$^{0}/_{00}$**)** to 18WAP (-12.72$^{0}/_{00}$**)** in both sites. No significant interaction effect between treatments and age of the crop was recorded.

Table 4.10: Maize shoot δ ^{13}C ($^{0}/_{00}$) from *Desmodium* intercropping system with *D.uncinatum* and *D. intortum* relative to a sole maize system with or without urea in Matayos (Busia County) and Nyabeda (Siaya County) during LR2010 and SR2010.

Busia	**Long rainy season 2010**						**Short rainy season 2010**					
Treatment/WAP	**4**	**10**	**13**	**15**	**18**	**Mean**	**4**	**10**	**13**	**15**	**18**	**Mean**
D. intortum	-12.32	-11.80	-11.91	-12.18	-12.85	**-12.21**	-11.81	-12.05	-12.45	-12.21	-12.82	**-12.27**
D.uncinatum	-12.10	-11.87	-12.18	-12.20	-12.74	**-12.22**	-11.68	-12.05	-12.33	-12.35	-12.84	**-12.25**
Sole maize control	-12.13	-11.84	-12.03	-12.10	-12.77	**-12.17**	-11.97	-11.99	-12.31	-12.34	-12.74	**-12.27**
Sole maize +urea	-12.19	-11.84	-12.04	-12.25	-12.71	**-12.21**	-11.59	-12.05	-12.31	-12.28	-12.72	**-12.19**
Mean	**-12.18**	**-11.84**	**-12.04**	**-12.18**	**-12.77**	-12.20	**-11.76**	**-12.04**	**-12.35**	**-12.29**	**-12.78**	-12.24
SED $_{Treatments\ (T)}$	**0.053**						**0.067**					
SED $_{Sampling\ time\ (ST)}$	**0.061**						**0.075**					
SED $_{TxST}$	**0.126**						**0.150**					
Siaya												
D. intortum	-12.08	-11.93	-12.07	-12.16	-12.66	**-12.18**	-11.63	-12.05	-12.46	-12.33	-12.77	-12.25
D.uncinatum	-12.12	-11.96	-11.80	-12.23	-12.65	**-12.15**	-11.76	-12.03	-12.44	-12.59	-12.75	-12.31
Sole maize control	-12.16	-11.95	-11.98	-12.19	-12.65	**-12.19**	-11.68	-12.10	-12.24	-12.35	-12.80	-12.23
Sole maize+urea	-12.09	-11.85	-11.95	-12.48	-12.63	**-12.20**	-11.71	-12.02	-12.24	-12.39	-12.38	-12.15
Mean	**-12.12**	**-11.92**	**-11.95**	**-12.26**	**-12.65**	**-12.18**	**-11.69**	**-12.05**	**-12.35**	**-12.42**	**-12.67**	-12.24
SED $_{Treatments\ (T)}$	**0.049**						0.086					
SED $_{Sampling\ time\ (ST)}$	**0.055**						0.094					
SED $_{TxST}$	**0.120**						0.204					

Note ***SED-*** *Standard error of the difference,* ***D-*** *Desmodium,* ***WAP-****Weeks after planting*

4.3.12 Maize nitrogen concentration

Table 4.10 presents total (maize and stover) total maize N concentration during LR2010 and SR2010 in Busia and Siaya sites. During LR2010, intercropping system with *D. intortum* and *D. uncinatum* recorded the highest total maize N concentration in Busia (38.8 kg N ha^{-1}) and Siaya (78.07 kg N ha^{-1}), respectively. In Busia, intercropping system with *D.intortum* significantly increased total N concentration relative to sole maize control during LR2010. In Siaya however, intercropping system with *D. uncinatum* significantly increased total N concentration relative to sole maize control and gave comparable total maize N concentration to sole maize with urea applied. Application of urea in sole maize system significantly increased maize N concentration in Siaya site.

During the fourth season (SR2010) crop in Busia was adversely affected by low rainfall and termite attack and on average low grain yield and total N concentration were recorded in Busia (1.12 t ha^{-1} and 52 kg N ha^{-1}) compared to Siaya (2.90 t ha^{-1} and 80.8 kg N ha^{-1}). Intercropping system with *D. uncinatum* produced significant higher total N concentration compared to sole maize control in both Busia and Siaya sites. Urea application resulted into a significant increase in maize N concentration in the sole maize system during SR2010 in Siaya site alone.

Table 4.11. Maize yield (t ha^{-1}) and nitrogen concentration (Kg N ha^{-1}) from *Desmodium*-maize intercropping system with *D. uncinatum* and *D. intortum* relative to a sole maize system with or without urea application during LR2010 and SR2010 in Matayos (Busia County) and Nyabeda (Siaya County).

	Long rains 2010	**Short rains 2010**
Treatments	Total N (grain +stover) concentration (Kg N ha^{-1})	Total N (grain +stover) concentration (Kg N ha^{-1})
Busia		
D. intortum intercrop	38.77	47.07
D. uncinatum intercrop	35.90	51.90
sole maize control	26.00	48.33
sole maize + urea	39.90	60.53
Mean	**34.99**	**51.96**
SEDt$_{reatments}$	**5.844**	**9.348**
Siaya		
D. intortum intercrop	70.77	78.53
D. uncinatum intercrop	78.07	89.07
sole maize control	52.80	57.23
sole maize + urea	90.97	98.33
Mean	**73.15**	**80.79**
SED$_{treatments}$	**9.945**	**13.421**

Note: SED- *standard error of difference*.

4.4. Discussion

Significant higher amounts of NO_3-N and total N were observed in *Desmodium*-maize intercropping system with *D. intortum* than with *D. uncinatum* in 0-30 cm soil layer at both sites presumably as a result of rapid release of N from decomposing surface litter in the former. It was observed that *D. intortum* produced large biomass, increased shading and resulted to greater litter accumulation on the soil surface compared to *D. uncinatum.* Shelton *et al*., (1987) reported increased soil nitrogen levels which was attributed to positive effects of shade on the rate of nitrification from soil organic nitrogen sources. This also explains the slightly higher though not significant organic carbon obtained in *Desmodium*-maize intercropping system with *D. intortum* relative to *D. uncinatum* during LR2010 and SR2010. In addition, *D. intortum* has lower levels of tannins (2-4%) compared to *D. uncinatum* (9-17%) (Baloyi *et al*., 2001; Tolera and Sundst, 2001; Getachew *et al*., 2000) and therefore, most likely mineralization rate was higher in the former. Further, *D. intortum* has a deep tap root while *D. uncinatum* has a shallow rooting system (http://www.fao.org/ag/agp/AGPC/doc/Gbase/data/pf000030.htm, http://www.fao.org/ag/AGP/AGPC/doc/Gbase/data/pf000026.htm). It is possible that *D. intortum* roots penetrated deeper and were able to use soil water and capture N that leached to lower depths. Indeed, there was an evidence of accumulation of NO_3-N deeper soil layer (>60cm soil depth) in sole maize system compared to *Desmodium*-maize intercropping system with *D. intortum* in Siaya. This was probably caused by the high amounts of NO_3-N in sole maize system beyond 60 cm, an evidence of a "leachy" system in absence of deeper roots (Chikowo, 2004).

Desmodium intortum accumulated the greatest biomass, which resulted in the greatest N fixation and concentration by *Desmodium* in all the two sites. Although root length densities of the two *Desmodium* species were not determined in this study, observation in the field showed that *D. intortum* had dense fine roots networks and higher proportion of effective nodules than *D. uncinatum*. Chikowo (2004) while working with Sesbania and Acacia in Zimbabwe found that the fine roots give the plant a greater capacity for water and nutrient concentration. It was observed that maize intercropped with *D. intortum* was greener than either maize intercropped with *D. uncinatum* or sole maize control which could be attributed to increased N concentration in this system. High maize N concentration in *Desmodium* intercropping system relative to sole maize control confirmed increased N levels in this system relative to sole maize control. *Desmodium* cutting regime had a significant impact on N_2 fixation and the largest N fixation was obtained when cutting was imposed at either 12 or 18WAP as opposed to 9WAP apparently due to the fact that symbiotic BNF occur at higher demand stages; flowering. FAO (2011) estimated that N fixed by *D. uncinatum* ranged from 90 kg N ha^{-1} $year^{-1}$ in *Desmodium*/grass stands and 110 kg N ha^{-1} $year^{-1}$ in pure stand. In another study, Whitney and Green (1969) found that *D. intortum* in pure stand fixed 213 kg./ha/year in 90-cm rows, and 264 kg/ ha/year in 45-cm rows.

Although *D. intortum* consistently gave higher biomass, biologically fixed nitrogen and carbon compared to *D. uncinatum*, cumulative maize biomass in the *Desmodium* intercropping system was lower when intercropped with *D. intortum* than with *D. uncinatum*. First *D. intortum* accumulated larger biomass and because of its root structure most likely there was competition for soil resources between maize and *D.*

intortum, which resulted in reduced maize growth. Secondly, since *Desmodium* biomass was not incorporated back to the soil after cutting, removing large *D. intortum* biomass from the farm could have resulted in large quantities of soil N being exported.

Although maize shoot $\delta^{13}C$ values of sole maize system and maize intercropped with *Desmodium* spp did not differ significantly, maize shoot $\delta^{13}C$ values decreased as growth progressed with the lowest values being recorded at 18WAP. Changes in $\delta^{13}C$ values can result from several environmental factors such as nutrients availability, soil water status, pollution etc. It is likely that the effect of environmental factors including water availability on maize grown either in sole or in *Desmodium* intercropping systems was comparable. This confirms results of Khan *et al*., (2008b) that *Desmodium* in the PPT has multiple benefits among them moisture conservation. Howerver, significant lower $\delta^{13}C$ values as growth progressed were an indication that the plants suffered from water stress as they advanced in age.

4.5 Conclusion

Increased mineral N in the top 0-30 cm soil layer and reduced accumulation in deeper soil layers of *Desmodium* intercropping system relative to sole maize was an indication of enhanced N mineralization and reduced N leaching in the former. *D. intortum* consistently gave higher biomass, biologically fixed nitrogen, total mineral N and carbon compared to *D. uncinatum*. *Desmodium* cutting regime had a significant impact on N_2 fixation and the largest N fixation was obtained when cutting was imposed at either 12 or 18WAP as opposed to 9WAP. Maize shoot $\delta^{13}C$ values of sole maize system and maize intercropped with *Desmodium* spp did not differ significantly but decreased as growth progressed.

CHAPTER FIVE

5.0 THE EFFECT OF DESMODIUM SPECIES AND CUTTING REGIME ON THE AGRONOMIC AND ECONOMIC PERFORMANCE OF DESMODIUM-MAIZE INTERCROPPING SYSTEM IN WESTERN KENYA

This chapter reports the results of field experiments conducted in Busia and Siaya counties which tested the hypothesis that maize yield, the degree of *Striga* suppression and economic returns of intercropping maize with *Desmodium* are affected by (i) the *Desmodium* species, related to its biomass production and (ii) the cutting regime of the *Desmodium*. The experiment was started in the long rainy season of 2009 (LR2009) and ended after the short rainy season of 2010 (SR2010). Two *Desmodium* species were intercropped with maize and cutting regime of *Desmodium* was varied. Sole maize with and without urea were included as reference treatments. A paper on this work has been published in Field Crops Research Journal (Kifuko- Koech, *et al*., 2012).

Abstract

Field trials were conducted in two locations in western Kenya during 4 consecutive seasons to test the hypotheses that maize yield, the degree of *Striga* suppression and economic returns of intercropping maize with *Desmodium* are affected by (i) the related biomass production by different *Desmodium* species and (ii) the cutting regime of the *Desmodium*. Maize was intercropped with *Desmodium uncinatum* or *Desmodium intortum*, and treatments with sole maize (with and without urea) were included for comparison. Starting from the second season (SR2009), the first two *Desmodium* cutting events were fixed at land preparation and 4 weeks later, following a recommended practice, while the third cutting was varied and conducted at 9, 12 or 18 weeks after planting maize. To eliminate phosphorus (P) and potassium (K) deficiency, all treatments received basal P and K fertilizers at a rate of 60 kg P ha^{-1} and 60 kg K ha^{-1} respectively. Maize yield in *Desmodium* intercropping system was only higher than sole maize without urea from the third season. This implies that when P and K are not limiting, inclusion of *Desmodium spp* into maize cropping system would provide a substitute for inorganic N fertilizers to enhance crop growth and yield after two to three seasons when *Desmodium* is well established. Cumulative maize grain yield over the four seasons with the *D. intortum* and *D. uncinatum* intercrops were 6.3 and 7.0, and 10.9 and 11.6 t ha^{-1} in Busia and Siaya sites respectively. Average net benefits from *Desmodium* intercropping over the four seasons were increased by 1290 and 918 \$ ha^{-1} compared to the sole maize control in Busia and Siaya, respectively. Varying the time of the third *Desmodium* cutting had little effect on *Desmodium* biomass yield or maize grain yield in Busia, while in Siaya, *D. intortum* biomass yield were highest when cut at 12 weeks after planting. In the *Desmodium* intercropping systems, *Striga* counts were reduced by 95 % in Busia

and by 65-90 % in Siaya with higher reductions recorded when *Desmodium* was cut at 18 weeks after planting. In conclusion, the use of PPT provides robust and high economic benefits to smallholder farmers in western Kenya. Based on the results generated, the use of *D. uncinatum* with the third cutting at 18 weeks after planting is recommended, but can be modified according to the need for fodder without much effect on maize yield or revenue.

5.1 Introduction

Maize (*Zea mays* L.) is an important cereal crop for most of sub-Saharan Africa countries (Pingali, 2001). Previous studies in western Kenya have shown that low soil fertility, and particularly low nitrogen (N) and phosphorus (P), African witchweed (*Striga* spp.), lepidopteran stem borers (*Chilo partellus* Swinhoe) and unreliable rainfall are major causes of low maize yields (De Groote *et al*., 2010; Odendo *et al*., 2001). Soil nutrient mining and the resultant soil fertility decline occur in most areas in Kenya, as observed by the negative N, P and potassium (K) balances at the farm level (Smaling *et al*., 1997). The *Striga*–prone area forms a band around Lake Victoria in Western Kenya region (De Groote *et al*., 2008). *Striga hermonthica* is estimated to affect about 200,000 hectares of land causing crop yield losses varying between 5 and 100 % (Hassan *et al* 1994; Parker and Riches, 1993). Stem borers occur in all major agro-ecological zones of Kenya, and cause average crop losses of 13.5% countrywide and 16.6% in the moist mid-altitude zone (De Groote *et al*., 2010).

Research has provided a sound knowledge base on cropping systems; crop and land management practices that improve soil fertility while repressing the *Striga* spp. (Dahlin and Stenberg, 2010 ; Kifuko *et al*., 2007 ; Ojiem *et al*., 2007 ; Kanampiu *et al*., 2003 ; Khan *et al*., 2002). However, in some areas of western Kenya, the adoption of these technologies has been slow (Okalebo *et al*., 2006) due to socio-economic reasons. Recent study by Murage *et al*., (2011) have shown that adoption of a technology is likely to be faster if it is able to solve more than one farming limitation. To improve crop production in western Kenya, there is therefore need to practice integrated soil fertility management (ISFM) approaches (Vanlauwe *et al*., 2010) but given that pest significantly reduces cereal production in this region, ISFM can only be effective when used in combination with integrated pest management (IPM) approaches that reduces pest infestation with minimal toxic substances into the environment.

