UNIVERSITY OF NAIROBI

CLIMATE SMART AGRICULTURAL INTENSIFICATION WITH DESMODIUM LEGUME COVER CROPS IN COFFEE FARM AT KABETE IN TIMES OF CLIMATE CHANGE.

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DECLARATION.

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

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APPROVAL

This thesis has been subimmited for the award of a degree with our approval as University Supervisors.

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May Gods abundant grace shower your lives with the blessings to make you achieve your goals.

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List of Abbreviations

AFFA- Agriculture Food and Fisheries Authority

ASDSP – Agricultural Sector Development Support Program

CAADP - Comprehensive African Agriculture Development Programme

CBK – Coffee Board of Kenya

CIAT – International Centre for Tropical Agriculture

CO2 – Carbon dioxide.

CRF- Coffee Research Foundation

DM – Dry matter

ECJRC - European Commission Joint Research Centre

FAO- Food and Agriculture Organisation

GCP- Global coffee platform

GOK – Government of Kenya

HLPE- High level panel of experts on Food Security and Nutrition

ICIPE- International Center of Insect Physiology and Ecology

IFAD- International Fund for Agricultural Development

I**PCC-** Intergovernmental Panel on Climate Change.

KSh- Kenya shillings

LER – Land Equivalent ratio

MA – Millennium assessment

NDMA – National Drought Management Authority.

SDG – Sustainable Development Goals.

SOM – Soil Organic Matter

UNFCC – United Nations Framework on climate change

USD – United States Dollar

WCED- World Commission on Economic Development

WMO- World meterological Organization

ABSTRACT

The conventional coffee production systems has promoted intensive weeding relying heavily on the common broad-spectrum herbicide named glyphosate and manual regular weeding for weed control. These practices have been shown to increase the risks of soil erosion and the associated loss of beneficial ecosystems services, increased rate of soil degradation and related reduction in coffee productivity. The loss of the soils ability to provide the necessary ecosystem services have resulted in the need for compensation using synthetic inputs especially herbicides and fertilizers despite their associated negative environmental impacts. Climate change has been documented to adversely affect coffee and livestock production with declining yields and reduced incomes while perpetual shortages of livestock fodder is pushing farmers to rely heavily on commercial feeds increasing cost of production and reducing earnings. This study at the University of Nairobi Kabete farm evaluated the performance of desmodium legume fodder as a suitable legume cover crop for coffee to benefit from the associated ecosystem services without farmers suffering from yield penalties and provide livestock fodder. A survey on knowledge, attitude and practices of coffee farmers' in Githunguri on integration of legume cover crops for ecosystem services and serving as livestock fodder was carried out. A medium term experiment was done at the University of Nairobi in 2019, at Kabete coffee plantation comparing soil moisture, nutrient relationship and coffee production among 3 weed control treatments of desmodium legume fodder cover crop, glyphosate herbicide and tillage using hand hoes. A completely Randomized Block Design was utilized where the 3 treatments were replicated 3 times where ANOVA was used to compare moisture differnces, weed control, biomas production and effect of each treatment on coffee production. Soil sampling used montly assessment using 9 cores of 30 cm and then analysed at the University of Nairobi Kabete laboratory. A face to face structured questionnaire using snowball sampling for 97 farmers was also administered in Githunguri area in Kiambu where a farmer’s knowledge, attitude and practices was evaluated being an area characterized by coffee farmers recording appreciable milk production income and_data analysed using Arch GIS survey tool and regression analysis. Desmodium was able to sufficiently suppress weed growth serving as a cover crop in the plots while the fresh biomass production was extrapolated showing a yield potential of 17 tons/year per hectare. Analysis of soil moisture content indicated better soil moisture retention at 36% where legume cover crop represented by desmodium. comparative coffee yield results on the experimental plots indicated increased coffee productivity where desmodium was intercropped with 1.8 times higher than herbicide treatment and 1.2 times superior than manual weeding. The savings for farmers on the purchase of commercial feeds was estimated at USD 750, per hectare per year which is a significant earning associated with better land use. The results of the farmer’s survey on knowledge, attitude and practices in relation to adoption of legume cover crops in coffee farms in Githunguri indicated a low adoption of desmodium but other annual crops species are widely used as intercrops despite their lacking of complementarity. The logistic regression model used to evaluate the relationship between commercial feeds and milk production showed a significant correlation at r^2 being less than 0.699, which on average calculation contributed a cost of KES. 19 (USD 0.2) per litre of milk produced. The findings were significantly important as an indicator of farmers reliance on the expensive commercial feeds for the success in milk production despite farmers having planted napier grass (pennisetum purpuleam) while losing on the potential savings of having the supplementary fodder from the desmodium legume fodder cover crop in coffee. Implications of this study on the climate-smart adaptation strategy of adopting desmodium legume cover crops in coffee production controlling weeds, thereby reducing costs of labour, maintaining soil ecosystem services through provision of habitat for soil microbial community and generating fodder biomass for livestock.

Policy makers need to appreciate the value of ecosystem services and increase sustainable agricultural intensification practices such as legume fodder cover crops

CHAPTER ONE

1.0 Introduction to the Study

Agriculture plays a significantly important economic role in Kenya attributable to 30% share of the GDP and contributing to 56 % employment opportunities for the Kenya population (Amwata and MoALF, 2020). Kenyan exports comprise 65% of agricultural products mainly comprising coffee, horticulture, fruits and tea indicting its value in national development (GOK, 2010). This brings to the forefront the importance of soil conservation practices in Kenya's aspiration in the achievement of sustainable development goals. There is a huge domestic market for milk and milk products making dairy farming an important sector in the country's agricultural economy. The significance of this magnitude exemplify the intrinsic value of the importance of soil conservation practices in Kenya's aspiration in the achievement of sustainable development goals (ECJRC, 2018; GOK, 2010).

Challenges associated with climate change are calling for the mitigation of greenhouse gas emissions in the agricultural sector, which will require reduction on the intensive use of inorganic nitrogen fertilizers and reduction of practices that result in the soil releasing greenhouse gases emissions to the atmosphere such as intensive tillage practices (Bain *et al*., 2017). Changing climate which increases variability and distribution of rains has increased the frequency of episodes of drought affecting many coffee farmers (Senegal *et al*., 2014).

The conventional traditional coffee production systems that relies upon heavy usage of glyphosate a broad-spectrum herbicide and intensive manual weeding have magnified the associated risks of the loss of beneficial ecosystems services, increased rate of soil degradation and related reduction in productivity (Brühl and Zaller, 2019). The loss of the soils ability to provide ecosystem services have resulted in the need for compensation with heavy reliance on synthetic inputs despite their negative environmental impacts (Kumari *et al*., 2014). Sustainability challenges to coffee production have been associated with some of the above negative impacts associated with these current conventional practices (Velmourougane and Bhat, 2017).

The common practice farming practicing monocropping in coffee, requires reorientation with adoption of legume cover crops. Previous studies have approximated sediment losses in the range of 21 tons per acre per year in bear soil in sloping areas which comprises of organic matter, up to 89% soil nitrogen, between 20- 70% soil phosphorous and a host of microorganism responsible for keeping the soil healthy (Beniston *et al*., 2015). Bare soils have also been shown to have higher soil temperatures leading to increased moisture evaporation leading to increased crop stress. Increased soil erosion has also been attributed to soil compaction, loss of soil structure and related ecosystem services further accelerating the rate of soil degradation (Blanco-Canqui et al., 2020).

Nitrogen is the most depleted nutrient in coffee growing areas lost through erosion, volatilization and leaching and with depressed coffee prices, most farmers are unable to put fertilizers at the recommended quantities leading to lower yields (Mosier *et al.*, 2021). Nutrient mining and soil erosion accelerate the soil nutrients depletion resulting in poor coffee yields which has been attributed to soil degradation and lost capacity for crop production (Mosier *et al.*, 2021). The overall results associated in declining coffee yields are more elevated especially when weeds compete with the coffee due to its not so well developed rooting system to mine nutrients in the row planting next to the top soil (Mosier *et al.*, 2021).

There is an urgent need for improvement of the production efficiencies in these systems by using sustainable agricultural intensification practices that produce more on less land using less resources widely advocated as a climate-smart adaptation (Herrero *et al*., 2012). Synergy in the adoption of sustainable agricultural intensification practices delivering more from less or same land while reducing the overall usage of agrochemicals is also urgently needed(Juma *et al.*, 2013). Among the major challenges associated with declining agricultural productivity is the farmers ecological illiteracy in the face of depletion of nitrogen a key nutrient for crop growth and sustaining agricultural productivity which is depleted through leaching, plant absorption and volatilization (Wyckhuys *et al.*, 2019). The resulting outcomes lead to the increased impacts on the environmental and social economic impacts associated with changing climate (DeSchutter, 2010).

For increased climate resilience, there is need for transformation of agro-ecological monocultures through deliberate increase of the landscape heterogeneity and field diversity resulting in increased productivity and sustainability (Gomes *et al.*, 2020). The climate-smart adaptations range from the adoption of agroforestry with diversified farming system and crop improvement (Gomes *et al.*, 2020). Meeting the associated challenges of climate change and mitigation of greenhouse gasses in mixed crop-livestock production systems, will require farmers to engage in agricultural biodiversity adaptations (Mijatović *et al.*, 2013). This will increase their resilience with restoration and protection of ecosystems services, while ensuring efficient sustainable use of water resources (Karuri, 2021). Cover crops like desmodium have been studied in different cropping systems and have been shown to have ability to reduce soil erosion and are associated with atmospheric nitrogen fixation thereby reducing the need for inorganic nitrogen sources which leaches easily and improves on the overall soil health while benefiting livestock systems with forage (FAO, 2011).