One promising integrated approach that accommodates principles of ISFM and IPM is “Push-Pull technology” (PPT). Push-Pull technology involves three crops (maize, *Desmodium* and napier grass) but in western Kenya, farmers have adapted the technology differently based on the available resources, land availability and farming systems. Thus, in some instances where land is limiting, soil fertility is of a greater concern and stemborer is not a problem, Napier grass has been left out (*Farmers pers comm.*). Beside the N-fixing capacity of *Desmodium* spp., chemicals released by *Desmodium* roots induce abortive germination of the parasitic *Striga* weed, providing a measure of control of this noxious weed (Midega *et al*., 2010; Khan *et al*., 2002). *Desmodium* and napier grass are nutritious fodder to livestock, while the former also offers a good cover to the soil that leads to improved soil moisture content, organic matter and reduced weeds. In some cropping systems with integrated animal production where lack of quality feed and low dry matter intake are major constraints (Omore *et al.,* 1996), both *Desmodium* and napier grass can provide a highly nutritious fodder supplement. Farmers may also require fodder at different times during the season, but subjecting *Desmodium* to different cutting strategies can have an impact on crop yields. Cutting leys have been shown to increase senescence and turnover of nodules and roots (Jarvis and MacDuff, 1989), but also reduce root biomass compared with intact plants (Dahlin and Stenberg, 2010). The PPT has been demonstrated equally effective in controlling stem borer and *Striga* with concomitant maize yield increases under farmers' conditions in western Kenya (Khan *et al*., 2008a, 2008b; Khan *et al*., 2001), but effect of varying *Desmodium* cutting regime on the yield performance of the system is not known. Also, despite the relatively well-documented role of *Desmodium uncinatum* in controlling cereal pests and increasing maize yields (De Groote *et al*., 2010; Khan *et al*., 2006a) in western Kenya, little information exists on other *Desmodium* spp. *Desmodium* species adapt differently to several environments, which also affects their production. It is therefore important to evaluate the performance of maize- *Desmodium* intercropping system using a *Desmodium* species with a higher biomass yield potential, such as *D. intortum*. The objectives of this study were therefore to (i) assess maize grain yield and *Desmodium* fodder yield in maize-*Desmodium* intercropping system using two *Desmodium* spp (ii) assess how varying the *Desmodium* cutting regime impacts on maize production and *Striga* incidence, and (iii) determine the economic viability of the different *Desmodium* spp. and cutting regimes.

5.2 Materials and Methods

5.2.1 The study area

The experiments were installed in two fields of smallholder farms in Nyabeda site, Siaya County and Matayos site, Busia County, located in western Kenya. Detailed site description is given in section 3.1.

5.2.2 Experimental design and treatments

The experimental design and treatments are described in section 3.2 and the layout is outlined in Appendix 2 and 3.

5.2.3 Plant sampling and *Striga* counts

Maize was harvested at maturity (about 18 WAP), and grain and stover dry matter yield were assessed. *Desmodium* dry matter yield was determined at each cutting event from a net plot of 81 m^2. *Striga* emergence was determined after the second weeding (around 12 WAP) by counting the emerged *Striga* plants inside each experimental plot (10m X 10m) containing all the maize plants without removing the *Striga* plants.

5.2.4 Economic analysis

A financial analysis using discounted partial budgets was conducted to evaluate and compare the economic returns of producing maize and *Desmodium* under different *Desmodium* cutting regimes. Unit prices of production inputs and of maize grain, stover and *Desmodium* fodder were recorded at local stockists and markets in both Matayos and Nyabeda, and averaged over the four seasons (Table 5.1.). Production costs included labour for land preparation, planting, weeding, *Desmodium* cutting and harvesting of maize, and purchase of farm inputs. The time taken to perform every activity was recorded and the labour was valued at Ksh 150 (USD 1.76) per working day (6 h). Opportunity costs of capital were taken into account by discounting at 10 % per year (5 % per season), a rate commonly used in studies involving resource-poor smallholder farmers (Rommelse, 2000) which is also the interest rate that money invested by farmers in most banks acrue. The four economic performance indicators used were (i) total net benefits (NB), which allows comparisons of different options and to find out the technology with the highest discounted profit at the end of the study period (De Groote *et al*., 2010), (ii) benefit cost ratio (BCR), which gives the profitability of the systems by comparing (discounted) benefits and costs, (iii) marginal rate of return (MRR) which compares benefit to cost. First, the technologies were ranked in order of descending total discounted benefits or NPV and the extra benefit of moving from one technology to the others was compared to the extra cost (CIMMYT,1988). When the technologies were evaluated from bottom up, the first profitable technology was sole maize with no urea application which was selected as a base level with which comparison of the alternatives was done using MRR and (iv) total costs.

Table 5.1: Parameters used for the financial analysis of the different cropping systems in Matayos (Busia) and Nyabeda (Siaya).

Parameter	Value
Price of urea (USD kg^{-1})	0.60
Price of Triple Super Phosphate (TSP) (USD kg^{-1})	0.69
Price of IR maize seed (USD kg^{-1})	1.88
Price of *Desmodium* seed (USD kg^{-1})	14.1
Labour wage (USD $6h^{-1}$)	1.76
Maize grain (USD kg^{-1})	0.53
Maize dry stover (USD t^{-1})	22.1
Desmodium green fodder (USD t^{-1})	33.0

***Note** :1 USD = 85 KES.*

5.2.5 Statistical analysis

The generated data were subjected to analysis of variance (ANOVA) to determine the effect of cropping systems, intercropped *Desmodium* species and cutting regimes using mixed procedure (SAS Institute Inc., 2003), with the treatments considered as fixed factors, and 'replicate' as a random factor, separately for each site. A one-way ANOVA was used to evaluate differences between the eight treatments (6 intercropping systems and 2 sole maize systems), as well as a two-way ANOVA for evaluating the interaction effects between *Desmodium* species and cutting regimes in the 6 treatments with the intercropping systems separately. Treatment differences were evaluated by computing least square means and the standard errors of difference (SED), referred to as SED1 and SED2 for the one-way and two-way ANOVA, respectively. Data on *Striga* count were converted to counts per square m (m^2) and transformed using logarithm transformation (Log_{10}) to improve homogeneity of variance before analysis of variance. Significance of difference was evaluated at $p \leq 0.05$ and $p \leq 0.01$.

5.3 Results

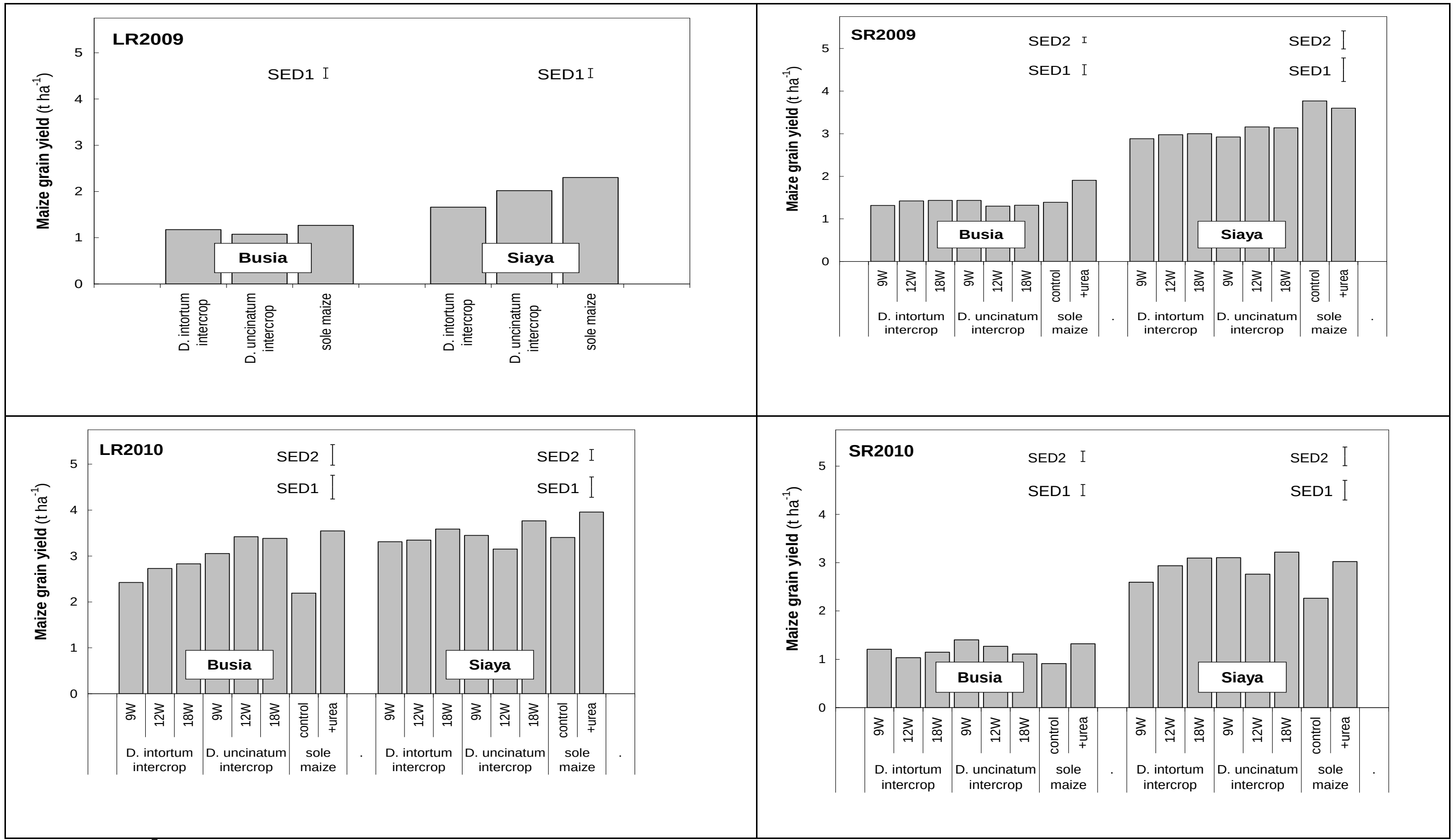
5.3.1 Maize grain and stover yields

The effect of *Desmodium* intercropping and cutting regimes on maize grain and stover yield differed significantly ($p<0.05$) between seasons and sites (Fig. 5.1. and 5.2). In the first season (LR2009), during which the systems were established and cutting regimes and urea application were not yet imposed, average maize grain yields of 1.1 and 1.9 t ha^{-1} were obtained in Busia and Siaya, respectively, while stover yield was on average 2.4 t ha^{-1} in both sites. There was no significant maize grain and stover yield difference between sole maize, and maize intercropped with the two *Desmodium* species in both sites. During the second season (SR2009), maize grain and stover yields were not affected by *Desmodium* intercropping in Busia, while in Siaya, a maize grain and stover yield losses of about 0.8 and 1.6 t ha^{-1}, respectively, were recorded, relative to the sole maize system. *Desmodium* species or cutting regime did not significantly affect maize grain and stover yield in the SR2009 season in the two sites. In LR2010, grain and stover yields in the intercropping systems were similar to or higher than yields in the sole maize treatment without urea application in both sites. Maize from *Desmodium* intercropping showed improved vigor compared to sole maize without urea (Plate 5.1).

(Source: Author, 2013).

Plate 5.1: Improved maize vigor from maize intercropped with Desmodium intortum (left) compared to sole maize without urea (right.

In Busia, maize grain yield in the intercropping system with *D. intortum* (2.7 t ha^{-1}) was significantly lower than with *D. uncinatum* (3.3 t ha^{-1}) but comparable to the yield of the sole maize with urea applied. Maize stover yields were comparable with the sole maize system with urea applied when intercropped with *D. uncinatum* (about 3.7 t ha^{-1}), but lower when intercropped with *D. intortum* (3.0 t ha^{-1}). Maize grain and stover yields were not affected by cutting regime in Busia. In Siaya, maize grain yield was significantly higher when *Desmodium* was cut at harvest (18 WAP) than when cut at 9 or 12 WAP, and not affected by *Desmodium* spp. Stover yields in Siaya were higher than in Busia, but no significant effect of *Desmodium* spp. or cutting regime was observed. In the last season (SR2010), average maize grain yield from all the treatments in Busia was low (1.2 t ha^{-1}) due to poor rainfall (Fig 4.1) and its distribution and not affected by treatments. Maize stover yields in the *Desmodium* intercropping system were again lower when intercropped with *D. intortum* (1.3 t ha^{-1}) than with *D. uncinatum* (1.7 t ha^{-1}) and not affected by cutting regimes. In Siaya, treatments had no effect on maize grain yield and yields obtained in *Desmodium* intercropping system were comparable to the yields of the sole maize crop with urea applied. In Busia, cumulative maize yields over the 4-season period were highest for the sole maize crop with urea (8.0 t ha^{-1}), followed by the intercrop with *D. uncinatum* (7.0 t ha^{-1}). Yields were lowest and similar for the sole maize crop without urea and the intercrop with *D. intortum* (6.1 t ha^{-1}). In Siaya, cumulative maize yield differences were relatively smaller, but also lowest for the intercrop with *D. intortum* (10.9 t ha^{-1}), and highest for the sole maize crop with urea applied (12.9 t ha^{-1}). The cutting regime of the *Desmodium* did not affect maize yields in any of the two sites.



(Source: Author, 2013).[5]

Fig 5.1: Maize grain yield from *Desmodium* intercropping systems with *D. uncinatum* and *D. intortum* and different cutting regimes, relative to a sole maize system with or without urea application over 4 subsequent seasons in Matayos (Busia) and Nyabeda (Siaya)

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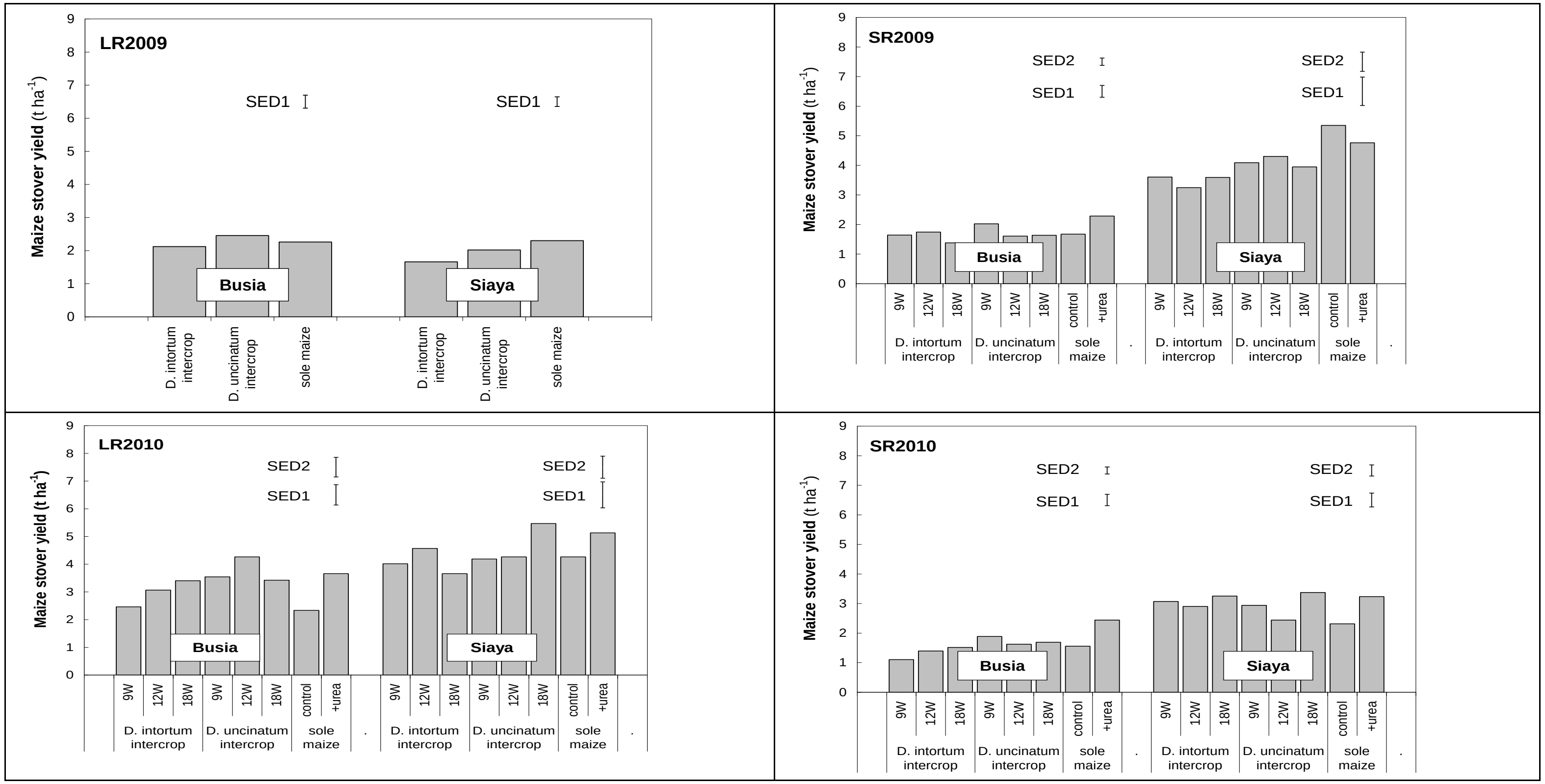
[5] *SED1 and SED2 -standard errors of difference for comparison of all treatments (one-way ANOVA) and for the interaction effect of Desmodium species and cutting regime (two-way ANOVA), respectively. W - weeks after planting maize*



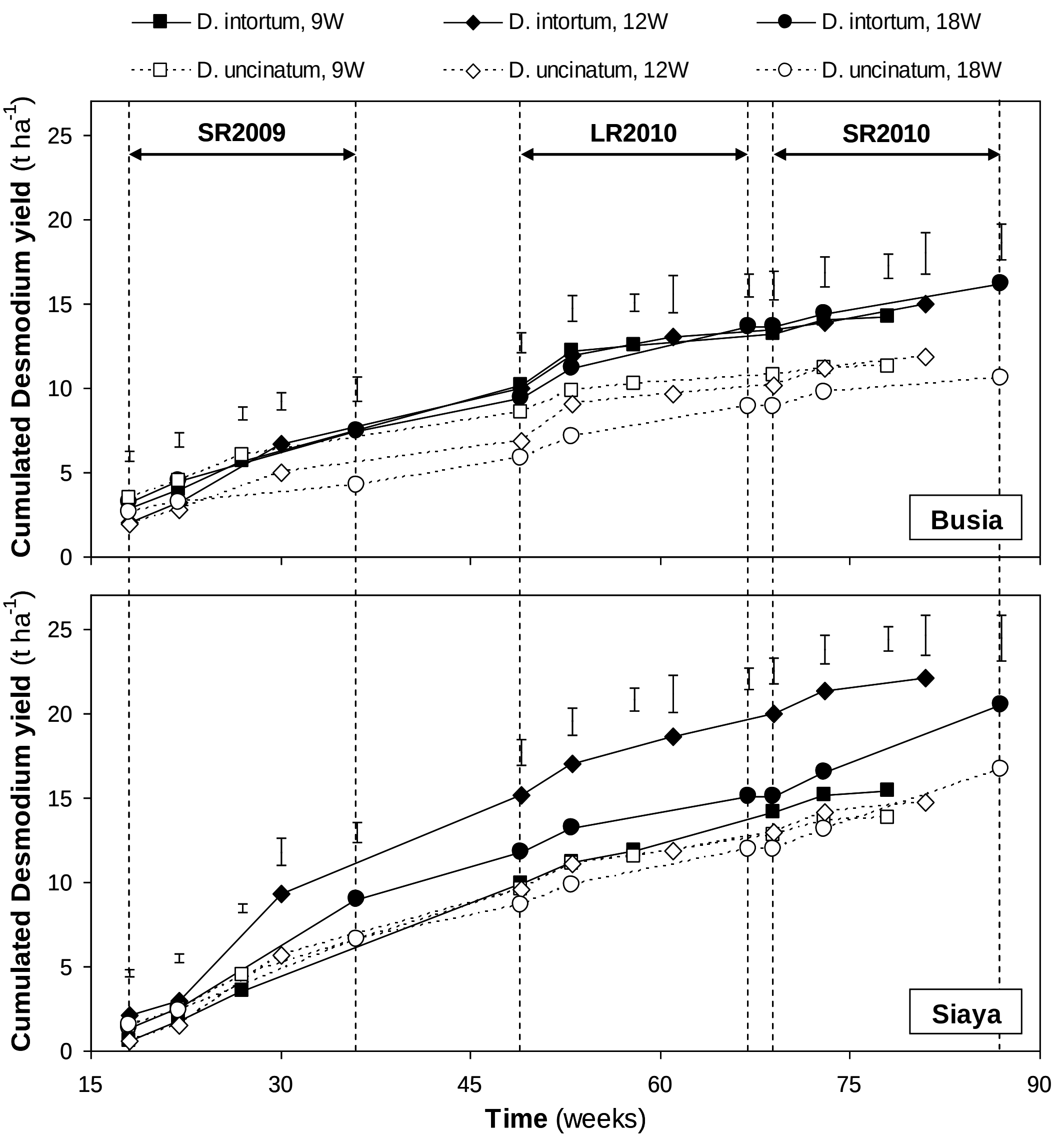
(Source: Author, 2013).

Fig 5.2: Maize stover yield from *Desmodium* intercropping systems with *D. uncinatum* and *D. intortum* subjected to different cutting regimes, relative to a sole maize system with or without urea application over 4 subsequent seasons in Matayos (Busia) and Nyabeda (Siaya)[6].

[6] *SED1 and SED2 – standard errors of difference for comparison of all treatments (one-way ANOVA) and for the interaction effect of Desmodium species and cutting regime (two-way ANOVA), respectively. W - weeks after planting maize*

5.3.2 *Desmodium* biomass yields

During the first season (LR2009), the plants of *Desmodium spp* was not cut but allowed to establish. In subsequent seasons, *Desmodium* biomass yield was higher in Siaya than in Busia, irrespective of the *Desmodium* species or cutting regime (Fig. 5.3.). During the SR2009 season, initially no differences in cumulated *Desmodium* biomass yields were observed, but at the third cutting at 12 or 18 WAP, yields were higher for *D. intortum* than for *D. uncinatum* in both sites. At the start of the LR2010 season, cumulative *Desmodium* biomass yield was significantly higher by 1.8 t ha^{-1} for *D. intortum* than for *D. uncinatum*, irrespective of the cutting regime in Busia, while in Siaya, biomass yields were higher for *D. intortum* only when the third cutting had been done at 12 or 18 WAP in the preceding season. These trends persisted up to the end of the SR2010 season. In Busia, *Desmodium* biomass yields were unaffected by the cutting regime, and *D. intortum* biomass was 2.9 - 5.6 t ha^{-1} significantly higher than biomass of *D. uncinatum*. In Siaya, biomass yields (3.8 - 7.4 t ha^{-1}) were significantly higher for *D. intortum* than for *D. uncinatum*, but only if the third cutting was done at 12 or 18 WAP. Significantly highest biomass yields were observed for *D. intortum* cut at 12 WAP than 9 or 18 WAP.



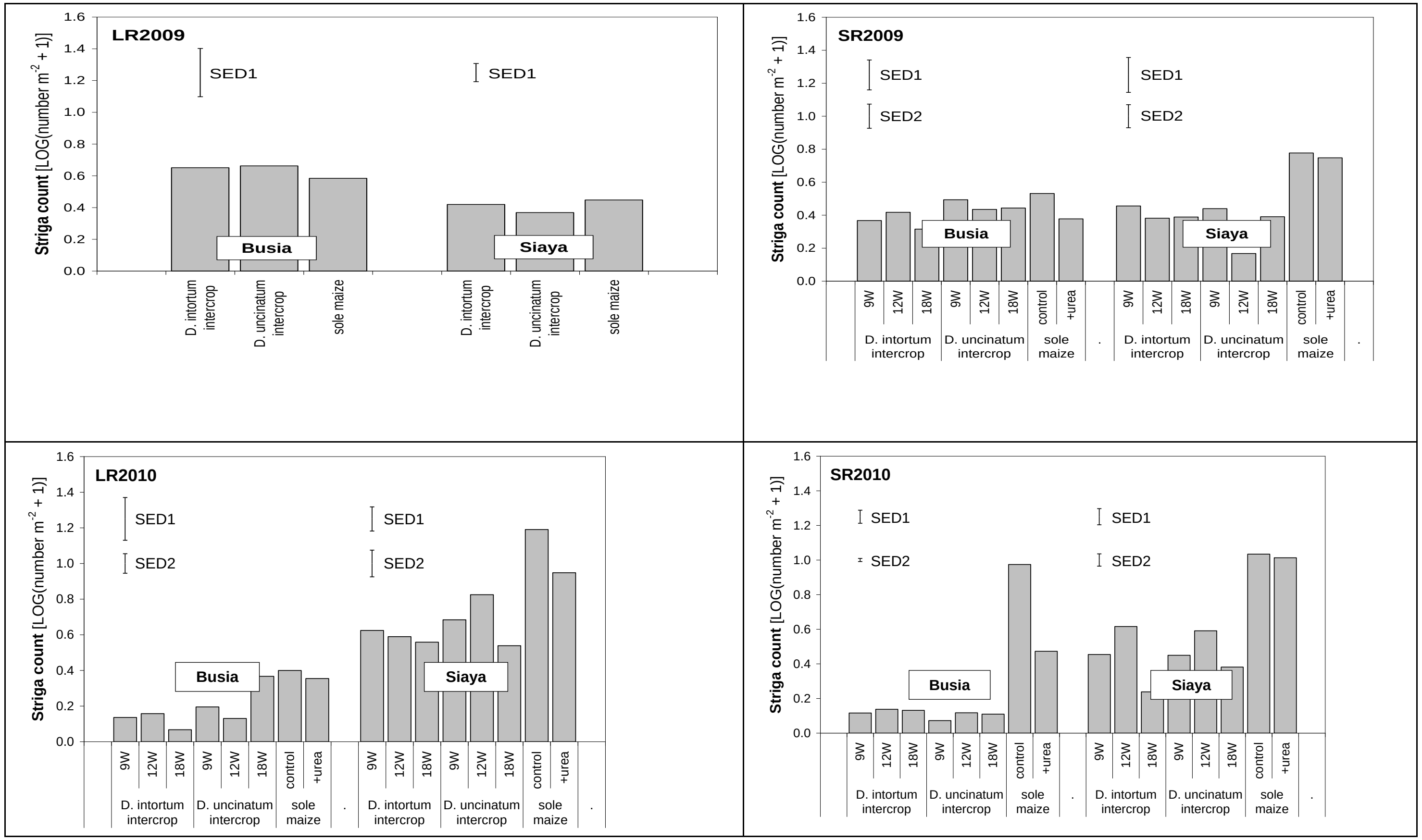
(Source: Author, 2013)[7]

Fig 5.3: Cumulative *Desmodium* yield from *Desmodium* intercropping systems with *D. uncinatum* and *D. intortum* subjected to different cutting regimes in Nyabeda (Siaya) and Matayos (Busia)

7 *The first two and the last two error bars in each season are SED1 and SED 2 respectively. SED1- comparison of all treatments (one-way ANOVA) and SED2 -interaction effect of Desmodium species and cutting regime (two-way ANOVA). W- Weeks after planting maize.*

5.3.3 *Striga* plant counts

During the first season (LR2009), *Striga* plant counts were not affected by intercropping with *Desmodium*, and equaled about 3.3 and 1.6 plants m^{-2} in Busia and Siaya, respectively (Fig. 5.4). In the subsequent season (SR2009), *Striga* counts were similarly not affected by treatments in Busia. In Siaya, in contrast, *Striga* counts equaled 4.8 plant m^{-2} for the sole maize crops, while in the intercropping systems, three times less plants were observed, independent of *Desmodium* species or cutting regime. In the LR2010, similar trends were observed. *Striga* counts were not affected by treatments in Busia, while in Siaya, *Striga* counts were highest in the sole maize crop without urea application (14.5 plants m^{-2}), followed by the sole maize crop with urea application (7.9 plants m^{-2}). Intercropping with *Desmodium* reduced *Striga* counts by 76 %, irrespective of the species or cutting regime. In the last season (SR2010), *Striga* counts were highest in the control sole maize system in both sites, followed by the sole maize system with urea application. In Busia, *Striga* counts were reduced by over 90 % in the *Desmodium* intercropping systems, relative to the sole maize crop without urea. In Siaya, reductions in *Striga* counts depended on the cutting regime, but not on the *Desmodium* species. *Striga* counts were lower when *Desmodium* was cut at 18 WAP (1.0 plants m^{-2}) than when cut at 12 WAP (3.0 plants m^{-2}) or 9 WAP (1.8 plants m^{-2}).