The scientific community is already being led into analyzing how cover crops influence carbon sequestration and greenhouse gas emissions from the soil (Basche *et al.*, 2014; Delgado *et al.*, 2021). Using cover crops with the aim of reducing the intensity of soil operations have been suggested as a great way to reduce emissions related with exposing the soil to direct impacts of the sun (Bain *et al.*, 2014; Delgado *et al*., (2021); Basche *et al*., 2014). The possibility of enhanced interactions of legume cover crops with other crops will subsequently be used for the enhancement of nutrient cycling and the need to amplify their promotion in more agro-ecosystems where farmers can increase ecosystem benefits (Basche *et al*., 2014). The recommendation on the adoption of strategies such as cover crops which facilitate carbon sequestration improves the ability of the production system to sink greenhouse gases into the soil while providing livestock fodder and should be encouraged (Karuri, 2021).

The increasing population in Kenya is reducing available land for cultivation while increasing demand for agricultural products requires intensification where possible to minimize the impacts of agricultural activities on the emission of greenhouse gases (Kabubo-Mariara and Mulwa, 2019).

Coffee production experiences challenges in weed control due to the big spaces between coffee bushes often indicated as a major coffee production problem in Kenya with resulting yield penalties estimated around 50% and above (Ndiritu *et al.*, 2021; Njoroge and Kimemia, 1989). Poor weed control or late weeding results in substantial yield penalties making farmers reduce their incomes in both coffee quality and quantity (Daramola, 2020). The most common weed control method utilized by most smallholder farmers relies mainly on traditional implements dominated by machetes and hoes (Njoroge and Kimemia, 1989).Manual wedding nevertheless has become expensive in addition to its being tedious with scarcity experienced during the peak periods during rainfall when crop growth is more rapid (Migwi *et al.*, 2017).

The mixed crop-livestock systems are regarded as adaptation measures that help improve food security (Wani *et al.*, (Eds.), 2009) for product diversification and utilization of manure for fertilizing the soil and is widely practiced in Kenya where cropping resources support livestock production. There is an indicated probability of increased intensity of conflicts related to water and pasture access in semi-arid tropics where 90% of crop production is by rain-fed agriculture, the likely intensification of drought stress due to increased evapotranspiration from increased temperatures and therefore need to intensify production to support livestock resources (Usman and Nichol, 2022). The number of milking cattle in Kenya according to the (KNBS, 2019) census was 3.4 million exotic breeds and 14.1 million indigenous breeds, a number which indicates the important and significant role played by the livestock sector in the rural economy contributing 3.5 % of the GDP (GOK, 2010).

Unfortunately, Kenya's livestock farmers are faced with a prevalent under nutrition which is associated with low milk yields which is common among smallholder farmer production systems (Wani *et al.,* (Eds.), 2009). These production systems are also associated with great variations in the quality and availability of animal feed resources throughout the year (Ayantunde *et al.,* 2005). Increased land pressure for crop production and seasonal weather variations have been made worse by changing climate that have resulted in multiplicity of feeding inconsistency resulting in great milk production variations (Herrero *et al*., 2012). Milk production studies in Kenya (ASDSP, 2014) have indicated the relationship between feed quality and milk production indicating a big variance of an average of 9 kg against the potential 20 kg per day dairy animal. There has been a notable breed improvement in Kenya, but this has not been met with equivalent supply of quality feeds to match the breed performance (Staal *et al.*, 2008). Inadequate feeds and low quality variety of feeds has been given prominence in studies by (Ouma and Owour, 2009) as a major constraint among dairy farmers in Kenya. The highest proportion of feed cost is associated with supply of roughages ranging from 54 % during normal weather and shooting to 73% during dry conditions when more concentrates have to be added due to feed shortage (Alvarez *et al* ., 2008).

Many farmers Kenyan farmers provide low quality fodder such as maize stover with low digestability and deficient in crude protein leading to low intake and feed inefficiency resulting to reduction in animal productivity due inability of the feeds to meet daily requirement for both energy and milk production (Ayantunde *et al.*, 2005; FAO *et al.*, 2015). Among the advantages of having legumes as protein supplements in low quality diet regimes for smallholder farmers production systems is their availability at the farm, accessibility, reduction in cost of commercial concentrates component, improvement of the diet variety, reduction in feed cost and thus impact on profitability (Herrero *et al*., 2012; Sumberg, 2002). Desmodium which is a legume fodder has been recommended as ideal for use as a cover crop has a high tannin content but have good digestibility (50-60%) and crude protein in the range of 12 – 25% (Puchala *et al*., 2012). Availability and adequacy of protein has been defined as among the most important principle nutrients for daily cow being the building blocks of most amino acids (Hatfield *et al*., 2011). Protein being an expensive nutrient and conversion rate being questionable becomes expensive when any wastage is encountered despite its breakdown by rumen microorganism with expulsion through enteric methane emission during digestion and excretion as urea (Beauchemin, 2009; FAO *et al.*, 2015).

With the concern on emissions from livestock being a major subject of discussion, the rumen degradable protein as broken down by microorganisms is resynthesized into bacteria protein for its utility while giving some of the output in the form of methane (Beauchemin, 2009). Provision of high quality protein fodder preferably with inclusion of legumes that contain condensed tannins, yet promoting digestibility are being promoted for their ability to reduce methane emissions (ICF International, 2013; Roldan *et al*., 2022). Undegradable protein referred as bypass protein due to their resistance to microbial breakdown in the rumen pass to the small intestines where digestion and direct absorption occurs (Gerber and FAO, 2013). Milk comprises 3.2- 3.5 % protein which could be translated to mean that for a cow to produce 25 kgs, requires to secrete between 800- 900 grams of protein daily (FAO, 2016). Protein storability is a challenge and therefore for maintenance of daily milk production, protein must be supplied in the rate of 15-18% of daily ration (FAO, 2016). Most feed rations are low in proteins limiting dairy production in Kenya due to unavailability of high quality forages (FAO, 2011).

Documented rumen fermentation processes show resulting gross energy loss equated to as much as 15% to the animal during the transformation processes that lead formation of methane during the anaerobic fermentation by microorganism (CH4) (Patra and Saxena, 2010). There are suggestions that 40 % reduction on methane emissions can be achieved with manipulation of livestock diets with better performance achieved with improved nutrition (Eckard *et al.*, 2010). Presence of condensed tannins have been attributed to having ability to reduce the production of methane in the animal gut digestion process (Kongvongxay *et al.*, 2011; Puchala *et al.*, 2012). Methanogen microorganisms' growth suppression in the rumen is dependent on type and dosage of condensed tannins (Williams *et al*, 2015).

Since forage quality determines methane production in the rumen, digestibility and rumen passage rates of the forage plays a key role with higher quality producing less methane (Boadi and Wittenberg, 2012). Legume forage produces less methane with their high dry matter content increasing passage speed thereby contributing less methane emissions than grasses (Archimède *et al.*, 2011). Some tannin-rich forage have been attributed to reduction of methane production by up to 55 % in livestock (Ramirez-Restrepo *et al.*, 2005). High concentrations of condensed tannins however have negative impacts on livestock feed intake and could be the reason their utilization is still limited (Beauchemin *et al.*, 2010).

Desmodium is a perennial with good shade and drought tolerance with deep roots enabling it to support nitrogen fixation while providing nutrient rich fodder for livestock while being elevated for its low methane emissions (Heuzé *et al*., 2017). The condensed tannins present in desmodium reduce protein degradation in the rumen with increased bypass protein flowing to the small intestines that favors milk production and weight gain while being low in methane production (Min *et al.*, 2006; Roldan *et al*., 2022). Retaining the intake of condensed tannins at less than 7% has been realized to be effective since excess condensed tannins result to reduction in voluntary feed intake and could result in some harmful effects on the gut micro biota (Tavendale *et al*., 2005). Studies using Luceana leucocephala and Acacia magnium indicated reduction in the production of methane in the range of 43 and 65 % (Jayanegara *et al*., 2011; Rivera *et al.*, 2018). In relation to milk production, moderate condensed tannins of 88 g per kg of dry matter led to increased milk production of 10 – 20 %, which was a better performance than cows fed on grass ration alone (Anantasook *et al* ., 2015; Dey and De, 2014)

1.1 Background of the Study

Climate change is being accelerated by the increase in the production of anthropogenic gases also referred to as greenhouse gasses that increases carbon dioxide and other gases to the environment resulting in temperature increase and unpredictable weather (UNFCC, 2010). The climate change impacts negatively on agricultural production from increased dry periods or flooding and thus affecting farmers' incomes from coffee production and increasing scarcity of fodder for livestock (Lin, 2007). Agriculture contributes to its fair share of environmental pollution with the usage of herbicides and inorganic fertilizers that volatilize in the form of nitrous oxides considered as greenhouse gases with high global warming potential (IPCC, 2014; 2022). Residues of the many pesticides used in agricultural production and other inert ingredients end up in the riparian areas through runoff and soil erosion affecting many species in the ecosystem (Gunstone *et al*., 2021). Soils which gets into contact with direct application of glyphosate formulated herbicides, have been found to have numerous residues that have both direct and indirect impacts to the environment (Aktar *et al*., 2009; Brühl and Zaller, 2019).