(Source: Author, 2013)

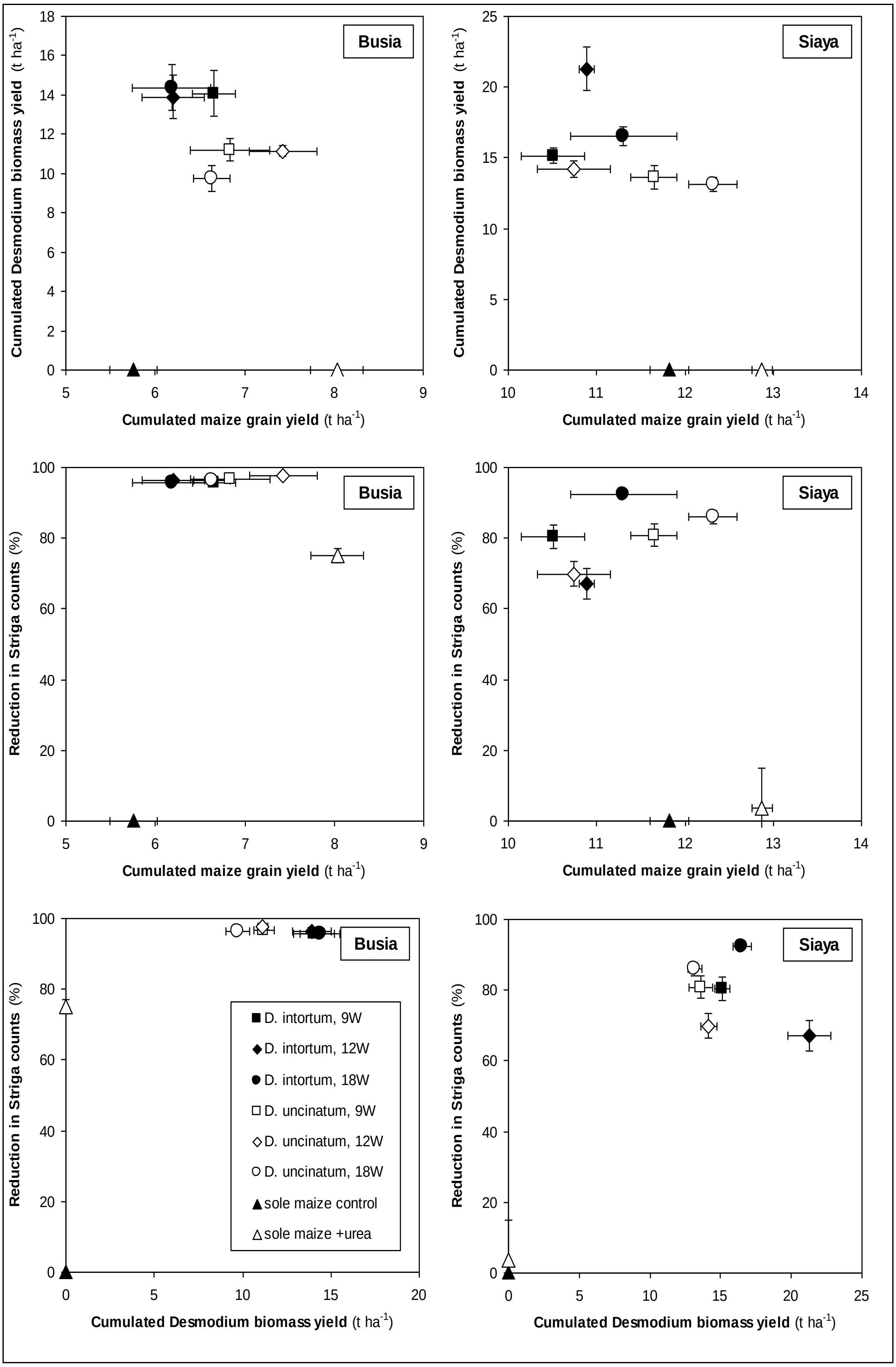
Fig 5.4: *Striga* plant count (number/m^2) from *Desmodium* intercropping systems with D. *uncinatum* and *D. intortum* subjected to different cutting regimes, relative to a sole maize with or without urea in Matayos (Busia) and Nyabeda (Siaya) .[8].

[8] *SED1- comparison of all treatments and SED2 -interaction effect of Desmodium species and cutting regime W- weeks after planting maize*

5.3.4 Trade-offs between production sub objectives

Three sub-objectives were considered in these production systems, namely; producing maize grain, producing *Desmodium* fodder, and reducing *Striga* infestation. Indicators considered for each of these objectives were cumulative maize grain yield over the 4-season period, cumulative *Desmodium* biomass yield at 4 WAP in season SR2010 (last simultaneous cutting in all treatments), and *Striga* counts in the last season (SR2010). In both sites, it was observed that *Desmodium* biomass can be produced with minimal effect on maize yield, since cumulative maize grain yields for a sole maize crop without urea were similar or lower, relative to the intercropping systems (Fig. 5.5). Assuming that *D. uncinatum* was replaced by *D. intortum* (and the third cutting conducted at 12 WAP in Siaya), this could have increased *Desmodium* biomass production by 32-56 %, but 6-9 % of the maize grain production needed to be traded in.

In Busia, all *Desmodium* intercropping systems effectively reduced *Striga* counts, while in Siaya, cumulative maize grain yields were correlated with the reduction in *Striga* counts, especially when intercropped with *D. uncinatum* ($r^2 = 0.64$, $p \leq 0.01$). *Striga* was most effectively controlled when *Desmodium* was cut at 18 WAP, which also tended to result in highest maize grain yields. Reduction in *Striga* counts was not related to *Desmodium* biomass production because *D. intortum* gave higher biomass yields but was not more effective in controlling *Striga* than *D. uncinatum*.

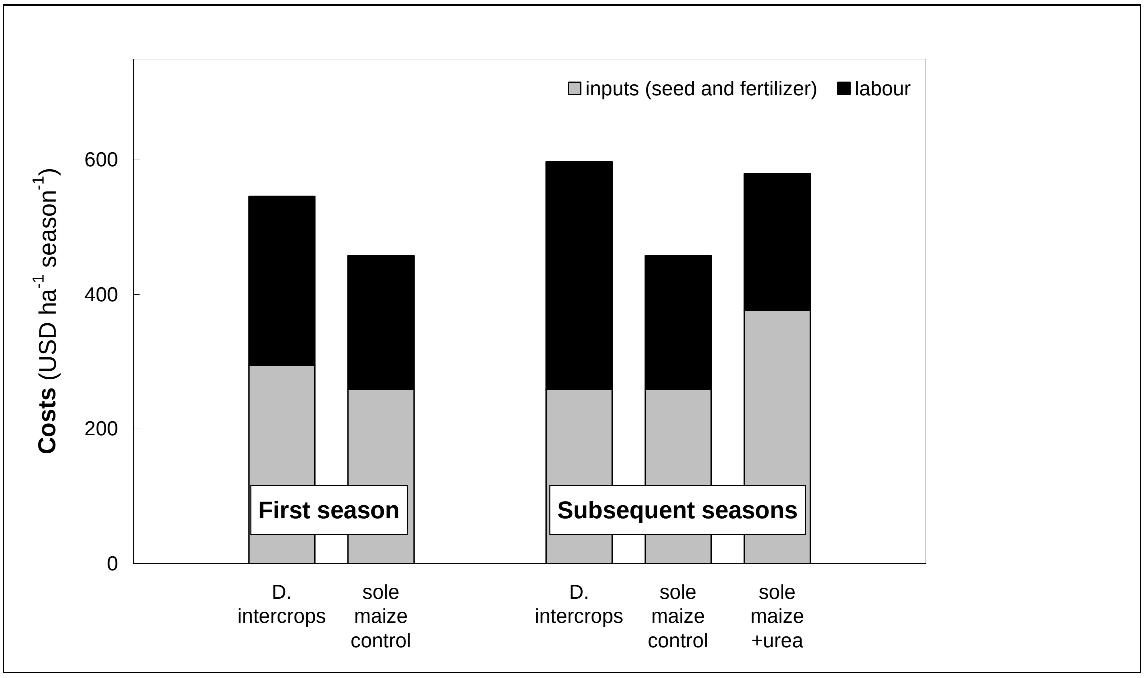


(Source: Author, 2013).

Fig 5.5: Relationship between (i) cumulative *Desmodium* biomass yield with cumulative maize grain yield and (ii) reduction in Striga count with cumulative maize grain and *Desmodium* biomass yield in Nyabeda (Siaya) and Matayos (Busia)

5.3.5 Economic analysis

In the first season (LR2009), total crop production costs were higher in the *Desmodium* intercropping systems than in the sole maize system in all the sites. This was attributed to the cost incurred for purchasing *Desmodium* seeds, and the extra labour required to plant and maintain the *Desmodium* (Fig. 5.6). Net benefits were significantly lower in the intercropping systems, and BCR values were less than one meaning that farmers incurred more costs compared to the benefits they obtained from a maize-*Desmodium* systems during the first season (Table 5. 2.). After the second season, cumulative and discounted NBs were not affected by treatments in either site. In Siaya, the BCR was still significantly higher for the sole maize crop without urea application due to the lower cost. At the end of the third season, some BCRs were above 2, NBs were least for sole maize control in both sites and BCR ranged between 1.95 and 2.57 in Busia and between 3.24 and 3.80 in Siaya. Net benefits were not affected by *Desmodium* species or cutting regime. At the end of the fourth season (SR2010), cumulative NBs were twice as high in the *Desmodium* intercropping systems than for the sole maize crop without urea in Busia. By the fourth season, both the BCR and MRR in Busia were favorable and ranged between 1.76-2.36 USD USD^{-1} and 2.47-3.67 USD USD$^{-1,}$ respectively irrespective of the treatments. In Siaya, average cumulative NBs were also significantly lowest for the sole maize crop without urea at the end of the SR2010 season, and significantly highest for the *Desmodium* intercropping systems, especially when the third cutting was done at 18 WAP (5680 USD ha^{-1}, BCR = 3.6 USD USD^{-1}) rather than at 12 or 9 WAP (5053 USD ha^{-1}, BCR = 3.3 USD USD^{-1}) irrespective of *Desmodium* spp. The system with *Desmodium uncinatum* cut at 18 WAP had highest net benefits, and the most favorable BCR and MRR, and was more profitable than the sole maize crop with urea application.



(Source: Author, 2013).

Fig.5.6: Total costs (USD ha^{-1} season^{-1}) across *Desmodium* species, cutting regimes, sole maize systems and seasons in Nyabeda (Siaya) and Matayos (Busia)

Table 5.2: Financial analysis of *Desmodium* intercropping systems with *D. uncinatum* and *D. intortum* subjected to different cutting regimes, relative to a sole maize system with or without urea application over 4 subsequent seasons in Matayos (Busia) and Nyabeda (Siaya).

		LR2009[§]			SR2009			LR2010			SR2010		
		NB	BCR	MRR	NB	BCR	MRR	NB	BCR	MRR	NB	BCR	MRR
Busia													
D. intortum intercrop	9W			-	1172	2.03	2.49	2503	2.48	3.32	2752	2.27	3.17
	12W	124	1.23	-	820	1.71	0.98	2255	2.32	2.55	2438	2.10	2.24
	18W			-	813	1.70	0.93	2279	2.34	2.66	2596	2.19	2.74
D. uncinatum intercrop	9W			-	743	1.66	0.78	2160	2.30	2.62	2464	2.15	2.68
	12W	78	1.15	-	970	1.86	1.74	2609	2.57	3.90	2927	2.36	3.67
	18W			-	521	1.47	-	2114	2.28	2.56	2348	2.11	2.58
sole maize control		264	1.58		563	1.63		1247	1.95		1298	1.76	
sole maize + urea					720	1.71	1.30	1972	2.28	3.18	2123	2.04	2.47
SED1[†]		120	0.24		249	0.25		394	0.27		448	0.22	
SED2[†]					258	0.22		337	0.19		466	0.21	
Siaya													
D. intortum intercrop	9W			-	1821	2.63	-	3744	3.24	0.23	4826	3.23	1.05
	12W	385	1.71	-	2193	2.86	-	4230	3.41	1.27	5440	3.40	1.95
	18W			-	2236	2.93	-	4074	3.38	1.02	5544	3.50	2.33
D. uncinatum intercrop	9W			-	2204	2.96	-	4082	3.44	1.15	5283	3.45	2.07
	12W	574	2.05	-	1932	2.69	-	3586	3.13	-	4664	3.13	0.66
	18W			-	2445	3.15	0.37	4332	3.57	1.78	5816	3.67	3.10
sole maize control		820	2.79		2355	3.64		3660	3.80		4344	3.55	
sole maize + urea					2228	3.21	-	3706	3.41	0.20	4651	3.28	0.91
SED1[†]		119	0.25		354	0.36		528	0.35		615	0.30	
SED2[†]					183	0.15		260	0.14		335	0.15	

Note: Net benefits (NB) and benefit-cost ratios (BCR) are cumulative and discounted at 5 % per season, and marginal rates of return (MRR) are calculated relative to the sole maize control. [†] SED1 and SED2 indicate standard errors of difference for comparison of all treatments (one-way ANOVA) and for the interaction effect of *Desmodium* species and cutting regime in the intercropping systems alone (two-way ANOVA), respectively. [§] During LR2009, *Desmodium* cutting regimes were not yet imposed, and the values given are treatments averages.

5.4 Discussion

Maize grain and stover yield from *Desmodium* intercropping was only higher by 26% compared to sole maize without urea (control) from third season in both sites. This contradicted earlier results that reported higher increase in maize (>50% above control) in PPT (Khan *et al*., 2007; 2007b; 2008a; 2008b), starting from the second season. The present results are attributed to a combination of factors. First, there was a slow establishment of *Desmodium* during the first season, a phenomenon which has been reported in some studies (De Groote *et al*., 2010) and a good establishment was achieved during the second season (SR2009). Secondly, unlike the previous PPT studies, which have used sole maize absolute control (no fertilizer), in this study all treatments including the sole maize control received basal P and in a place like Siaya where P was limiting than N, the N response was delayed in *Desmodium* intercropping. Thirdly, even though frequent trimming of *Desmodium* was carried out, a reduction in maize production could result from the competition in the *Desmodium* intercropping especially under periods of limiting moisture. This notwithstanding, in sites where P is not limiting, inclusion of *Desmodium spp* into maize cropping system would provide a substitute for inorganic N fertilizers to enhance crop growth and yield after *Desmodium* becomes well established. These results corroborate the findings of Vanlauwe *et al*., (2008) in western Kenya who recorded yield increases in PPT relative to a maize-bean intercrop after two seasons.

Although *D. intortum* consistently gave higher biomass compared to *D. uncinatum*, cumulated maize grain and stover yields in the *Desmodium* intercropping system were lower when intercropped with *D. intortum* than with *D. uncinatum*. This can be attributed to the morphological characteristics of the two species whereby *D. intortum* is a large trailing and scrambling plant with a deep tap root while *D. uncinatum* may grow several meters long by trailing over surrounding vegetation and has a large but shallow root system. It is therefore most likely that there was reduced competition for light and nutrients with the latter species, which resulted to enhanced maize growth. Visual observations of the two species' rooting system (after escavating) showed that *D. intortum* had higher numbers of active nodules compared with *D.uncinatum*. Higher N fixation may enable *D. intortum* to produce more biomass, and provide more N to the maize which may partly compensate for the increased competition. Rainfall conditions may also interact with the performance of the system. It was observed that when moisture was not limiting, *Desmodium* regrew faster after cutting, which affects N uptake from mineralized roots and the degree of competition with the maize crop. It is however worthy to note that although this study did not assess the effect of varying *Desmodium* cutting regimes on forage quality, it is most likely that this may influence fodder quality and for crop-livestock farmers, quality would be important.

Production cost was higher in *Desmodium* intercropping compared to sole maize system during the first season due to additional cost of *Desmodium* seeds. Although, production cost in the intercropping system reduced in the subsequent seasons the overall cost remained higher due to the additional labour requirement to maintain and cut *Desmodium*. This is contrary to the observation made by De Groote *et al.*, (2010), who reported reduced overall cost for PPT relative to sole maize with fertilizer in the later seasons which possibly could be attributed to differences in labour costs in the two studies. In this study, it was observed that very careful weeding is required during the first season to allow the slow-growing *Desmodium* to establish while in the subsequent seasons, extra labour is required to remove weeds in the *Desmodium*-maize cropping and to cut the *Desmodium*. Cumulated net benefits in the *Desmodium* intercropping system were higher than in the sole maize system after 4 seasons irrespective of site, *Desmodium* species and cutting regimes. The reported profit not only originated from the increase in maize yield, which occurred only after *Desmodium* was well established, but also from the value of the *Desmodium* fodder, which contributed 20-30 % of the total profit. De Groote *et al*., (2010) and Khan *et al*., (2008a) also reported higher initial establishment cost, followed by economic benefits after establishment of the *Desmodium*-maize intercropping system in western Kenya. The *Desmodium* cutting regime had little effect on the net benefits or costs, which is advantageous to farmers with crop-livestock farming systems as they can cut fodder according to their need. After 3-4 seasons, the *Desmodium* intercropping system resulted in MRR values (>2.5) that were above the critical value of 1.18 (CIMMYT, 1988), hence every additional cost made relative to the sole maize crop is well compensated by an additional net benefit. The MRR was unaffected by *Desmodium* species or cutting regime in Busia. In Siaya, the MRR was highest with *D. uncinatum* cut at 18 WAP. CIMMYT (1988) reported that the MRR for a new technology needs to be at least 50% for a simple adjustment and 100% for acompletely new technology The MRR for *Desmodium* intercropping reported after 4 seasons in this study is far above 100% threshold so it’s most likely that farmers would switch to this technology. The limitation to this is that the reported profit should be taken with caution. This is because first, *Desmodium* is not yet considered a valuable fodder by many farmers in the study area, secondly, livestock still graze freely in open fields and finally, *Desmodium* is currently not widely grown in the study area. It is expected, nevertheless, that as population increases, the demand and value of *Desmodium* fodder will rise, and net benefits will be higher than values reported here. In a scenario where *Desmodium* has no economic value, profitability would remain higher to a sole maize crop without urea due to the improvements in maize grain yield which compensate for the additional labour cost. However, a sole maize crop with urea application would then be more profitable, as it is similar in total cost but results in higher grain yield than *Desmodium* intercropping.

Although there was weak correlations between *Desmodium* biomass with cumulated maize grain and *Striga* reduction, *Desmodium* intercropping system was highly effective in reducing *Striga* plant counts especially during the last season. Varying the time of cutting *Desmodium* did not affect *Striga* plant counts in Busia, whereas in Siaya, *Striga* emergence was lowest when the third *Desmodium* cutting was done at 18 WAP, irrespective of the *Desmodium* species. *Desmodium* spp. control *Striga* by a combination of shading, N addition and an allelopathic mechanism (Khan *et al*., 2002). It was observed that from the second season, both *D. intortum* and *D. uncinatum* reduced *Striga* counts in both sites to similar degrees. Khan *et al*. (2007) also reported similar results and proposed that the two species may demonstrate comparable phytochemical attributes, but this would need to be further investigated. The lower number of *Striga* plant counts in *Desmodium* intercropping system relative to sole maize systems indicates a reduced potential for flowering and capsule production, and consequently a reduced capacity of increasing the seed bank in the soil (Massawe *et al*., 2001), which is crucial for *Striga* control in the long term. The fewer *Striga* counts in sole maize with urea applied compared with control sole maize are similar to other reports that N application controls *Striga* (Khan *et al*., 2002; Showemimo *et al*., 2002).

The impacts of soil fertility levels and rainfall on maize and *Desmodium* yields were clear in all seasons. Results showed that the effect of *Desmodium* intercropping and cutting regime on maize and *Desmodium* yields differed significantly between seasons and sites. Siaya consistently recorded higher maize and *Desmodium* yields. This was likely due to the higher soil fertility as well as higher rainfall in Siaya compared to Busia. Response to urea application in the sole maize crop was significant starting from the second season in Busia, and from the third season in Siaya. The soil in Busia had lower N status than Siaya and continuous maize cropping without N inputs (in sole maize control) resulted to N deficiency more rapidly in the former site. Maize grain and stover yield in the *Desmodium* intercropping systems was only comparable to sole maize with urea from the third or fourth season. *Desmodium* yields were lower in Busia than in Siaya. It is likely that *Desmodium* was not able to fully express its potential in sandy, shallow and stony soils of Busia which had low organic matter content, but established well in the deep clayey soils of Siaya. During the 4^{th} season (SR2010) in Busia, biomass yields were also drastically reduced due to the low rainfall.

5.5 Conclusion

The results showed clearly that when P is not limiting, inclusion of *Desmodium spp* into maize cropping system may provide a substitute for inorganic N fertilizers to enhance crop growth and yield only after *Desmodium* becomes well established. The present study extends the recommendation of the PPT systems to farmers who apply basal P fertilizer as they can increase their soil nitrogen and organic matter levels after *Desmodium* becomes established. Varying the time of cutting the *Desmodium* had little effect on maize yield, but affected *Desmodium* biomass production in Siaya site.

Desmodium intortum consistently gave higher fodder yield compared to *D. uncinatum*, but resulted in lower maize grain yields. *Desmodium* intercropping could be a profitable enterprise for western Kenya in comparison with a sole maize system, but cumulative and discounted net benefits were only superior after 3-4 seasons, and the system requires a higher labour investment, both for establishment and for maintenance during subsequent seasons. Conducting the third *Desmodium* cutting at the end of the season (at 18 WAP) resulted in more effective *Striga* control in Siaya. The use of *D.* uncinatum with the third cutting at 18WAP is recommended but can be modified according to the need for fodder without much effect on maize yield or revenue. A further multi-locational and multi-seasonal evaluation of the PPT would be required to investigate whether the system is also advantageous in terms of yield stability and sustainability.

CHAPTER SIX

6.0 MAIZE GROWTH RESONSE AND PHOSPHORUS AVAILABILITY FOLLOWING BUSUMBU PHOSPHATE ROCK APPLICATION IN A *DESMODIUM*-MAIZE ROTATION SYSTEM

The previous study (Chapter 5) demonstrated that when P is not limiting, inclusion of *Desmodium spp* into maize cropping system would provide a substitute for inorganic N fertilizers to enhance crop growth and yield. However, many studies in western Kenya have shown that widespread phosphorus (P) deficiency limits the growth of cereals and legumes. Indeed, in a preliminary greenhouse trial conducted before the onset of this study, it was clearly shown that *Desmodium* could not establish at all without P additions. This prompted establishment of a P response trial to establish optimal basal P application for *Desmodium* prior to setting of the *Desmodium*-maize rotation trial whose result is presented in this chapter. Most legumes are however able to access sparingly soluble P in the soil and also solubilize insoluble phosphate rock. To determine if *Desmodium* spp like the other legumes can access soil P and increase P solubility from phosphate rock, a *Desmodium*-maize rotation greenhouse experiment was conducted in two phases. In the first phase of the experiment, *Desmodium* and maize were grown separately with and without Busumbu phosphate rock (BPR) while in the second phase of the experiment sole maize was grown with no P application in the same pots. Treatments with soluble P sources were included as reference treatments. Biomass yield and Olsen available P were assessed at the end of each experimental phase. This chapter reports the findings of this greenhouse experiments.

Abstract

Phosphorus (P) is cited as a frequently limiting macronutrient after nitrogen (N) for plant growth in western Kenya. It has been demonstrated that in soils deficient in plant available P, legumes supplied with phosphate rocks (PR), increase P availability and uptake by the succeeding crop. The aim of this study was to assess the extent to which *Desmodium* spp fertilized with Busumbu phosphate rock (BPR) can increase soil available P, P uptake and biomass yield of maize planted after *Desmodium* spp in a greenhouse experiment conducted in two phases. In the same pots, sole maize and two *Desmodium spp*: (*D. intortum* and *D. uncinatum*) with and without BPR were grown separately in the first phase of the experiment followed by sole maize with no P application in the second phase of the experiment. Pots were arranged in a completely randomized design replicated four times. Reference treatments with soluble P (KH_2PO_4) were included. Results showed that in the first phase of the experiment, application of BPR significantly increased above ground dry matter yield (DMY) of *Desmodium* spp but not of maize, suggesting enhanced BPR solubilization in *Desmodium* grown soils. When BPR was not applied, soil available P was higher in soils with *D. intortum* compared to either *D. uncinatum* or sole maize an indication that this legume was efficient in absorbing sparingly soluble P in the rhizosphere. In

the second phase of the experiment, above ground maize DMY, P concentration and available P were higher in maize following *Desmodium spp* compared to maize following maize whether BPR had been applied or not. *D. intortum* previously fertilized with BPR gave the highest and significant above ground maize DMY (6.05 g container^{-1}) and P concentration (16.15 g P container^{-1}). This study demonstrated that *Desmodium spp* receiving BPR enhances yield and P availability of the following maize crop compared to sole maize systems.

6.1 Introduction

Phosphorus (P) is one of the miner alnutrients for plant growth. It is an integral part of the cellular activities of living organisms. It has defined roles in plant metabolisms such as cell division, development, photosynthesis, breakdown of sugars, nutrient transport within the plant, transfer of genetic characteristics from one generation to another and regulation of metabolic pathways (Aerts and Chapin, 2000; Armstrong, 1988; Theodorou and Plaxton, 1983). Phosphorus is frequently a limiting macronutrient for plant growth (Schachtman *et al.*, 1998). Although P deficiency is widespread in east Africa, it is most severe in the intensively cultivated highlands of western Kenya. About 80% of the smallholder land used for maize production in this region is deficient in available soil P (Jama and van Straaten, 2006). Responses of maize to P are significant even at rates as low as 10 kg P ha^{-1} (Jama *et al.*, 1997) indicating the importance of adding P to soils in this region.

Inorganic P fertilizers are often not within economic reach of smallholder farmers, and therefore, alternative strategies are needed to improve P nutrition of crops (Pypers *et al.*, 2007). Use of rock phosphate as a source of P fertilizer is worthwhile in tropical acidic soils because many rock phosphate deposits exist in the region with conducive environmental conditions that favor their use (Abd-Elmonem and Amberger, 2000; Chein *et al.*, 1996). However, due to their low solubility and slow P release, they are rarely used as a direct P input (Pypers *et al*., 2007; Stamford *et al*., 2005). Use of BPR from eastern Uganda, particularly in western Kenya is limited because it is not available in the market and alternatively Minjingu phosphate rock (MPR) has vastly been promoted in this region (Kifuko *et al*., 2007; Ndungu *et.al*., 2006). Although BPR (neutral ammonium solubility (NAS) of 2.3%) is of lesser reactivity than MPR, its close proximity to western Kenya (< than 20 km away) compared with MPR (>820 km away) makes it attractive in this region (van Straaten, 2002). Therefore, to overcome P deficiencies in western Kenya soils, there is need to exploit ways that can avail sparingly soluble P in the soils and at the same time enhance solubility of existing PRs.

Microbial acidification of phosphate rocks, in leguminous cropping systems could be used to enhance P solubility from PRs (Ndung'u-Magiroi *et al.,* 2011; Salimpour *et al.*, 2010, Vessey, 2003, Vanlauwe *et al*., 2000). Some legumes have been reported to chemically alter P speciation in the rhizosphere and mobilize sparingly soluble P (Pypers *et al*., 2006a, b; Braun and Helmke, 1995). The main mechanisms resulting in enhanced PR utilization are acidification of the rhizosphere (Pypers *et al*., 2007; Hinsinger and Gilkes, 1997; Bekele *et al*., 1983) through exudation of organic acids (Hoffland, 1992). It is speculated that in this way, legumes are able to convert PR into a more available P source without altering soil pH to levels that may negatively affect plant growth (Pypers *et al*., 2007). A cereal crop following the legume can then benefit directly from the enhanced P availability in the soil and acquire P released from the decomposing legume residues (Pypers *et al*., 2007; Horst *et al*., 2001). In addition, legume crops with extensive deep rooting have been known to increase phosphorus (P) pools in the cropping system because of their ability to access sparingly soluble P sources in deeper horizons (Nuruzzaman *et al*., 2005). Vanlauwe *et al*., (2000) have shown that the utilization efficiency of PR can be improved by using legume-maize rotation systems.

Desmodium spp have become increasingly popular in western Kenya mainly due to its *Striga* and stemborer suppressing capacity, in the context of the "push- pull" system (Khan *et al*., 2008a, 2002). In addition, *Desmodium* spp *is* able to biologically fix substantial amounts of atmospheric N_2 and is known to improve soil fertility (Whitney *et al.*, 1967). Despite the widely reported role of *Desmodium* in control of *Striga* and stemborer, it remains unclear to what extent a *Desmodium* crop supplied with PR would directly improve P availability and plant growth when grown in rotation with maize. The need to understand this concern prompted the research presented in this chapter. Pot experiments were conducted to i) determine optimal P rate for maize production (ii) compare the growth, available P and P concentration of two *Desmodium* spp with that of sole maize in a soil treated with BPR and (iii) determine whether the influence of *Desmodium* on subsequent growth and P concentration in maize was due to the effect of P solubilization and hence availability by *Desmodium*.

6.2 Materials and methods

6.2.1 Soil collection and characterization

Greenhouse experiments were conducted in Soil Science Department, University of Eldoret. Bulk soil was obtained from a site in Matayos, Busia County (0° 26.1' N, 34° 52.2' E, 1182 m above sea level) at a plough depth of 0-20 cm. A soil sample was taken from the bulk soil for the initial soil characterization analysis according to procedures outlined by Okalebo *et al*., (2002). The remaining bulk soil was air dried and passed through a 5 mm sieve to remove clods and debris. Soil characteristics are described in section 4.3.1. The sieved soil was weighed (2 kg for the P response trial and 4.5 kg for P solubilization trial) into each pot. To eliminate deficiency of other macro and micronutrients, all pots received a blanket application of nutrients in solution containing $CaCl_2.2H_2O$, $MgCl_2.6H_2O$, $MgSO_4.7H_2O$, $ZnSO_4.7H_2O$, $CuSO_4.5H_20$, $MnSO_4.4H_2O$ and H_3BO_3 salts. The optimal nutrients doses were calculated based on an average of maximum and minimum tissue concentration of the respective nutrients in maize crop and biomass production of 15 g for 2kg $soil^{-1}$ and 30 g for 4.5kg $soil^{-1}$ for P response and P solubilization trials, respectively.

6.2.2 Experimental design

(a) P response trial

From a preliminary greenhouse study, it was found that when P application was not done, *Desmodium* seeds germinated but eventually dried up before reaching a height of 2 cm. This was attributed to low soil P which might have caused poor root development given that *Desmodium* is a small seed with very little nutrient reserve. Phosphorus is very important for root development producing a large effective root system which exploits the soil volume for nutrients and anchorage (Marshner, 1995). The aim of this experiment was therefore to determine maize response to different rates of soluble P in order to establish optimal basal P rate for the *Desmodium*-maize rotation experiment. Six treatments were tested in the P response experiment which included soluble P (SP) in the form of KH_2PO_4 salt applied at the rates of 0, 20, 40, 80, 160, 320 mgP kg^{-1} in a completely randomized design. Sole maize (Kenya Seed

Company, H513) was used as a test crop planted at a rate of 3 seeds per pot and thinned to 1 seedling per pot one week after germination.

b) *Desmodium*-maize rotation experiment

This experiment compared *Desmodium* –maize rotation system with continuous maize mono cropping system. Th*e* objectives of this experiment were: i) to compare the growth and P concentration of two *Desmodium* spp with that of sole maize in a soil treated with BPR and (ii) to determine whether the influence of *Desmodium* on subsequent growth of maize and P concentration in maize was due to the effect of enhanced P availability from BPR. To achieve the above objectives, this experiment was conducted in two phases. In the first phase, *Desmodium* and maize were planted separetely in pots fertilized with BPR and reference treatments with soluble P (SP) applied in form of KH_2PO_4 salt were included. The second phase was a continuation of the first phase in which after harvesting maize and *Desmodium* biomass in the first phase, maize was planted in the same pots and reference treatments with soluble P included. In the first phase, the experimental treatments were fifteen in total (Table 6.1). The first six treatments (T1-T6) had a factorial structure with two factors namely; first crop (sole maize, *D. uncinatum, D. intortum*) and BPR application which were arranged in a completely randomized design replicated four times. This was followed by sole maize with no P applied in the second phase of the experiment. The remaining nine treatments (T7-T15) in the first phase were reference *Desmodium*-maize systems with two factors: first crop (sole maize, *D uncinatum, D. intortum*) and P application (without P, with BPR and SP) followed by SP applied as KH_2PO_4 to sole maize in the second phase of the experiment.