The mixed crop-livestock sector practiced commonly among many smallholder coffee farmers makes their carbon footprint to include crops and livestock methane emissions (Boadi and Wittenberg, 2012). Livestock production practices are associated with emissions of carbon dioxide and methane gases (nitrous oxide) adding up to the contribution of the greenhouse gases that are linked to global warming (Boadi and Wittenberg, 2012). There is a standardized global warming potential equivalent index expressed as carbon dioxide equitants (C02 Eq) (IPCC, 2022). The potential global warming comparison uses carbon dioxide as a reference gas with a value of 1 kg of C02 Eq per kg of carbon dioxide. IPCC carbon equivalent for methane is 34 CO2-eq per kg and nitrous oxide is 310 per kg CO2-eq (Farinha *et al.*, 2021). The global warming potential of methane and nitrous oxide are of global concern due to their higher equivalence index (Farinha *et al*., 2021). Eckard *et al*., 2010) analyzing the impact of livestock on the greenhouse gas emissions have given estimates of between 120 - 450 litres of methane per animal per day depending on factors such as amount of feed intake and the animal rumen micro flora. Overall global contribution of greenhouse gases associated directly with livestock production is estimated at 14.5% (Gerber and FAO, 2013) , which could be higher when land use change for livestock production is factored. The low efficiency and productivity of smallholder livestock systems can be attributed to having higher concentrations of greenhouse gases due to excess loss of energy, organic matter and nutrients (Gerber and FAO, 2013). Production of forage and animal feeds from grains including the processing and transportation increase the contributions of GHG related to the livestock sector (Herrero *et al*., 2012; IFAD, 2010)

Legume fodder as one of the products to be produced has high protein content as an animal feed, contains condensed tannins and its availability is expected to reduce overgrazing and reduce the need for opening up of new land for protein feed production (Ayantunde *et al*., 2005). Therefore, desmodium as a companion cover crop in coffee can significantly reduce the carbon foot print in coffee production (Vukicevich *et al*., 2016) and be a big source of livestock fodder with its positive impact in reducing methane emissions from livestock due to containing condensed tannins. With the sustainable development concept and the sustainability theory, there is need to focus on ecological synergies in crop production to ensure there is minimal waste of opportunities that can result in ecological sustainability (Holmes and Wortman, 2017).

Plantation crops like coffee in Kenya, estimated at 350,000 hectares (GCP, 2018) and employing more than 500,000 households is among the crops that are known to have a high usage of inorganic fertilizers and herbicides associated with nitrous oxide emissions (Ngare, 2021). Being tree crops, their carbon footprint through carbon sequestration can be enhanced with use of desmodium as a legume cover crop to reduce on the usage of inorganic fertilizers as source of nitrogen and reduce herbicide usage (Bunn *et al*.,2015). Desmodium is a nitrogen fixing vining creeper that have a perfect history in enriching soils, suppressing weeds and controlling some pest species in crops like maize (FAO, 2011; Midega *et al.*, 2015). FAO, (2011) have indicated the great potential of desmodium showing the positive relationship by fixing nitrogen in cropping systems and this should be extended to coffee production systems for actual quantification. However, there is a gap in policy direction for advanced research and mass scale up in coffee plantations and governance challenges related to availability of planting material and end user communication leading to the low adoption rate despite the immense environmental benefits.

1.2 Statement of the Research problem

Coffee production in Kenya comprises both large scale and small scale production in different locations. The increasing climate variability and associated environmental impacts resulting from intensive use of pesticides and inorganic fertilizer usage has both short term and long term environmental impacts (Aktar *et al*., 2009; Gunstone *et al*., 2021). The substitution on the use of herbicides for weed control and use of inorganic fertilizers as a source of nitrogen need to be substituted with climate-smart alternative technologies that are more environmentally friendly for safeguarding diversity and promoting ecosystem services (Altieri *et al*., 2015; Irmak *et al*., 2018). Further assessment of governance challenges that has resulted in low widespread adoption of the desmodium legume as a cover crop in plantations such as coffee needs to be evaluated and solutions to the gaps identified be addressed. The adoption of climate smart knowledge based on synergistic ecological practices rather than the current input intensive agriculture that has a huge carbon foot print needs to be encouraged with alternatives that are more environmentally focused (Lipper *et al*., 2014; Ratcliff *et al.*, 2006).

The increased carbon footprint from livestock production activities needs to be managed with the aim of reducing emissions of greenhouse gases by optimizing available opportunities for fodder production (Hall *et al*., 2008). Large amounts of condensed tannins ranging from 3 - 12 % of the dry matter are present in desmodium (Naumman *et al*., 2017), which is associated with expulsion of nematodes in the form of intestinal worms and reduction of methane production (Tolera *et al*., 2012). The tannins present are beneficial in increasing bypass protein proportion without interfering with the ammonia nitrogen levels in the gut and rumen microbial synthesis (Animut *et al., 2008; Tolera and Sundstøl, 2000)* therefore providing sufficient nitrogen for the rumen bacteria. Condensed tannins digestability has been improved with addition of polyethylene glycol (Mbugua *et al*., 2008). Legume forages like desmodium which has a considerable content of condensed tannins could be used for the reduction of methane production in livestock (Naumann *et al*., 2017). Replacement of 30-45 % forage portion with a diet containing condensed tannins in the range of 3- 9 % have been assessed for their ability to decrease methane production without decreasing the necessary gas production for the rumen functions (Naumann *et al*., 2017).

Desmodium fits in the cut and carry system such as being a cover crop for coffee where it can be consumed fresh or conserved as hay for future use, with yields attainable reaching 15 tons per year per hectare of dry matter (FAO, 2011). Desmodium among the legumes is able form the symbiotic relationship with rhizobia enabling it to have high biological nitrogen fixation of between 90 – 150 kg per ha on pure stands (FAO, 2016). Having high levels of condensed tannins ranging from 9-17%, desmodium feeding in large quantities is limited by its astringency which reduces palatability (Mbugua *et al*., 2008). The crude protein present in desmodium has the ability to bypass rumen as undegraded protein and supplied in the intestines where is supports milk production and animal growth (Baloyi *et al*., 2009). The current presence of tannins have been thought to have some astringency in feeding thus reducing feed intake, although drying improves the palatability (Baloyi *et al*., 2001). Desmodium intortum is highly nutritious with high content of crude protein, acid detergent fibre, acid detergent lignin, neutral detergent fibre, dry matter, ash, soluble tannins 143 g/kg and condensed tannins 78.6 g/kg (FAO, 2011). Desmodium fodder is rich in supplying some mineral elements based on previous analysis giving the following range of minerals; calcium 7.6 g/kg, Phosphorous 3.5 g/kg, sodium 0.15 g/kg, potassium 17.8 g/kg, magnesium 1.6 g/kg, manganese 91.4 mg/kg, cobalt 120.7 mg/kg, copper 17.9 mg/kg, iron 264 mg/kg and zinc 25.3 mg/kg (Heuzé *et al*., 2017). The lower neutral detergent fiber present in desmodium than grass forages makes its digestion to be faster which is associated with increased productivity (Heuzé *et al., 2017).*

Manual weed control practices predisposes the soil to the risk of soil erosion leading to increased burden of siltation in the riparian areas and increased eutrophication of water bodies from residues when inorganic fertilizers and herbicides are used (Gunstone *et al*., 2021). Additionally increased fertilizer usage increases the rate of release of nitrous oxide resulting from volatilization of inorganic fertilizers (Aktar *et al*., 2009; Brown *et al*., 2001). Adoption of cover crop species that proffer farmers with competitive advantage of weed control through their weed suppressing ability with their canopy structure while having the ability to tolerate shade and providing livestock with forage is among the most ideal options for climate-smart agriculture which fits desmodium(Blanco-Canqui *et al*., 2020). The sustainable climate-smart agroecological alternative of weed control using desmodium legume cover crops have not been well investigated from previous studies (Schipanski *et al*., 2014).

1.3 Objectives

General objective

Assessing climate smart advantages in coffee plantations using desmodium legume cover crop for enhanced productivity

Specific objectives

i. To compare soil moisture concentration at different times in the treatment plots in the coffee plantation after establishment of desmodium and the ability of desmodium to control weeds.
ii. To determine the desmodium cover crop fodder production potential in coffee plantations.
iii. To assess the coffee yields on the different treatments of herbicide, manual weeding and desmodium legume fodder cover crop.

iv. To evaluate the knowledge, attitude and practices of the coffee farmers in relation to using desmodium cover crop as part of their production system in Githunguri.

These objectives will guide on the ability of desmodium legume fodder cover crop to be considered as being climate smart with superior performance to the other treatments of herbicide application and manual weeding. The expected results are expected to guide on the policy directions on how farmers who generally have coffee and dairy animals can incorporate climate smart agricultural practices as climate change impacts continue to affect both the coffee production and livestock production sectors.

1.4 Significance and Justification of the study

Ecological interactions have been documented to increase farmers benefits associated with ecosystem benefits which are expected to be realized by coffee farmers who understand them and integrate them in their production systems (Altieri *et al*., 2015). Desmodium legume cover crop has been shown in previous studies in other crops such as maize to improve on the overall soil conditions through reduced soil disturbance, weed control, reduced soil erosion, retention of soil nutrients, carbon sequestration and additional income from the harvest of the legume fodder for animal food (Hooper *et al*., 2015). This study is aimed at overcoming the science research gap and look at the governance challenges why the practice of using desmodium legume as a cover crop in coffee production has not been extensively practiced by farmers in coffee plantations despite these advantages which are important in time changing climate. Previous legislation of the Coffee Act Cap 333, had made restrictions in regard to intercropping crops with coffee, there have been several amendments of the Crops Act in 2013 which increases farmer’s flexibility (Nyangito and Ndirangu, 2002). Crops Act 2013 cover many coffee general regulations with a great focus on marketing and licensing (AFFA, 2013). The crops act has however not expressly developed guidance on ecological interactions in coffee production using legume cover crops making this study important as among the basis for evaluating the ecological and economic advantages of using legume cover crops as a contribution to policy makers. There is need for further evaluation various legumes fitting as suitable cover crops candidates ideal for soil erosion and weed control management in central Kenya smallholder coffee production systems with different legume species recommended desmodium among other evaluated legumes as a suitable solution in weed control and soil management without elaboration on the ecosystem benefits (Zhang *et al.*, 2017).

This study was aiming at increasing the body of information and knowledge in relation the increased adoption of sustainable agricultural intensification by farmers in the face of changing climate, farmers embracing ecosystem services and increased production of livestock fodder. The study aims at contributing to policy makers guidelines on farmer's increasing resilience in the face of changing climate and environmental protection through reduction of soil degradation.

1.6 Scope and the limitations

The scope of the study was based on the concern for the environmental stewardship and increasing the farmers' resilience to the variations in the climatic patterns associated with changing climate within the coffee growing areas of Githunguri Constituency and the University of Nairobi College of Agriculture and Veterinary sciences coffee plantation.