Table 6.1: Treatment structure for comparing *Desmodium*-maize rotation system and sole maize cropping system as affected by BPR application.

No	Treatments	Crop 1	Supplied with	Crop 2	Supplied with
T1	Maize(0P)/maize(0P)	maize	-	maize	-
T2	Maize (BPR)/maize (0P)	maize	BPR	maize	-
T3	*D. uncinatum* (0P)/maize (0P)	*D. uncinatum*	-	maize	-
T4	*D. uncinatum* (BPR)/maize (0P)	*D. uncinatum*	BPR	maize	-
T5	*D. intortum* (0P)/maize (0P)	*D. intortum*	-	maize	-
T6	*D. intortum* (BPR)/maize (0P)	*D. intortum*	BPR	maize	-
T7	Maize(0P)/maize(SP)	maize	-	maize	SP
T8	Maize (BPR)/maize (SP)	maize	BPR	maize	SP
T9	Maize (SP)/maize (SP)	maize	SP	maize	SP
T10	*D. uncinatum* (0P)/maize (SP)	*D. uncinatum*	-	maize	SP
T11	*D. uncinatum* (BPR)/maize (SP)	*D. uncinatum*	BPR	maize	SP
T12	*D. uncinatum* (SP)/maize (SP)	*D. uncinatum*	SP	maize	SP
T13	*D. intortum* (0P)/maize (SP)	*D. intortum*	-	maize	SP
T14	*D. intortum* (BPR)/maize (SP)	*D. intortum*	BPR	maize	SP
T15	*D. intortum* (SP)/maize (SP)	*D. intortum*	SP	maize	SP

Note*: SP- Soluble Phosphorus, BPR- Busumbu phosphate rock*

Basal P application was based on the optimal P obtained in the P response experiment which was observed to be 120 mg P kg^{-1} soil applied as KH_2PO_4. In the first six treatments (T1-T6) additional P was applied as BPR (500 mg P kg^{-1} soil) while in the reference treatments with soluble P, additional P was applied at 250 mg P kg^{-1} as KH_2PO_4 during the first phase of the experiment. In the second phase of the experiment, soluble P was applied to reference treatments only at a rate of 250 mgP kg^{-1} soil as KH_2PO_4. The pots of the various treatments and their replication were arranged in a completely randomized design with daily rotations to reduce local bench effects. Due to the earlier recorded poor *Desmodium* seeds germination rate, thirty *Desmodium* seeds were planted and later thinned to the required population of 12 seedlings per pot. In the maize treatments, three maize seeds (Kenya Seed Company, H513) per pot were planted three weeks after planting *Desmodium* and later thinned to 1 seedling per pot. Kenya Seed Company, H513 maize seed was selected because it is a short duration maturing crop which is widely grown in western Kenya (Kenya Seed Company). Before planting, the water holding capacity of the soil was determined by adding water to a known weight of soil, allowing the soil to drain freely for 48 hours and determining the retained water (i.e. 100% water holding capacity). Before and immediately after germination, pots were watered at 70% water holding capacity followed by 80% and finally 90% at maturity using N free water. The pots were manually maintained weed free and pest free by application of appropriate insecticides. Arrangement of the pots in the greenhouse appeared as shown in Plate 6.1.

(Source: Author, 2013).

Plate 6.1: Pots arrangement in the greenhouse during the first phase of the experiment

6.2.3 Sampling and laboratory analysis

Maize shoots were harvested at 6 weeks after planting (WAP) in the P response experiment while in the *Desmodium*-maize rotation experiment, *Desmodium* biomass and maize shoots were harvested at 10 and 7 WAP, respectively and soil sampled for analysis of the soil available P (Olsen method). For both experiments, biomass was put in a well labeled paper bag and fresh weight recorded. The samples were oven at 65 ^oC and ground for analysis of total P (Okalebo *et al*., 2002). At the end of the second experiment, maize plants were harvested at 7 WAP and soil and plant tissue taken. Average relative dry matter yield was computed as shown below:

$$RDM = \left(\frac{DMY_{treatment}}{DMY_{\max imum}} \right) x100 \ldots\ldots\ldots\ldots\ldots\ldots \textit{Equation 6.1}$$

Where: **RDM**- Relative dry matter yield
DMY- Dry matter yield
Maximum DMY- The highest yield obtained with soluble P sources

6.2.4 Statistical analysis

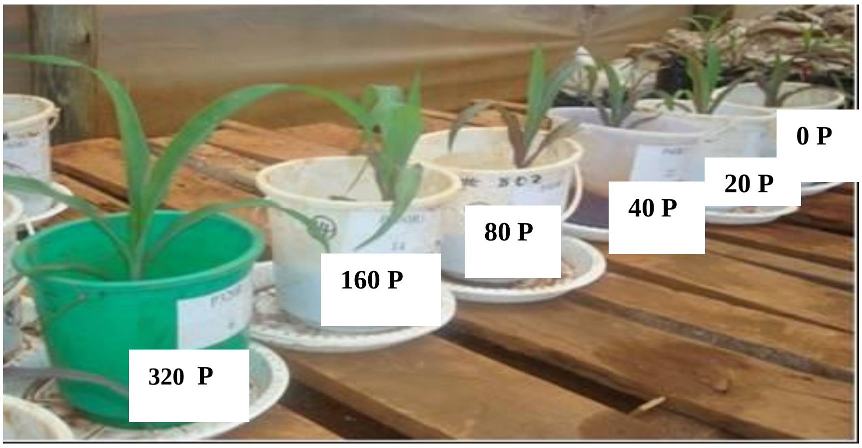
A one-way analysis of variance (ANOVA) was conducted to evaluate differences between all the treatments as well as a two-way ANOVA for evaluating interactions between *Desmodium* spp and BPR rates using mixed procedure (SAS Institute Inc., 2003). Treatment differences were evaluated by computing least square means and the standard errors of difference (SED), referred to as SED1 and SED2 for the one-way and two-way ANOVA respectively.

6.3 Results

6.3.1 Maize DMY response to soluble P application in the P resonse trial

Average dry matter yield (DMY) ranged from 1.46 to 14.27 g container^{-1} whereaas the relative dry matter (RDM) yield ranged from 10.23 to 65.39 % (Table 6.2).

Application of P at a rate between 20 and 80 mgP kg^{-1} gave comparable DMY with control and only P applied at 160 and 320 mg P kg^{-1} eliminated P deficiency (Plate 6.2) and significantly ($p<0.05$) increased DMY by 84 and 90 %, respectively above the control treatment.



(Source: Author, 2013)..

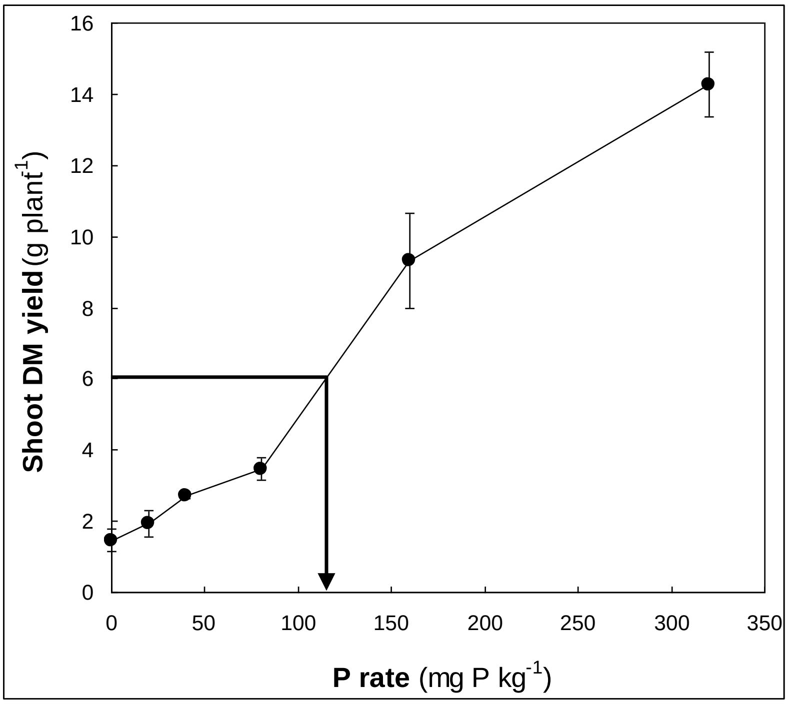
Plate 6.2: Maize growth response to soluble P application (0, 20, 40, 80, 160 and 320 mg P kg^{-1} soil from right to left).

Table 6.2: Dry matter yield (g/pot) and relative yield from different P rates

Phosphorus application rates (mg P kg^{-1} soil)	**Dry matter yield (g container^{-1})**	**Relative yield (%)**
0	1.46	10.23
20	1.94	13.62
40	2.72	19.07
80	3.46	24.24
160	9.33	65.39
320	14.27	100
SED	**0.989**	

Note: SED- *standard error of the difference*

Optimal yield was attained at a P rate of 120 mgP kg^{-1} soil (Fig 6.1). This is a rate that gives at least 50% yield increase above the control and eliminates P deficiency, a rate below which maize production is not considered beneficial (Njoroge, 2010).



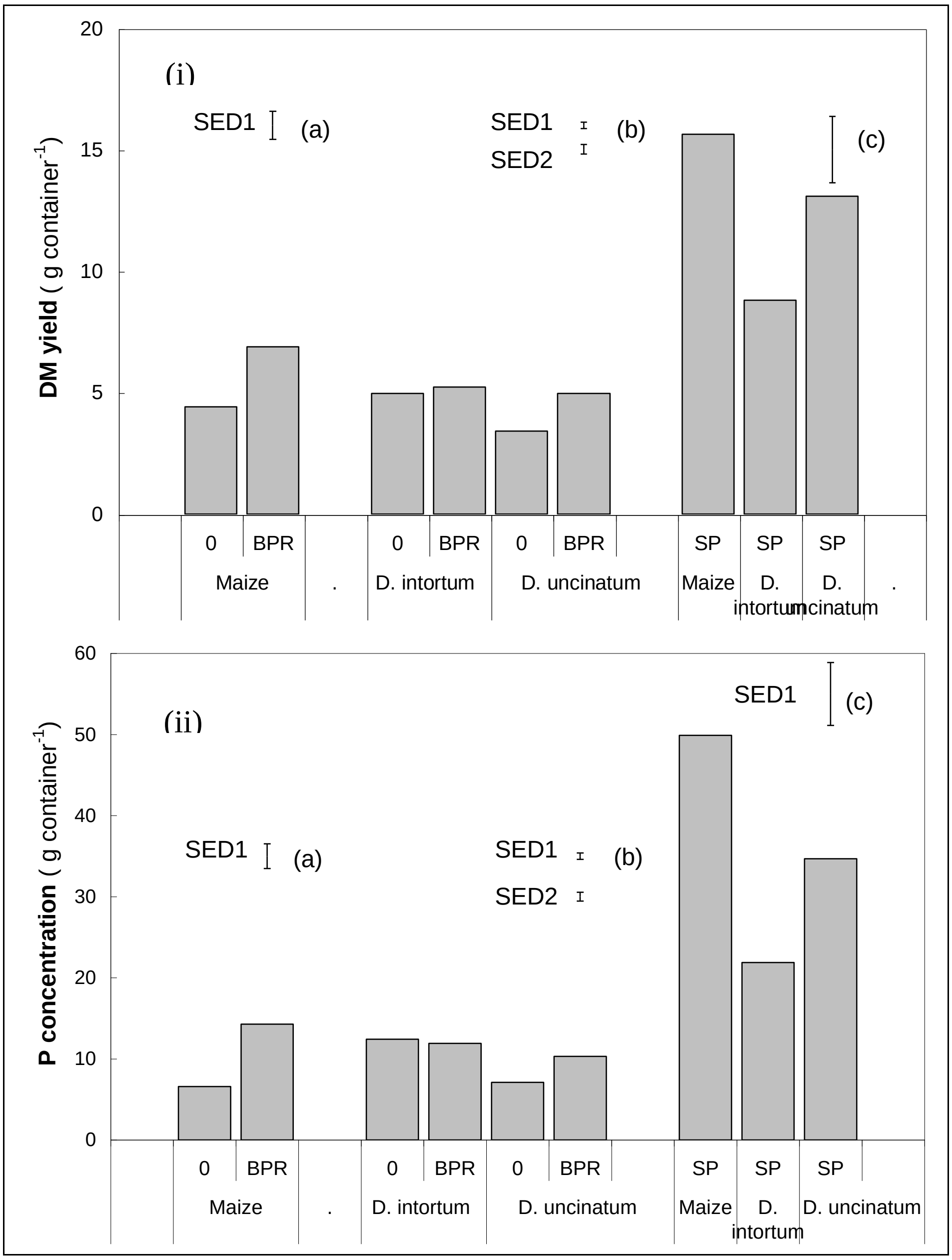
(Source: Author, 2013)

Fig 6.1: Maize yield response to different soluble P rates showing the optimal P rate (Source: Author, 2013).

6.3.2 Above ground maize DMY and P concentration in maize and *Desmodium* as affected by BPR application in *Desmodium*-maize rotation experiment (First phase).

In the first phase of the experiment, application of BPR to *D. uncinatum* significantly ($p<0.05$) increased DMY by 1.55 g $container^{-1}$ above DMY of *D. uncinatum* with no P application (Fig 6.2). The DMY of *D. intortum* with or without BPR application were similar (Fig 6.2). The DMY of *D. intortum* was significantly higher than *D. uncinatum* with or without BPR application. Application of BPR to *D. intortum* and *D. uncinatum* achieved 59 and 38 % respectively of the maximum yield observed when the two *Desmodium* spp were fertilized with soluble P (Table 6.3).

Phosphorus concentration in sole maize and *Desmodium* cropping systems were comparable with or without BPR application (Fig 6.2). Phosphorus concentration in *D. intortum* was significantly ($p<0.05$) higher by 3.46 g P container^{-1} compared to concentration in *D. uncinatum* with or without BPR application. Significant interaction ($p<0.05$) effect between *Desmodium spp* and BPR on P concentration was observed but only *D. uncinatum* grown with BPR significantly ($p<0.05$) increased P concentration above *D. uncinatum* with no P applied.



(Source: Author, 2013)

Fig 6.2: Biomass yields (i) and P concentration (ii) of maize and two *Desmodium* spp as affected by BPR applications in the first phase of the experiment[9]

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[9] *SED1 and SED2 -standard errors of difference for comparison of treatments (one-way ANOVA) and for the interaction effect between Desmodium species and BPR (two-way ANOVA), respectively (a) represent SED for comparisons of sole maize system (b) represent SED for comparisons of Desmodium system (c) represent SED for comparisons of all the 9 treatments*.

Table 6.3: Relative yield increase to soluble P fertilizer of maize and two *Desmodium* supplied with BPR in *Desmodium* maize rotation (First phase).

Crop	**P Source**	**Yield (g container^{-1})**	**Relative yield (%)**
Maize	0	4.15	28.23
	BPR	6.87	43.92
	SP	15.64	100
D. intortum	0	4.96	56.42
	BPR	5.22	59.38
	SP	8.78	100
D. uncinatum	0	3.42	26.12
	BPR	4.96	37.97
	SP	13.08	100

***Note**: SP- Soluble phosphorus, BPR- Busumbu phosphate rock*

6.3.3 Soil available P following application of BPR to maize and *Desmodium* in *Desmodium*-maize rotation experiment (first phase)

During the first phase of the experiment, application of BPR had no significant effect on soil available P in sole maize system (Table 6.4). Significantly ($p<0.05$) higher amount of available P was obtained when the two *Desmodium spp* did not receive BPR compared to when BPR was added. *D. intortum* with no BPR applied significantly increased available P by 26.59 mg P container^{-1} above *D. intortum* with BPR applied. Increase in available P in the soil did not result to corresponding increase in plant P concentation.

Table 6.4: Available P (mgP kg^{-1} soil) from maize and two *Desmodium* spp as affected by BPR applications (first phase).

Crop	**P source**	**Available P (mgP kg^{-1})**
Maize	control (no BPR)	20.30
	BPR	20.61
Mean		**20.45**
SED1 (a)		**1.386**
D. intortum	control (no BPR)	45.20
	BPR	18.62
D. uncinatum	control (no BPR)	38.98
	BPR	30.46
Mean		**33.32**
SED1 (b)		**6.716**
SED 2 (b)		**6.716**
Maize	SP	65.74
D. intortum	SP	75.38
D. uncinatum	SP	70.98
Mean		**70.7**
SED1 (c)		**5.982**

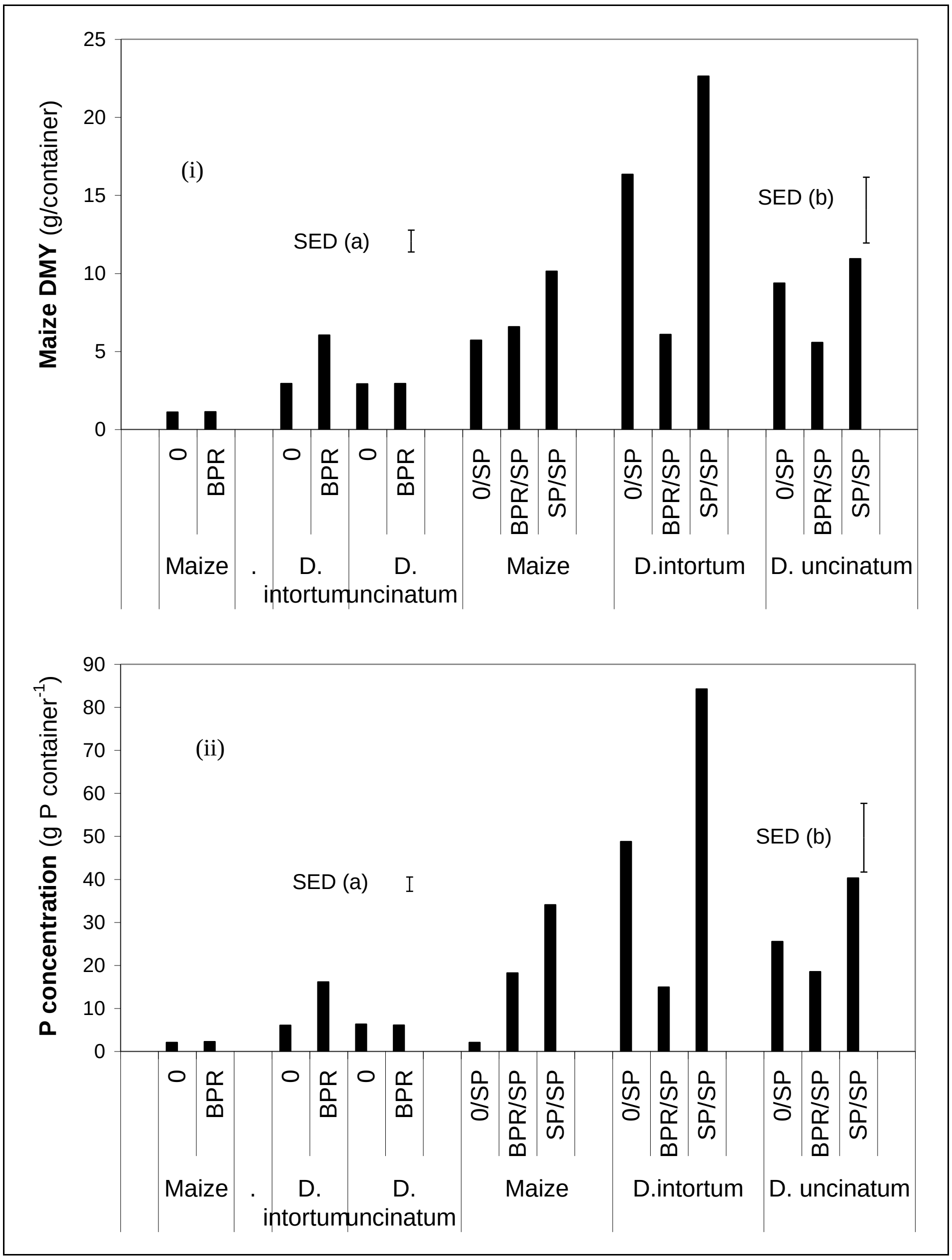
Note: *SED1 and SED2 -standard errors of difference for comparison of treatments (one-way ANOVA) and for the interaction effect between Desmodium species and BPR (two-way ANOVA), respectively (a) represent SED for comparisons of sole maize system (b) represent SED for comparisons of Desmodium system (c) represent SED for comparisons of all the 9 treatments.*

6.3.4 Maize DMY as affected by previous cropping system (maize or *Desmodium*) and BPR application in *Desmodium*-maize rotation experiment (second phase).

The average maize DMY following *Desmodium* (3.71 g container^{-1}) was more than twice as large compared to maize following a first maize crop (1.12 g container^{-1}) (Fig 6.3.). This significant positive effect of previous *Desmodium* growth on the second phase maize DMY occurred with or without BPR application. Significant ($p<0.05$)

interaction effect was observed but only *D. intortum* previously fertilized with BPR improved maize vigor (Plate 6.3) and significantly ($p<0.05$) increased maize DMY in the second phase of the experiment by 3.12 g pot $^{-1}$ above *D. intortum* previously not receiving BPR. *D. intortum* previously with BPR achieved 49 and 46% of the maximum yield observed in the reference treatment previously without and with BPR additions but followed by application of soluble P in the second phase of the experiment respectively (Table 6.5.). In the second phase of the experiment however, maize DMY from *D. uncinatum* previously with or without BPR addition and followed by no P application were similar.

Phosphorus concentration in maize following *Desmodium* was more than three times as large compared to maize following first maize with or without BPR application (Fig 6.3). The previous cropping system and BPR application in isolation had no significant effect on P concentration but a significant increase in P concentration occurred in the combined treatment. *Desmodium intortum* previously fertilized with BPR and followed by no P application significantly increased maize P concentration in the second phase of the experiment above unfertilized *D. intortum*.



(Source: Author, 2013).

Fig 6.3: Maize DMY (i) and maize P concentration (ii) as affected by the previous cropping system (maize, *D. intortum* and *D. uncinatum*) and BPR application[10]

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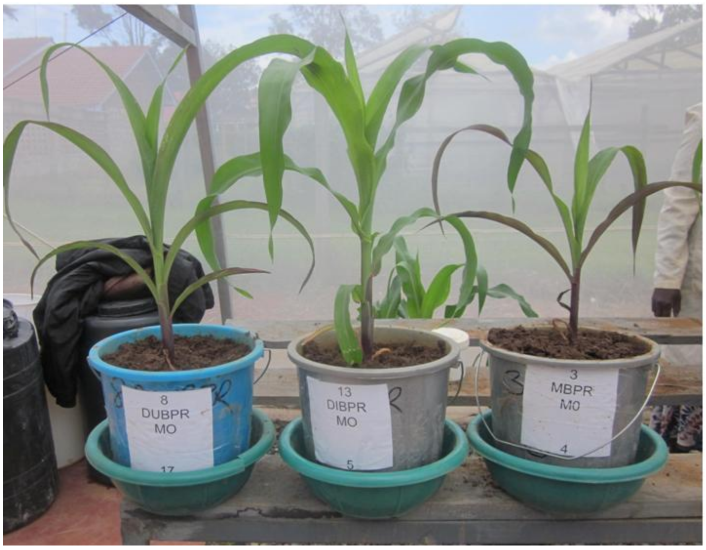
[10] *Additional treatments (see Table 6.1) include reference treatments with previous crop (maize, D. intortum and D. uncinatum) with no P, BPR, or soluble P applied followed by second crop (maize) with soluble P applied. (a) represent SED for comparisons of the first six treatments while (b) represent SED for comparisons of all the 15 treatments.*



(Source: Author, 2013)

Plate 6.3: Improved maize vigor in maize following two Desmodium species previously fertilized with BPR.[11]

Table 6.5: Relative maize DMY increase to soluble P application as affected by previous BPR applications on on *Desmodium* and maize cropping systems (second phase).

	1st crop	2nd crop	Yield (g/container)	Relative yield (%)
Maize	BPR	0	18.84	
Ref 1	0	SP	52.9	35.62
Ref 2	BPR	SP	58.15	32.4
Ref 3	SP	SP	87.05	21.64
D. intortum	BPR	0	19.2	
Ref 1	0	SP	39.15	49.03
Ref 2	BPR	SP	41.86	45.86
Ref 3	SP	SP	72.56	26.45
D. uncinatum	BPR	0	20.15	
Ref 1	0	SP	45.39	44.39
Ref 2	BPR	SP	43.07	46.78
Ref 3	SP	SP	74.87	26.91

Note SP- Soluble phosphorus, BPR- Busumbu phosphate rock, Ref- reference treatment

[11] *From left DU- D. uncinatum, DI- D. intortum previously supplied with BPR followed by sole maize with no P (DUBPRMO, DIBPRMO) compared to stunted maize in maize previously supplied with BPR and followed by maize with no P (MBPRMO).*

6.3.5 Soil available P as affected by previous cropping system (*Desmodium* or maize) and BPR application (Second phase)

Generally, after the harvest of the second crop in the second phase of *Desmodium*-maize rotation experiment, the soil available P was lower compared to the harvest of the first crop irrespective of the previous *Desmodium spp* and BPR application. Available P in soils with maize following *Desmodium* system and sole maize following sole maize system were comparable (Table 6.6). This contradicted the larger dry matter yield and P concentration in maize following *Desmodium* crop and therefore this increase was not explained by soil available P. In fact negative correlation coefficient between available P and P concentration (r= -0.55), available P and yield (r= -0.57) were observed in the second phase of the experiment in maize following *Desmodium* with or without BPR application.

Table 6.6: Available P as affected by the previous cropping system (maize, *D. intortum* and *D. uncinatum*) and BPR application.

Crop	P source 1st crop	P source 2nd crop	Available P (mgP kg^{-1})
Maize	control (no BPR)	no P	16.21
	BPR	no P	18.84
D. intortum	control (no BPR)	no P	22.32
	BPR	no P	19.20
D. uncinatum	control (no BPR)	no P	27.03
	BPR	no P	20.15
Mean			**20.62**
SED1 (a)			**5.373**
Maize	control (no BPR)	Soluble P	52.90
	BPR	Soluble P	58.16
	Soluble P	Soluble P	87.06
D.intortum	control (no BPR)	Soluble P	39.15
	BPR	Soluble P	41.86
	Soluble P	Soluble P	72.57
D. uncinatum	control (no BPR)	Soluble P	45.39
	BPR	Soluble P	43.07
	Soluble P	Soluble P	74.87
Mean			**53.56**
SED1(b)			**8.78**

Note: *SED1- Standard error of difference for comparison of treatments (one way ANOVA) .(a) represent SED for comparisons of the first six treatments while (b) represent SED for comparison of all the 15 treatments. Additional treatments (see Table 6.1) include reference treatments with previous crop (maize, D. intortum and D. uncinatum) with no P, BPR, or soluble P applied followed by second crop (maize) with soluble P applied.*

6.4 Discussion

The P response greenhouse experiment demonstrated that maize DMY responded significantly to application of soluble P fertilizer. Significant maize response to P rates as low as 10 kg P ha^{-1} has been reported in western Kenya (Jama *et al.*, 1997). The optimum P rate for maize production obtained in this study was 120 mg P kg^{-1} (32.4 kg P ha^{-1}), a rate below which maize production is not beneficial. However, if resources are not limiting, application rate can be raised above 320 mg kg $^{-1}$ (86.4 kg P ha^{-1}) soil which also gave a significant yield increase above the control for maximum maize production. This corroborates earlier greenhouse work by Njoroge (2010) who reported that applying P at a rate between 108 - 215 mg P kg^{-1} soil in Busia soils increased maize DMY above the control, eliminated P deficiency symptoms and gave reasonable yields (50% increase above the control). In addition, Njoroge (2010) also reported significant yield increase above control in treatments with P applied up to 432 mg P kg^{-1} although the response did not differ significantly with P applied at 647 mg P kg^{-1}.

Application of BPR significantly increased DMY of *D. uncinatum* but had no impact on sole maize, demonstrating the ability of this forage legume to enhance P availability and uptake from BPR compared to sole maize. However, during the first phase of this experiment, higher amount of available P was obtained when the two *Desmodium spp* did not receive BPR compared to when BPR was added and this was more pronounced in soils where *D. intortum* had earlier been grown. This was possibly an indication that although the two species were able to access sparingly soluble soil P sources, *D. intortum* was more efficient. This observation could be attributed to differences in morphological characteristics of the two *Desmodium* spp, whereby *D. intortum* has an extensive, deep and fine rooting system compared to *D. uncinatum* (Imrie *et al*., 1983). Legume crops with extensive deep rooting system increase phosphorus (P) pools in the cropping system because of their ability to access sparingly soluble P sources (Hinsinger, 2001). Low levels of available P in BPR treated soils is because BPR is solubilized very slowly and most of it is fixed in acidic soils which results in P becoming unavailable (Jama *et al*., 1997). The neutral ammonium solubility (NAS) of BPR is relatively low (2.3%) compared to MPR which has a NAS of 5.6% which is reactive (van Kauwenberg, 1991).

In the second phase of *Desmodium*-maize rotation experiment, improved maize vigor maize yield and P concentration in treatments where previously *Desmodium* had been grown irrespective of BPR application compared to sole maize demonstrates that growing legume in a rotation enhances the growth and plant P uptake in the subsequent crop. The increase in maize DMY was however not explained by increase in soil available P and indeed there was a negative and significant correlation coefficient between maize DMY with available P in soils with maize following *Desmodium* crop. It is possible that most of the P that was made available was used by the growing maize crop which resulted to reduced levels of soil available P. Pypers *et al*., (2007) reported similar results while working with velvet bean, and concluded that, in addition to P there was possibly another limiting factor which was offset by the growth of legume.