Previous studies found the decline on the attention to coffee productivity was related to the Coffee Prices and Regulations which had a significant impact on the livelihoods of rural community in Kenya growing coffee due to reduced incomes (Ngare, 2021). Gathura, (2013) studies in Githunguri District found that marketing aspects and the complicated marketing value chain with subsequent delayed payment were the main factors that affected small-scale coffee production. Karuri, (2021) studies found that the delays in cherry payment by the cooperative societies was a negative incentive to smallholder farmers' morale in increasing coffee productivity and resulting yield decline. Okibo and Mwangi (2013) looking at the Effects of liberalization on Coffee Production in Kenya found that the prices were still low and farmers ability of increasing inputs for productivity was not improving their profits. Study on the impact of better regulations which increased the number of coffee marketers by cooperatives aimed at reducing the delay in payments and improved farmers revenues found that increasing labour and input costs was still making coffee farmers earn less profits and therefore less focus on productivity (Condliffe *et al.*, 2008). These previous studies focused on the factors that have resulted in coffee production decline focusing on intensive use of inputs and the unreliable marketing systems with cooperatives which have had several disincentives for farmers, however there is limited studies focusing on Agro-ecology using desmodium as cover crops for the ecosystem benefits of the farmers (CRF, 2012). This study was done at the University of Nairobi College of Agriculture and Veterinary sciences coffee plantation for the different treatments for 2 seasons covering the short rains of the year 2019 and long rains of the year 2020 after establishment of desmodium will compare the benefits of ecology legume cover crops.

1.7 Theoretical framework

1.7.1 Sustainability theory

The study was also based on the sustainability theory (WCED, 1987), as key context of “sustainable development” which presupposes that development should be oriented with a focus on the long-term health of the production resources meeting the needs of the current generation while safeguarding the life support systems of the planet earth (Thomsen, 2013; WCED, 1987).

Therefore, research should focus on how best to sustain the life support systems with focus on improving the environmental changes within local, regional and global systems influenced through human actions (DuVal *et al.*, 2019) . Since human activities are the major forces causing the shifts resulting in fundamental changes affecting economic development, social justice and sustainability, it is important to raise the aspects of stewardship to ensure the provision of services from the environment (Folke *et al.*,2016).

The midscale adoption of desmodium legume fodder cover is expected to reduce the pressure on increasing coffee production with excessive use of synthetic fertilizers, reduction of extra land needed for fodder production since the same land will lead to production of more resources, while livestock consumption of fodder that produces less methane will lead a reduction of the contributions from agricultural production. Other beneficial impacts such as reduction of soil erosion and reduced herbicide usage shall be experienced through the reduction of riparian ecosystem challenges associated with intensive agricultural practices.

In relation to the coffee sector since introduction, there has been a missing link between sustainability in terms of protecting the soil resources from losing their ecosystem services due to the absence of deliberate soil conservation measures that are also beneficial to the farmers. There is therefore the urgency needed in addressing this challenge which ahs been indicated in the conceptual framework here below.

1.8 Conceptual Framework

The agency theory can be used to analyze on the corporate governance that operates between the Coffee board of Kenya and the Coffee directorate by AFFA that has shown the aspect of control and self-interest oriented assumptions (Ansell and Gash, 2007). The coffee production and marketing decisions and policies affecting the coffee farmers have had little direct input from the farmers despite their being most affected. Coffee producers historically have received guidance, regulations and research studies, financing for activities from deductions on their produce. Some of the agency decisions have mainly focused levies from farmers for their own benefit while not focusing much on the benefits accruing to coffee farmers.

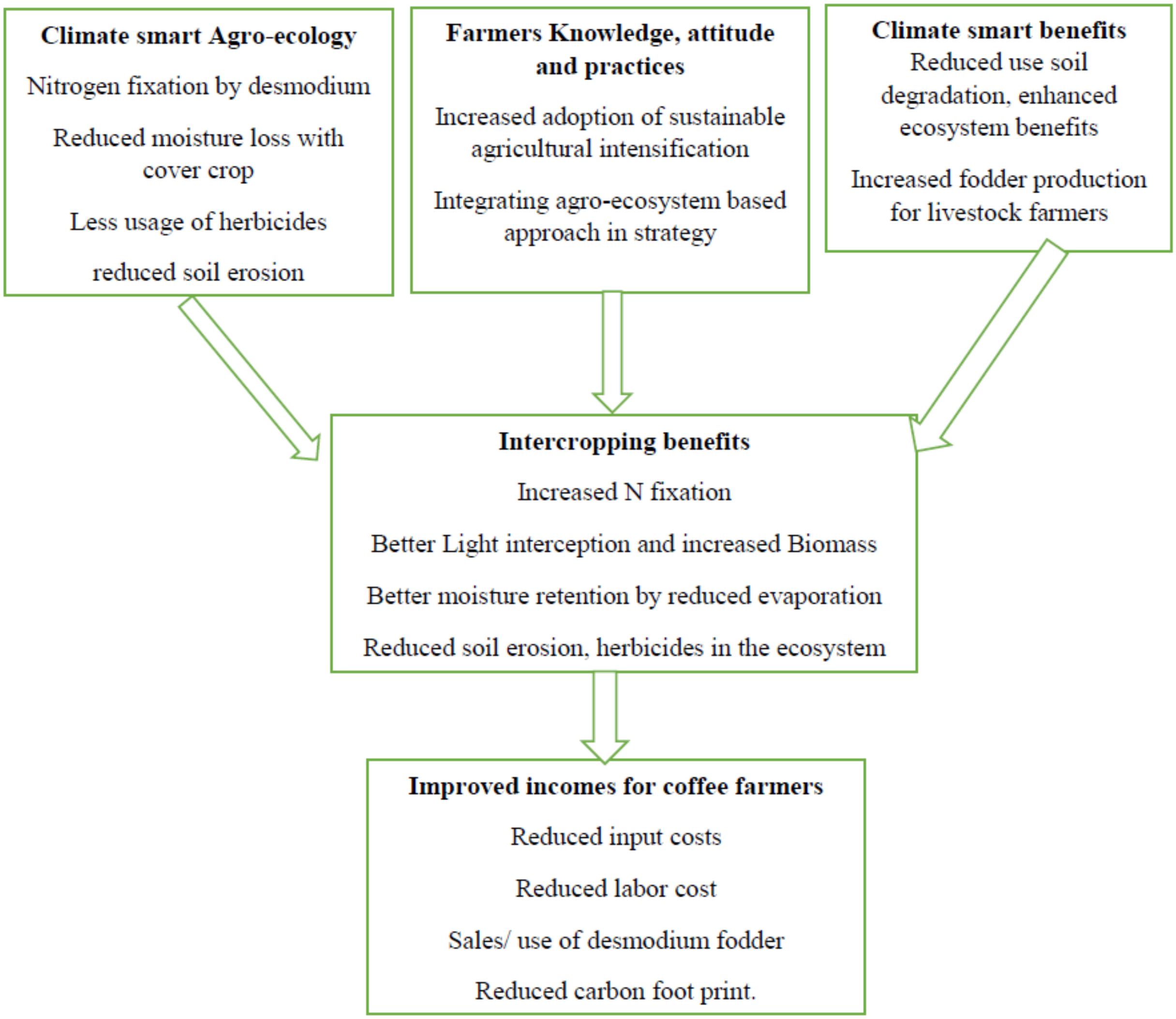

Figure 1. The Conceptual framework for climate smart desmodium cover crop in coffee farmer's adoption of agroecology

CHAPTER TWO

2.0 Climate Smart Agriculture and Climate Change

2.1.1 Climate change impacts on Agriculture productivity.

Global warming associated with the changing climate has been predicted to increasingly affect different countries differently basing on their geographic location and main economic occupation (IPCC, 2022). The challenges posed by changing climate clearly documented by the IPCC 2022 report bring to attention the urgency needed for small holders to cope with the ever increasing amplitude of climate change associated with unpredictable and prolonged droughts (IPCC, 2022). The IPCC modeling simulations indicates that rising carbon dioxide emissions resulting from human activities could lead to 1.4 to 5.8° C by 2050 in global surface temperatures negatively affecting rain season in terms of amounts and frequency (IPCC, 2014). Agriculture minimally contributes to total global carbon emissions (Appendix 1) estimated at 14% globally comprising of nitrous oxide (58%) of the total emissions mainly through fertilizer application, while 47% of the methane emanates from livestock and rice cultivation (IPCC, 2014).

With a large population estimated at 80% being dependent on agriculture in the sub-Saharan Africa, which is also among the most affected by changing climate, the vicious poverty cycle is exacerbated by the increasing drought cycles associated with changing climate (IPCC, 2022). The weather impacts in essence exacerbate the pest and disease challenges increasing the burden of the farmers aiming to sustain their production and sustain their livelihoods (Cavicchioli *et al*., 2019). The predictions of drought intensification by IPCC, (2022) and related stress due to increased evapotranspiration from increased temperatures are already evident with drought cycles increasing in intensity and frequency with many decision makers unable to provide reliable predictions for enhancing adaptation.

Intensive farming operations that leave the land bare increase the soil temperatures making the soils dry more quickly and when the rains comes, the same bare soils are subjected to higher magnitudes of soil erosion with associated nutrient loses (Messina *et al*., 2014). Bare soils with these challenges lose their soil structure and when heavy rains fall, soil crusting resulting from the loose sediments reduce rainwater percolation. Along with the lost sediments approximated at 21 tons per acre per year, is the rich organic matter that supports microorganisms with nitrogen and phosphorous also stored in the top soil layer (Kopittke *et al*., 2019). When the soil loses this quantity of fertility continuously (Appendix 2), the resulting poor yields must be supported with increasing levels of synthetic fertilizers associated with increased nutrient leaching and further changing the soil properties (UNFCC, 2010). Summarizing the negative soil impacts associated with Intensive agriculture shown in (Appendix 2) results increased soil emissions of methane and carbon dioxide, increased soil moisture evaporation, reduced rain water infiltration, increased runoff of rain water due to bare ground and compacted soils and consequently higher soil temperatures thus soil properties are compromised

The increasing climate change accelerates the soil degradation due to the increased soil exposure to high temperatures during hot weather and corresponding massive soil erosion episodes at the onset of the rains often in form of storms and have been categorized as very destructive (Borrelli *et al*., 2020; IPCC, 2022). This massive annual loss of the soil fertility increases yield penalties when massive synthetic fertilizers are not applied while the soil moisture loss is higher with the bare soils (Dragović and Vulević, 2021).The global impacts on the agricultural economy will significantly compound the incomes of countries dependent on commodities such as coffee, reducing national incomes and pushing farmers further into poverty (Frona and Harangi-Rákos, 2021).