Comparisons of the two *Desmodium* spp showed that in pots where previously *D. intortum* had received BPR, yield and P concentration were superior compared to pots where previously BPR had been added to *D. uncinatum*, suggesting that *D. intortum* was a more potent solubilizer of BPR. *D. intortum* is a higher yielder and has higher biological nitrogen fixing potential compared to *D. uncinatum*. This study demonstrated enhanced N mineralization in maize intercropping system with *D. intortum* compared to *D. uncinatum* with high amounts of NH_4^+ in the former. NH_4^+ ions are associated with increased P availability within the rhizosphere as they tend to lower the rhizosphere pH of the roots; hence P is brought to solution (Abd-Alla, 1994). Abd-Alla (1994) assessed the ability of *Rhizobium* and *Bradyrhizobium* strains to solubilize phosphate from hydroxyapatite in a medium containing NH_4Cl or KNO_3

and concluded that the presence of NH_4^+ in the medium resulted in higher solubilization of phosphate compared to the presence of NO_3^-. Several authors have however shown that legumes are able to increase the dissolution and utilization of PR P and reduce P sorption because of their acidifying effect on the rhizosphere (Pypers *et al.*, 2007, Melenaghen *et al*., 2004; Horst *et al*., 2001; Vanlauwe *et al*., 2000).

6.5 Conclusion

Maize DMY responded significantly to application of soluble fertilizer, signifying that P is a limiting nutrient to crop production and P addition is a prerequisite in western Kenya. In the first phase of *Desmodium*-maize rotation experiment, soil available P levels were generally low in soils treated with BPR. In the second phase of the *Desmodium*-maize rotation experiment, improved maize yield and maize P concentration in soils where *Desmodium* had previously been grown relative to continuous maize cropping demonstrates that growing *Desmodium* in a rotation enhances the growth and plant P uptake in the subsequent crop. Comparison of the two *Desmodium spp* showed that *D. intortum* was efficient in accessing sparingly soluble P in the soil and is a more potent solubilizer of BPR compared to *D. uncinatum*.

CHAPTER SEVEN

7.0 GENERAL CONCLUSIONS AND RECOMMENDATIONS

1) The field experiments were conducted on a Humic Acrisols of Siaya which had slightly higher amounts of nitrogen, carbon, clay and CEC compared to Orthic Ferralsols of Busia which showed slightly higher amount of available P.
2) *Desmodium intortum* consistently gave higher biomass, fixed N, soil carbon, and soil mineral N compared to *D. uncinatum*. The highest N fixed occurred during LR2010 when moisture was not limiting and when cutting of *Desmodium* was conducted at either 12 or 18WAP compared to 9WAP.
3) Maize shoot $\delta^{13}C$ contents of sole maize system and maize intercropped with *Desmodium* spp did not differ significantly, but decreased as growth progressed.
4) *Desmodium intortum* consistently gave higher fodder yield compared to *D. uncinatum*, but resulted in lower maize grain yields. Increase in maize yield and net benefits in *Desmodium* intercropping above sole maize system were only realized after 3- 4 seasons when *Desmodium* became well established.
5) *Desmodium* cutting regime had little impact on maize yields and net benefits but affected *Desmodium* biomass production in Siaya site. The use of *D.* uncinatum with the third cutting at 18WAP is recommended but can be modified according to the need for fodder without much effect on maize yield or revenue.
6) *Desmodium intortum* and *D. uncinatum* equally reduced *Striga* counts in both sites. Varying the time of cutting *Desmodium* did not affect *Striga* plant counts

in Busia, whereas in Siaya, *Striga* emergence was lowest when the third *Desmodium* cutting was done at 18 WAP, irrespective of the *Desmodium* species.

7) Growing *Desmodium* in a rotation with maize enhanced maize growth and P uptake. *Desmodium intortum* was efficient in accessing sparingly soluble P in the soil and was a more potent solubilizer of BPR compared to *D. uncinatum*.

8) The field and greenhouse experiments demonstrated that inclusion of *Desmodium* into maize cropping system is a viable option for replenishing soil fertility, enhancing productivity and diversification of small-holder farmers who largely depend on limited land resources. There is howerver need to conduct a further multi-locational and multi-seasonal evaluation of the PPT to investigate whether the system is also advantageous in terms of yield stability and sustainability across different soil types.

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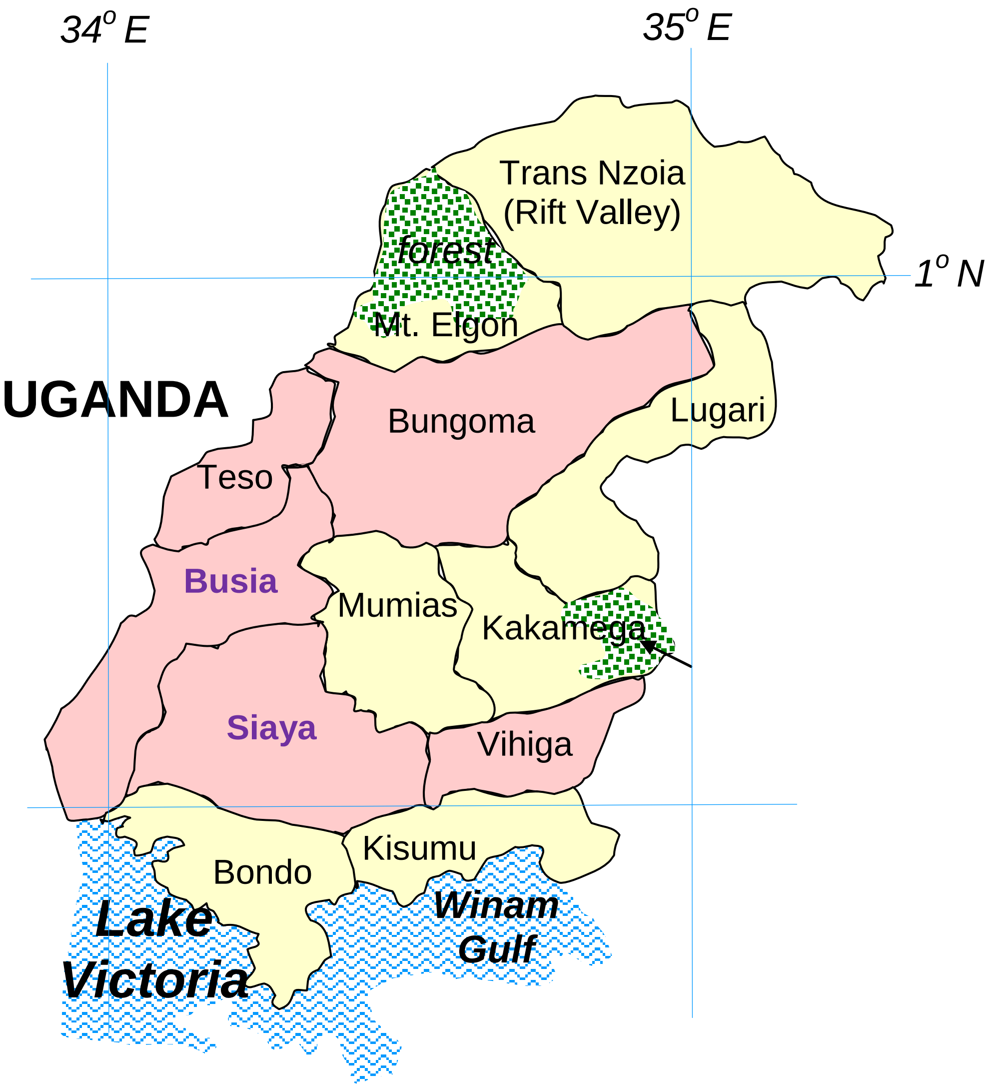
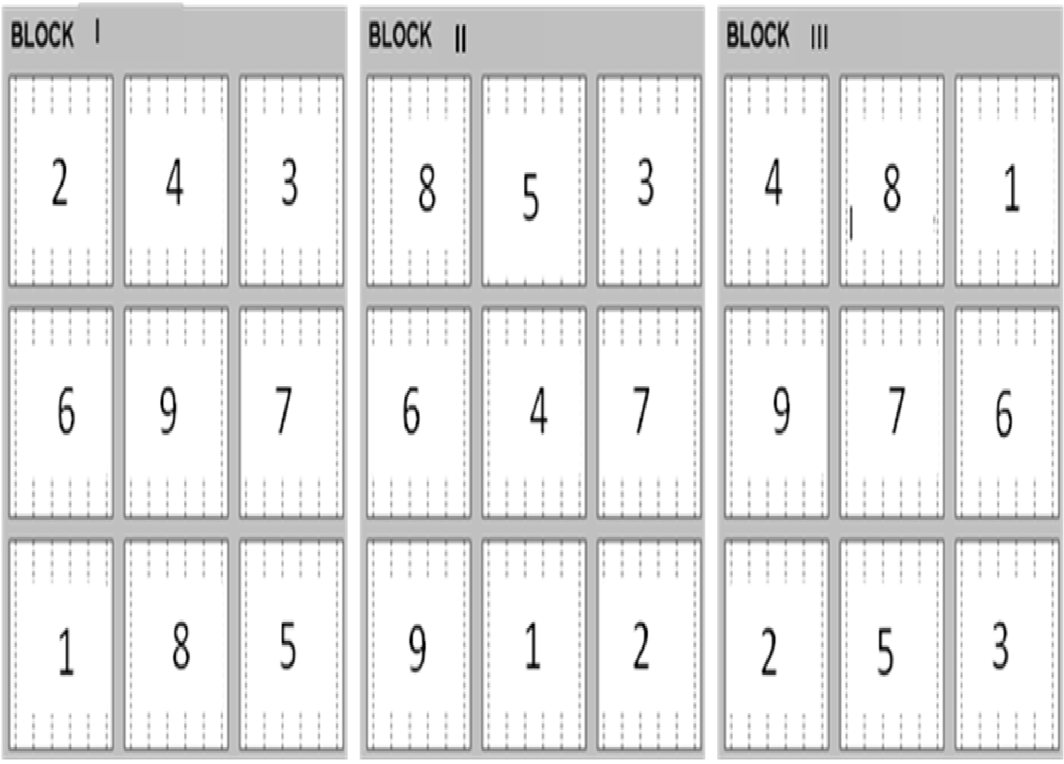
APPENDICES

Appendix 1: Study sites (Busia and Siaya in purple color)



(Source: Author, 2013)

Appendix 2: Experintal layout in Matayos (Busia).

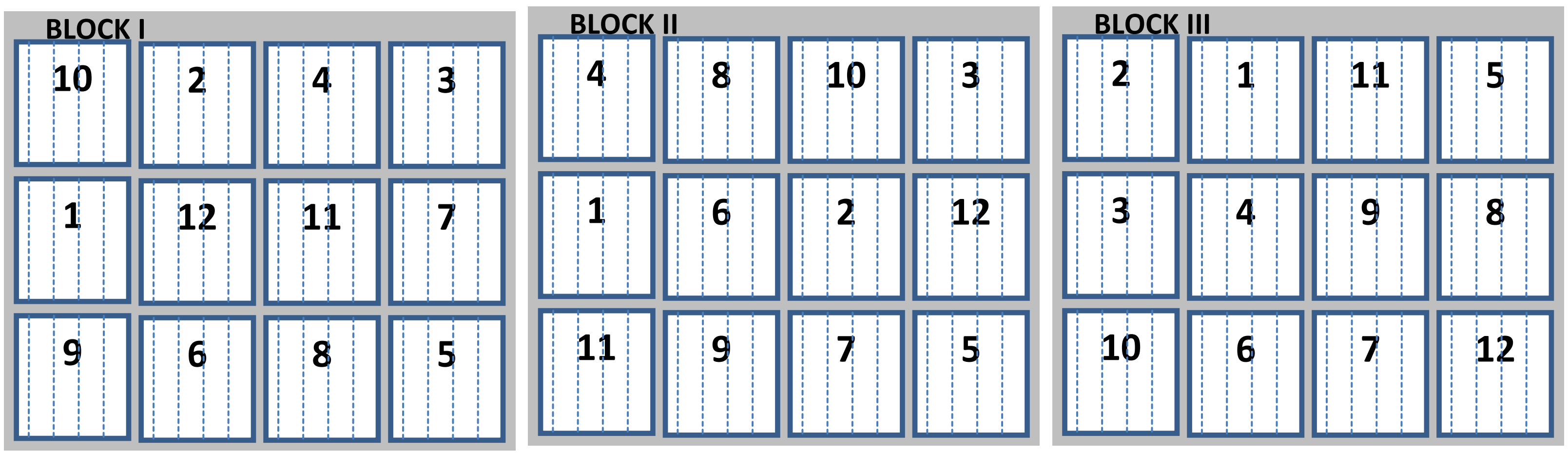


Treatment structure (Plot size 10mx10m).

No	Treatment code	Treatment
1	BMMC9W	Maize monocrop with and without urea harvested 9WAP
2	BMMC12W	Maize monocrop with and without urea harvested 12 WAP
3	BMMC18W	Maize monocrop with and without urea harvested 18 WAP
4	BDUM9W	*D. unicinatum* –maize intercrop, *Desmodium* cut at 9 WAP
5	BDUM12W	*D. unicinatum* –maize intercrop, *Desmodium* cut at 12 WAP
6	BDUM18W	*D. unicinatum* –maize intercrop, *Desmodium* cut at 18 WAP
7	BDIM9W	*D. intortum* –maize intercrop, *Desmodium* cut at 9 WAP
8	BDIM12W	*D. intortum* –maize intercrop, *Desmodium* cut at 12 WAP
9	BDIM18W	*D. intortum* –maize intercrop, *Desmodium* cut at 18 WAP

Note: In Busia, sole maize plots were divided in to two portions ($50m^2$), which were assigned to with and without urea treatments. **WAP**-Weeks after planting maize

Appendix 3: Experimental layout in Nyabeda (Siaya).



Treatments structure (Plot size 10mx10m)

Number	**Treatment code**	**Treatment**
1	SMMC9W	Maize monocrop without urea harvested 9 weeks after planting
2	SMMC12W	Maize monocrop without urea harvested 12 weeks after planting
3	SMMC18W	Maize monocrop without urea harvested 18 weeks after planting
4	SDUM9W	*D. unicinatum* –maize intercrop, *Desmodium* cut at 9 weeks after planting
5	SDUM12W	*D. unicinatum* –maize intercrop, *Desmodium* cut at 12 weeks after planting
6	SDUM18W	*D. unicinatum* –maize intercrop, *Desmodium* cut at 18 weeks after planting
7	SDIM9W	*D. intortum* –maize intercrop, *Desmodium* cut at 9 weeks after planting
8	SDIM12W	*D. intortum* –maize intercrop, *Desmodium* cut at 12 weeks after planting
9	SDIM18W	*D. intortum* –maize intercrop, *Desmodium* cut at 18 weeks after planting
10	SMMC9W+urea	Maize monocrop with urea harvested 9 weeks after planting
11	SMMC12W+urea	Maize monocrop with urea harvested 12 weeks after planting
12	SMMC18W+urea	Maize monocrop with urea harvested 18 weeks after planting

Appendix 4: Pictures comparing *Desmodium* intercropping and sole maize

Sole maize without urea

Desmodium intercropping with *D. intortum*

Desmodium intercropping with *D. uncinatum*

(Source: Author, 2013).