The increasing poverty associated with climate change impacts has pushed the poverty levels deeper making the achievement of the SDGs more impractical since bigger populations are losing their livelihoods (Frona *et al*., 2021; Jafino *et al*., 2020). Climate change impacts associated with increasing dry weather and increased temperatures directly affect the regeneration of pastures and livestock farmers are significantly affected by the dynamics of climate change with loses in the magnitude of 60% experienced in drought years due to scarcity of feed crops and forages (FAO, 2015). Milk yield decline in the magnitude of 75% often result to increased retail milk prices and competition on the grains meant for human feed comprising a significant portion of the commercial feeds for livestock production (FAO, 2015).

Countries reliant on rain fed agriculture like most of African countries are increasingly facing increasing failed seasons and reduced livestock resources as pastures dry up and water resources become scarce and inadequate (IPCC, 2014; IPCC, 2022). The increasing demand for adaptive mechanisms for smallholder farmers in the face of impeding crisis associated with climate change, Africa seems to bear the blunt of having more than 40% of the population being pushed into poverty and food insecurity resulting from floods, droughts, increasing heat and lost livelihoods (WMO, 2021).

The east African region has its economies relying heavily in agriculture with more than 63% of the population employed in the agricultural sector which is already significantly impacted by the changing climate thereby reducing national incomes (Dinar *et al*, 2012). Pests and diseases also become unpredictable with increasing temperatures leading to further decline in coffee yields while increasing the production costs resulting from drastic weather pattern changes increasingly reducing the profitability of the agricultural enterprises (Ripple *et al*., 2022). The horn of Africa has been experiencing several episodes of increasingly dry weather and extended droughts leading to many failed seasons for crops and lost livestock due to lack of feeds (WMO, 2021). In Kenya, the drought cycles previously experienced every 7 – 10 years have become regular and more severe every 3 years (WMO, 2021).

The IPCC, (2022) indicates that mitigation of climate change is the total sum of strategies that reduce anthropogenic gases emission in the climate system. Therefore reduction of use of nitrogen fertilizers is part of the mitigation strategies to reduce soil dependent greenhouse gases emissions to the atmosphere, whereby strategies such as cover crops that sinks greenhouse gases into the soil should be encouraged (Mosongo *et al*., 2022; Sistani *et al*., 2011). Opiyo *et al*, (2015) indicated that there is expected increased intensity of conflicts in Kenya related to water and pasture access which is also expected in other semi-arid tropics where 90% of crop production mostly relies on rain-fed agriculture.

This therefore calls for all stakeholders and decision makers to ensure that considerations for climate change impacts are well documented and the necessary interventions put in place to reduce the negative impacts associated with the massive climate change impacts. Kenyan farmers must use the information available to make adaptive choices in the face of climate change.

2.1.2 The coffee sector in Kenya.

Historically, Coffee was introduced in Kenya in Taita Hills at Bura in 1893, further trials done in Kibwezi under irrigation and moved inland into Kikuyu in 1904 (CRF, 2012) . The colonial government following the Devonshire White paper report off 1923 resulted in growing coffee outside the European settled areas in Meru and Kisii. This later brought in the Ordinance acts of 1933 which created the coffee board (CB) with regulatory, promotion, inspectorate and licensing capacity. In 1934, the coffee board of Kenya (CRF, 2012) was created to become the apex body regulating the Kenyan Coffee industry. The ordinance 26 of 1960 became the coffee ordinance Cap 333, which consolidated the coffee industry ordinance and the coffee marketing ordinance with specifications on coffee production which imposed coffee as a monocrop. Although the coffee Act Cap 333 has been under several amendments such as coffee act no 9 of 2001, which established the CBK as the only statutory body governed under the ministry of agriculture in relation to the regulations of the coffee industry, there has been several attempts at making coherence of the various statutes with lots of focus on marketing of coffee. The amendment of cap 333 in 2001 specified the roles of CBK as the industry regulator to formulate policies for enhancement of coffee production, processing and marketing (Ronge *et al*., 2005).

Coffee is among the main export crops that Kenya enjoys to obtain foreign exchange and already shifts in production regimes threaten this valuable income source for the farmers and the government (GCP, 2018). Arabica coffee the mainstay of many Kenyan farmers and it is predicted to be among the crops to be adversely affected by climate change and therefore adaptation measures are urgently needed to safeguard farmers' incomes and support their livelihoods (Wagner *et al*., 2021). There are indications of the appreciation of the value of the Kenyan coffee in the global market due to its superiority produced by an estimated 750,000 farmers comprising 300 cooperative unions and another 2000 privately owned firms (GCP, (2018). The production system is dominated by small holder farmers, and coffee is particularly sensitive to changing climate and farmers are already feeling the burden posed by the impacts of the climate change in terms of changing seasons and shifting weather patterns increasingly changing predictability and better prices would greatly improve their feeling on justice (Ripple *et al.*, 2022).

Coffee acreage in Kenya continues to compete with the negative impacts of climate change which has accelerated the encroachment of real estate development with increased growth of the urban centres increasingly encroaching on the peri-urban areas which has seen reduction of the coffee acreage from 112,000 hectares in 2018 to 105,000 hectares in 2021(GCP, 2018). Covid -19 disruption of supply chains and increased reduction of the industrial capacity in the region has significantly amplified the climate change impacts affecting the smallholder coffee farmers access to farm inputs or limiting availability due to the elevated prices reducing production capacity (Rwigema, 2021).

2.1.3 Sustainability policies in Agriculture to support climate adaptation.

Sustainable agricultural intensification where using the same size of land is aimed at producing more have been encouraged as a climate-smart adaptation measure that farmers should embrace in times of changing climate (HLPE 2016; Ires, 2021).The adoption of climate smart agriculture for the transformation of landscapes and farming practices in Africa has been premised to increase the farmer's adaptive capacity to the impending crisis by increasing the diversity of their production and harvesting multiple benefits from the specific land area (Abegunde and Obi, 2022). Despite policies being developed in the CAADP framework of climate change adaptation, in reflection of the Paris agreement, the policies are very broad and locally crop specific polies are urgently needed to address sector specific adaption gaps like in coffee (Mungai *et al*., 2020).

Biological carbon capture and nitrogen fixation through practices such as cover crops reducing excessive synthetic fertilizer and use of legume forages that have some tannins associated with reduction of methane from livestock digestion are among the climate smart agriculture practices being recommended for the overall sustainability of agriculture (Cheng *et al*., 2022). The degree of vulnerability of farming communities due to their reliance on the stock of natural and social capital makes it urgent for the need for new adaptations since where it's well developed, it makes their systems less vulnerable to climatic shocks (Altieri *et al*., (2015) .

2.1.4 Climate smart agriculture benefits with cover cropping adoption in coffee

Agricultural systems have been indicated that they will be confronted by some degree of climate change and therefore, it's important to develop adaptive mechanism to increase on resilience on the face of global warming (Howden *et al*., 2007). Promotion of sustainable and climate smart agriculture to achieve food security is required to meet sustainable development goals and climate commitments (Bunn *et al*., 2015). For increased climate resilience, agro-ecological transformation of monocultures is achievable by increasing landscape heterogeneity and field diversity (Altieri, 2002). Selectively fitted agroecology will comprehensively increase productivity and sustainability and result in reduction of some social economic and environmental impacts related with changing climate (De Schutter, 2010).

A large volume of research has correlated the impacts of global warming associated with changing climate with declining crop production by more than 60% (Lobell and Gourdji, 2012; Easterling *et al*., 2007). This, therefore, calls for creating resilient crop production cultures to enable farmers increase their ability to cope with adaptation mechanism that help them buffer these changing climate impacts (Bunn, 2019). These predictions will require adaptations by farmers to meet these drastic and unpredictable impacts (Bunn *et al*., 2015; Bunn, 2019). Several recommendations among them being adaptation by engaging in agricultural biodiversity to increase farmers' resilience with restoration and protection of ecosystems, efficient sustainable use of water resources, and adoption of climate-smart agriculture among the diversified farming systems and crop improvement (Mijatović *et a*l., 2013).

Studies on intercropping different crop species that produce differentiated produce for farmers helps them produce different crops simultaneously with enhanced risk minimization (Vandermeer, 1989). Some proposal have indicated that increasing the diversity of agro systems for the provision of ecosystem functions and environmental services (Appendix 3) will be a major requirement in all agro-ecosystems (Altieri *et al*., 2015). The benefits associated with cover crops can be summarized as leading to decreased soil emissions of methane and carbon dioxide, reduced soil moisture evaporation, improved rain water infiltration, and reduced rain water runoff due to presence of the cover crop and resulting lower soil temperatures thus better soil properties (Appendix 3).

Suggestions by Altieri *et al.*, (2015) like other agro-ecologists strongly recommend that new models of agriculture will need to be incorporated by farmers to increase in their success to adaptability to climate change. Arguments by among others Cabell and Oelofse, (2012), have already shown that the agro-ecosystems that will contain a degree of diversity will have better resilience to various types and degrees of climate shocks. Studies by Fiorella *et al.*, (2010) showed that resilience results from the creation of temporal diversity increasing the functional diversity and creating resilient systems which are less sensitive to temporal climate fluctuations. While studying the relationship to adaptation in Kenya's contour hedge rows of Senna spp and maize or cowpea, found that in maize, cow peas and grass strip mixtures, there was increased light interception and biomass formation than when compared with sole crop (Kinama *et al*., 2005a). The combination of C3 and C4 crops in agroforestry resulted in better yields indicating more light was intercepted and used for photosynthesis than in a sole crop.

The increase in diversity of species have been shown to act as buffer against failure resulting from environmental fluctuations through the enhanced compensatory capacity created by diversity in an agro-ecosystems since in case one species fails to perform well, others can play a compensatory role leading to a more predictable combined response in terms of ecosystem properties (Lin, 2007). Scientist working at ICIPE noted that were able to plant maize and desmodium and developed the push-pull system that repels maize stem borers that end up in napier grass reducing intensive application of pesticides for this invasive pest (Khan *et al*, 2010). The mixture of maize and desmodium resulted in less damage to the maize by stem borers with increased soil fertility from biological nitrogen fixation by the desmodium legume that led to 15-20% increase in maize yields and farmers eventually utilizing the fodder as animal feed for better milk yields (Midega *et al*., 2017). There are predictions that greater agro-ecosystem diversity may help in buffering from the impacts of shifting rainfall and temperature dynamics and possibly counteract declining yields in the long term where different crop varieties respond differently to climate shocks (Altieri *et al*., 2015).

Increase in the diversity that generates mulch, weed seed germination is hindered and on decomposition, some cover crops may release allelopathic compounds likely to suppress the growth of competitive weeds (Kebede, 2021). Studying the Sotonusco, Chiapas coffee systems Jha *et al*., (2014) observed that farms that had better plant diversity and vegetational complexity resulted in less severity to the damage caused by Hurricane Stan than the others with simplified coffee systems. The recognition that biodiversity is an integral part of the maintenance of ecosystem functioning and stresses on the need for crop diversification as a resilience strategy to cope with climate change (Altieri *et al*., 2015).

Dissemination of the methods of increasing resilience with the correct practices with already documented scientific studies documenting effectiveness of agro-ecological practices to extreme climatic events such as flooding and extended dry periods is urgently needed (Stigter, 2008). While intercropping maize and cowpeas with a comparison on a sole crop with the use of mulch from prunnings of Senna Siamea, (Kinama *et al*., 2005b), after 3 seasons realized reduced soil evaporation as a percentage of rainfall values to below 10% while the control sole crops had up to 50 % soil evaporation during the long rains. Studies focusing on cover crops like desmodium in different cropping systems have confirmed their ability to reduce soil erosion, fix atmospheric nitrogen, reduce need for inorganic nitrogen sources which leaches easily and improves on the overall soil health (Midega *et al*., (2015).

The scientific community have been analyzing how cover crops improve on carbon sequestration and greenhouse gas emission reduction from the soil which should be embraced by coffee farmers so as to reduce the carbon footprint in coffee production (Basche *et al*., 2014). These findings indicate that their interactions with other crops subsequently greatly enhance ecosystem services supporting ability to withstand extreme climate change and proposes the need for promotion of cover crops in more agro-ecosystems (Basche *et al*., (2014).

2.1.5 Desmodium considerations in agro-ecology and evidence in weed control.

Desmodium is a creeping branched perennial plant originally from Central America and currently adopted across the tropics along the suited to the temperatures between 25- 30 degrees, 30° south and 30° north of the equator favoring altitudes between 500 – 2500 m Above sea level and rainfall in the range of 700 – 3000 cmm (Heuzé *et al*., 2017). The plant can be grazed in pastures or established for fodder cut and carry systems as well as intercropped with other crops for the benefit of nitrogen fixation (Heuzé *et al*., 2017; Midega *et al*., 2017).

Weed control in most crops is an integral part in maximizing crop yields and this is important in coffee production systems which has been emphasized and amplified by the large spaces between bushes which readily receives sun energy and promotes rapid weed growth (CRF, 2003). Using cover crops for weed control has proven successful and the use of desmodium has proved important in striga weed infestation in grain cereals where this parasitic weed infestation without control can result in 100 % yield losses translating to an estimated USD 40.8 million in East Africa *(Midega et al*., 2015). The success in the use of Desmodium intercropped with maize in the “push pull” technology ICIPE has proved successful by not just reducing the impact of the striga weeds but also repelling stem borers in maize production (Cook *et al*., 2007). Desmodium helps in the suppression of the germination of the striga weeds in to the host plants, improves soil fertility through nitrogen fixation and acts as mulch for moisture retention (Khan *et al*., 2008). The establishment of the "push-pull" mechanism has been seen to favour increase the diversity of predatory arthropods reducing the pest population to even lower levels (Midega *et al*., 2017). Khan *et al*., (2010) have published studies showing that the "push pull" mechanism equally reduces the incidence of the invasive pest fall armyworm (Spodoptera Frugiperda) in small holder farmers saving the need for the intensive pesticide applications for control giving more reason why desmodium cover crop studies should extend beyond the "push-pull" technology in maize to other plantation crops like coffee.

Kudra *et al*., (2012), have also documented the direct negative effects of soil degradation in food production where it has been shown that soils with low fertility increases plants susceptibility to other biotic stresses. The approach of increasing resilience and sustainability through replenishment of soil organic matter and nutrient recycling in the advent of changing climate makes desmodium a suitable candidate for further evaluations in coffee production systems (Altieri *et al*., 2015). Studies have shown the potential of desmodium ability to fix adequate amounts of nitrogen per hectare per year under optimum conditions(Kebede, 2021). FAO, (2011) indicated the ability of the silver leaf desmodium as pure stand being able to add up to 90 kg nitrogen per hectare per year at 3:17 ratio, in desmodium / grass stands and up to 110kg nitrogen per hectare per year in a pure stand. Desmodium having the ability to control weeds by developing a canopy structure that prevents light penetration to support weed germination is also adapted to growing under moderate shade such as in coffee plantations and therefore providing livestock fodder makes it ideal as an option for the adoption by famers for the value of weed control and fodder provision (Andrews *et al*., 2011).

2.1.6 Desmodium Legume Forage species benefits in the nitrogen fixation mechanisms

Scientific studies have documented the biological nitrogen fixation complementing nitrogen availability in production systems with perennial legumes giving a greater advantage (Ambrosano *et al.*, 2011; Ovalle *et al.*, 2010). Cover cropping and intercropping have been utilized to give partial advantage of biological nitrogen fixation with perennial forage legumes ability to transfer over 90 % of their atmospheric nitrogen fixed (Appendix 4) to the companion crop compared to annual grain legumes shown contributing 50% (Ricci *et al.*,, 2005). Arbuscular mycorrhizal (AM) a symbiotic fungi, found in organically rich soils, helps other micro-organisms population influencing plant growth and soil productivity resulting in improved plant water relationship and increase drought tolerance by the host plants that has been evidenced in coffee systems (Garg and Chandel, 2010). The amount of nitrogen released is dependent on the legume recycling mechanism for own use and immobilization by soil microbial biomass (Ovalle *et al*., 2010).

Below ground nutrient transfers are facilitated by the presence of healthy mycorrhizal connections which are necessary for the direct transfer of nutrients between the donor and the recipient (fig 5) (Cooper and Scherer, 2012; Muneer *et al*., 2020). The age and management system of the legume species in addition to soil immobilization and microbial mineralization being key factors determining the amount of nitrogen available for transfer (Garg and Chandel, 2010). Intercropping coffee with a perennial, leucaena leucocephala (Lam) de Wit was reported to contribute 42% nitrogen to the coffee plant (Snoeck *et al*., 2000). Other studies on grapes indicated a contribution of up to 20% of nitrogen from annual pulse legume intercrops (Ovalle *et al*., 2010). The methods used for the determination of the nitrogen derived from green manure legume cover crops is isotopic enrichment in a controlled environment which enable isotope tracer to give comparison of the abundance of ^{15}N in the air with the biological fixation from the legume and the associated uptake by the recipient non legume plant (Ambrosano *et al*., 2011).

In the relationship between a legume donor and a non-legume recipient, nitrite accumulation in the root zone (20-40 cm depth) resulting from the legume fixation is sometimes higher than microbial uptake resulting in a higher concentration in the coffee root zone availing it for uptake (Dijkstra *et al*., 2009). Root exudation associated with the legume nitrogen fixation stimulates higher microbial activity thereby resulting in the soil having higher inorganic nitrogen (Kebede, 2021). The understorey desmodium legume cover crop serving as a live mulch (appendix 4) is able to utilize the light that penetrates the canopy resulting in greater capture of the light energy and reduce moisture evaporation which would otherwise promote weed growth (DaMatta *et al*., 2018).

The ability of the desmodium legume fodder to increase the nitrogen available for the coffee production system through biological nitrogen fixation (fig 5) will reduce the need for the intensive application of synthetic nitrogen fertilizers which will contribute to the mitigation of nitrous oxide emissions associated with synthetic fertilizers

2.1.7 Desmodium as a fodder to counter Climate change impacts

Increasing drier and warmer conditions in Sub Saharan Africa have been predicted to be greater than global average with more droughts being experienced regularly especially in the horn of Africa (IPCC, 2022) . With rainfall becoming less predictable with global weather modeling techniques indicating Kenya to be in precarious position, the vulnerable groups will be greatly affected by recurrent droughts (IPCC, 2022) . The increase in drought frequency and intensity will require farmers to urgently develop mechanism to develop resilience in their production systems. The increasingly dry conditions are resulting in inadequacy of feeds for the animals both dairy and beef due to pasture decline including shrubs for ruminants (Tolera and Abebe, 2007; Tolera and Sundstøl, 2000). With increasingly bigger losses crops and livestock as temperatures increase and dry weather persists, smallholder farmers face the equally devastating challenge of soil degradation (Kimaro *et al*., 2018). The increasing population growth has continued to put more pressure on land including grasslands and forests being cleared to make way for more land for cultivation. Increased livestock numbers and improved breeds has equally increased the demand for fodder in direct competition with human food production (Cheng *et al*., 2022).

With livestock population census by (KNBS, 2019) showing 17.4 million cattle (exotic and indigenous), 27 million goats and 17 million sheep, demand for livestock feed has been on the increase with reports on shortages and drastic price fluctuations. Herrero *et al*., (2012) were able to detail on the persistent feed shortage on quantity and quality in the dry season becoming the biggest risk to livestock production systems. Khan *et al*., 2010; Midega *et al*., (2015) , indicated that in addition to the use of Desmodium in the "push-pull" technology, had additional benefit of soil improvement through nitrogen fixation, weed control and source of fodder for livestock. legume cover crops research intercropping coffee with legumes has been shown to have ability to control weeds and increased the nitrogen content in the soil with desmodium among the positive candidates (Shackelford *et al*., 2019).

Kenyan farming systems will need to increase their resilience to climate shocks increasing the urgency for researchers to look for adaptation and coping mechanisms that are sustainable enhancing the reason why considerations for desmodium legume fodder cover crop in coffee plantations is considered as a perfect candidate for supplementary source of fodder and supporting overall coffee production. NDMA has not optimized on the available options for climate smart agriculture for coffee production farmers to support livestock programs with legume fodder cover crops in coffee production.

2.1.8 Condensed tannins in Desmodium considerations in reducing enteric methane emissions from livestock.

The reduction in production of enteric methane and reduction of the urinary ammonia by ruminants has been deemed of great value in reduction of impacts of livestock production systems to greenhouse gas emissions (Capozzolo *et al*., 2016; Carulla *et al*., 2011; Williams *et al*., 2015). Livestock consuming legumes considered less in fibre but having higher digestability thus better intake result in lower enteric methane production than low quality forages (Benchaar *et al*., 2001; Waghorn, 2008). Excreted ammonia is either converted in the soil into nitrate or nitrite oxidation resulting in the production of nitrous oxide (Katongole and Yan, 2020). This urea excreted from livestock is among the major sources of nitrous oxide emissions from livestock production (Brown *et al*., 2001; Katongole and Yan, 2020). The excretion of excess nitrogen from protein feeds once ingested is in the form of urine or feces and is the ammonia that is attributable to global warming potential (Williams *et al*., 2015). Diets given to animals containing high rumen degradable protein result in less protein being utilized by the feeding animals and as a result, there are higher nitrogen losses to the environment (Katongole and Yan, 2020).

High concentrate diets used in stall feeding results in higher emissions of nitrogen in the form of ammonia and nitrous oxides, the additional life cycle assessment adding up the fertilizer used in the production of the commercial feeds, compounds the greenhouse gas emissions attributable to livestock (Eckard *et al*., 2010). The estimates of 27% of the global nitrous oxide have been associated with livestock production systems and the manure management in the soil (Beauchemin *et al*., 2010). Methane production is considered as an energy loss in the animal digestive system, and reduction of its production by 25% has been seen to increase milk production by 1 litre / day, which is achieved through increasing feed efficiency (Bruinenberg *et al*., 2002; Eckard *et al*., 2010; Huang *et al*., 2010). During the period an animal consumes crude protein sources in the digestion system, protein escapes from the rumen as intact proceeding to the small intestines or it's broken down in the rumen by microbes with its transformation into ammonia (Hristov *et al*., 2013). Some of the ammonia is utilized by the rumen microbes as nitrogen source while some of the excess production can be absorbed in the rumen wall (Katongole and Yan, 2020). Conversion of the ammonia in the liver into urea makes it usable by the animal while the excess is excreted in the urine (Hristov *et al*., 2013).

In the search for the reduction of the greenhouse gas emissions in livestock production systems, condensed tannins have been found to be a good candidate for reducing the enteric methane production (Naumann *et al*., 2014). Replacement of 30-45 % forage portion with a diet containing condensed tannins in the range of 3- 9 % have been assessed for their ability to decrease enteric methane production without decreasing the necessary gas production for the rumen functions (Naumann *et al*., 2017). Condensed tannins like those present in desmodium are not degraded by rumen bacteria and the crude protein contained is able to convert into bypass protein that is absorbed in the small intestines without adversely affecting the rumen micro flora when in the right proportion (Naumann *et al*., 2017). Therefore legumes like desmodium which has a considerable content of condensed tannins could be used for the reduction of enteric methane production in livestock (Katongole and Yan, 2020). Tannins grouped as either hydrolysable or condensed are pervasive among different forage types available as feed resources for livestock in Kenya (Capozzolo *et al*., 2016).

The advantage of condensed tannins in feeds is the reduction of the protein breakdown by enzymes or the direct action by rumen micro-organisms aiding in the increased flow of dietary protein to the abomasum and the small intestines thereby increasing its bio-availability to the animal (Chen *et al*., 2021). Condensed tannins as well prevent bloat in cattle while aiding in suppression of worms (Kelln *et al*., 2021). Balanced supply of the forage high in condensed tannins should ensure proportionality due to palatability challenges and reduced digestability associated with excess consumption of tannins (Chen *et al*., 2021). Tannins are thought to exist in plants to reduce the herbivory challenges associated with animals and some protection against pathogens (Waghorn, 2008).   Under the rumen PH of above 5, tannin-protein complexes help protect protein from microbes' degradation in the rumen (Chen *et al*., 2021; McSweeney *et al*., 2001). Since the PH in the abomasum is below 3.5, the tannin- protein complex disassociate making them available for absorption by the animal (Yanza *et al*., 2021).

The protection of the plant protein ingested by the animals from degradation in the rumen, helps animals optimize on the protein derived from the feeds more efficiently and in addition reduce methane expelled from them as well as binding protein in feces instead of excretion in urine in the form of urea (Aguerre *et al*., 2016). Slow feces decomposition of livestock feeds high in condensed tannins helps reduce the nitrous oxide emissions from animal manure (Aguerre *et al*., 2016). In feces, nitrogen is organically bound making it more beneficial due to the slow hydrolysis process of changing urea to ammonia (deKlein and Eckard, 2008).

The use of forage that has some condensed tannins will therefore serve an important role in reducing enteric methane emissions from livestock and contribute to mitigation of the greenhouse gases associated with livestock production systems (Williams *et al*., 2015). Desmodium having condensed tannins fits in the description of the these forages that reduce the enteric methane emissions and the options for increased production such as adoption as cover crops in coffee production offers an advantage of increased production to increase availability to dairy farmers.

2.1.9 Evaluation of Farmers Knowledge, attitude and practices on Desmodium as a cover crop in coffee

Plantation monoculture systems such as coffee are particularly vulnerable to climate change and biotic stress increasing farmers' risks to poverty and poor living conditions (Chaudhary *et al*., 2019). Kenyan coffee national average yields have declined by 60 % over the last 40 years with associated factors being low coffee prices and high cost of inputs especially fertilizers, pesticides and labour cost (Karuri, 2021). The current average production in cooperatives served by smallholder farmers according to (CRF, 2012) is 200 kg/ ha with estates being able to do 700 kg/ ha. This level of production makes coffee production by smallholder farmers costly and therefore small holder farmers have the need to increase profitability per unit land area by eliminating improper practices have resulted in declining land productivity associated with soil degradation. Previously, labor intensive practices of terracing for soil conservation has become expensive with increasing labour cost and low coffee returns leading to farmers neglecting these labor intensive exercises making soils prone to soil erosion (CRF, 2003). CRF, (2005) had already indicated the decline in the use of manual labour in weeding leading to poor or late weeding and thus loss of moisture and nutrients from the weed competition. Previous studies in Murang'a small scale coffee farmer fields indicated yield depression of up to 50 % resulting from poor weeding practices (Gathura, 2013).

Using the aging contour hedge rows for 3 seasons on Afrisols on 15% slope in semi-arid Kenya, (Kinama *et al*., 2007b) were able to demonstrate the reduction of soil loss from just over 100 tons per hectare on sole crop, while only 2 tons per hectare were experienced when contour hedge rows with mulch were used. Contour hedge rows with mulch utilization the increased benefit of reduced water runoff from over 100 mm in the sole crop to just around 20 mm (Kinama *et al*., 2007b). The contour hedge rows and mulch served as an indicator of increased plant nutrient supply, improved soil moisture content and control of soil erosion through provision of ground cover. Some of the green manure legume cover crops were also seen to have the advantage of supplying animal feeds in areas where farmers practice zero grazing (Havlík *et al*., 2013).

Sustainable solutions aimed at adaptation to climate change and reduction of the greenhouse gas emissions will inevitably involve the promotion of integration of livestock systems with forestry and crop production (IFAD, 2010). Increasing farm diversity with integration of legume cover crop practices has been advanced as having the ability to improve livestock production, as well as the quality of soil, water, improve biodiversity habitat and contribute to nutrient cycling (Jose, 2009; Pearce and Wolfe, 2013). Additional feed improvement practices that improve livestock production efficiencies are desirable, with suggestions on feed conservation, diet composition modifications and inclusion of agroforestry species in animal diets (IFAD, 2010; Renaudeau *et al*., 2012; Thornton, 2010).

Farmers' knowledge, attitudes and practices limits adaptive capacity and speed of adoption of new mitigation measures to changing climate (Edwards-Jones and Cross, 2013). Incorporating the understanding of farmers' knowledge, attitudes and practices in policy development increases the achievement of objectives of better practices regarding environmental conservation (Islam and Toma, 2013; Oliver *et al*., 2012). Farmer education to help in decision-making for making choices based on risk perception to changing climate needs incorporation (Barnes *et al*., 2013). There is need for the dairy farmers to understand the need to engage in resilience measures to be able to cope with the unexpected challenges associated with changing climate. This study aims to specifically promote the use of desmodium cover crop, the positive results are a good indicator for its evaluation of legume fodder intercrops in coffee production systems all over the country, and there is a missing link in the practice of climate smart agriculture in coffee.

2.1.10. Governance challenges on the coffee sector in Kenya

Article 10 (b and) of the Kenyan constitution have indicated the national values and principles of governance and put good governance and sustainable development as among the key focus areas of observance in the pursuit of national development (GoK, 2010). Policy formation, coherence, coordination, implementation and evaluation are made with expected policy outcomes intended to address areas of interest to the government and its people. Success or failure of policy related to sustainable development is evidenced in the economic indicators such as the GDP/ capita, social indicators and environmental indicators. One of the challenges facing coffee growers is the many agricultural sector legislation, with over 300 pieces which are scattered and uncoordinated in several government ministries, parastatals and departments leading to inefficiency, incoherence and poor coordination with subsequent results of poor governance, confusion and conflict of interest among the industry players (Nyangito and Ndirangu, 2002). In the coffee sector even with (AFFA, 2013) with the coffee directorate, the ministry of Agriculture is in charge of policy formulation, extension and regulatory services while the rest of interventions are under the cooperatives and marketing with Counties being given the supervisory role. Many discrepancies between policy objectives and outcomes may result from inappropriate modes of governance, institutional framework and the communication strategy.

The positive policy outcomes resulting from identification of the most suitable solutions to the issues identified and their being correctly implemented will lead to a successful acceptance by the coffee farmers with their expected benefits. The current agency theory in the coffee sector where there is a divergence of managers having potential mischief in coffee management has led to the current challenges where managers gets higher rents than otherwise would be if the collaborative governance model was adopted where the engagement of stakeholders is done in a collective decision making formal process with deliberative and consensus based policy making and implementation (Bendickson *et al*., 2016; Imperial, 2005).

To realize human development needs and attain the right quality of productive function in a sustainable manner, good governance is required (Agrawal and Lemos, 2007), the competent management systems of a country resource with equity and response to people's needs is a requirement of good governance. Proper governance systems ensures political, social and economic priorities are participative and considers the consensus of the all including the poor and vulnerable in resource allocation (Booher, 2004). Good governance is a precursor in the attainment of inclusive development and helps in poverty alleviation with increased ability to meet sustainable development goals (Crosby, and Stone, 2015). Former UN Secretary General, Kofi Annan indicated that good governance is important for the protection of human rights, economic advancement and inclusive social development, further he insists that it instills best practices in a country's administration towards achieving sustainable development, the single most important factor in poverty eradication and promoting development (Choi and Robertson, 2014). The Methods of crop production which are based on sustainability with carbon sequestration and the additional advantage of being a cheaper source of crop fertilization needs to be evaluated and supported as the best farmer's options in their quest for adaptation in the climate smart agriculture options. The policies from AFFA have not yet expressly advised farmers on the best options for climate smart cover crop options in coffee production.

CHAPTER THREE

3.0 Materials and Methods

3.1 Study area

The study was conducted at the University of Nairobi College of Agriculture and veterinary sciences at the coffee plantation located in Kabete campus and Kabete Metrological station at a latitude of 1.21 South, Longitude of 36.75 degrees East, at an elevation of altitude of 1820 metres Above Sea level (5970 foot) (fig. 2). The average annual rainfall is estimated at 1100 mm and temperature range of 16 – 25^0C (Karuku *et al.*, 2012). Coffee research station (CRF) has been in research, selection and breeding processes especially with focus on flavour, resistance to diseases, drought and pests led to the development of through Scot Laboratory (SL) SL 34 (Gichuru *et al.*, 2008). The Nairobi University coffee plantation was established in the 1938 due to its ideal red volcanic soils, with the SL 34 coffee variety that has been managed continuously to produce better yields with a spacing of 2.74 m x 2.74 m, with the main weed control method being hand weeding and use of herbicide. The study area is ideal as there is minimal interference with other cultural practices that could interfere with the study results

The study period was for 2 rain seasons determined by the rainfall patterns in Kenya with the onset being September 2019 and the end point being December 2020. This was for 1 long rain seasons and 2 short rain season. The site location has acrisols formed from weathered volcanic rocks to give its distinct red volcanic soil with sub humid conditions ideal for coffee production. The elevation of the area is 1820 metres above sea level and enjoys bimodal rainfall. Onset of the Long rains season starts from mid-March and cessation is towards the end of May with a cold season extending to Mid-August, the second season has onset of rains in October and cessation in mid-December with higher temperatures extending to March before the onset of the long rains.

The mean annual rainfall is around 1000 mm (ASDSP, 2014). The second study where the farmer's questionnaire was administered, was in Githunguri sub County in Kiambu County which is the least affected by the urban sprawl of the Nairobi city while having similar climatic conditions as many other coffee growing areas in Kenya.

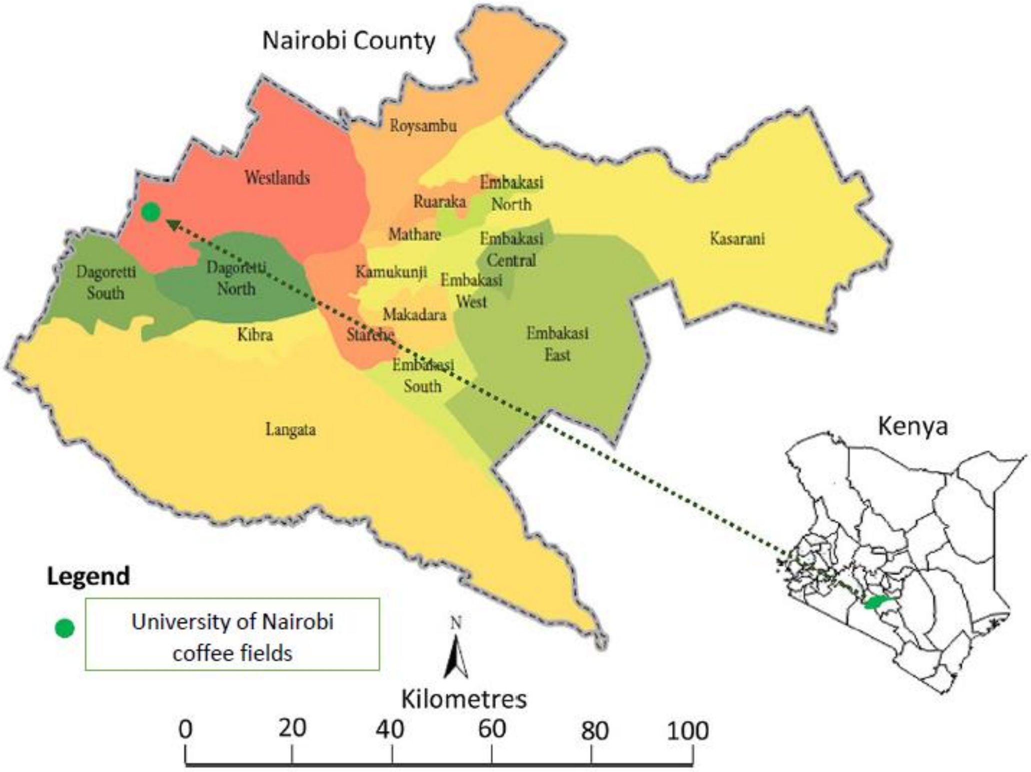

Figure 2: Map of the study area (University of Nairobi, Kabete coffee field plantation)
(Source; Extracted from google maps).

The methodology adopted the use of the randomized complete block design in the coffee plantation with 4 treatments (table 4) where manual weeding was initially done for all the treatments of the below practices:

a. Desmodium legume cover crop between coffee, 3 rows planted at 30 cm between rows
b. Manual weeding on the coffee rows as practiced by farmers (conventional tillage)

c. Herbicide (Glyphosate) weeding of the coffee rows as practiced by the university farm management(zero tillage)
d. Sole desmodium as control to compare on the biomass of desmodium planted alone

The 4 treatments were replicated 3 times in the same location

The design of the study adopted the block treatments where there was an equal distribution of the treatments as shown in the table 1.

Table 1: Treatment and block design for the expereiment at the University farm

Block 1 treatment	Block 2 treatment	Block 3 treatment	Block 4 treatment
A	A	C	D
B	C	B	D
C	B	A	D

3.2.0 Research Methods.

3.2.1. Study design.

To determine moisture and nitrogen concentrations at different times in the treatment plots in coffee plantation. The periodic monthly assessment of soil moisture and soil nutrients concentrations in the different treatments before and after the establishment of the desmodium cover crop at time of harvesting was recorded and tabulated in an excel table then evaluated with ANOVA analysis (Fisher *et al*., 1991) using the F statistic to check if there is any significant difference between the treatments means. The soil analysis was done just before the establishment of the desmodium cover crop for both nutrients and moisture through testing at the University of Nairobi faculty of Agriculture laboratory for all the treatments and then quarterly.

3.2.2 Data collection tools.

Soil moisture data was determined through the regular collection of soil samples from the baseline date in 2019 and using the blocks established in a zigzag way on the monthly basis period.

To evaluate the biomass yield of the fodder production at the appropriate harvesting stage of the desmodium planted at 30 cm apart and three rows between coffee plant rows and extrapolate the yields achievable per hectare using the treatments in the coffee plantation plots covering 6 m x 6 m (3 plots). The sole desmodium plots was also harvested and the yields extrapolated for yield per hectare.

Periodic 4 months harvesting of the desmodium fodder after establishment at the appropriate harvesting stage was dried at 40 degrees and weighed to establish the yield per square metre and extrapolate the equivalent yield per hectare after the establishment of the desmodium cover crop. The land equivalent ratio for the production of sole desmodium and the intercrop of desmodium and coffee was extrapolated to show the combined yields and individual yields of each of the crop planted independently.

3.2.3 Study Target population.

To assess the knowledge, attitude and practices of the coffee farmers in relation to using desmodium cover crop as part. An open ended questionnaire (Rowley, 2014) was administered with a purposive random sampling to ensure a fair mix of gender, difference in locality and difference in farm sizes with a stratified format to 95 farmers in Githunguri sub-County in Kiambu County which is the least affected sub County in the increased change of coffee plantations into housing units. GenStat was used to evaluate the responses and guide on the level of awareness of the advantages of the legume cover crops. An assumption of coffee farmers in Githunguri Sub

County being estimated at 55% CBK (2003) was used as a baseline for Githunguri Sub County. A sample size was determined using the method described in (Fisher *et al.*, 1991) as shown below.

$$n=Z^2pq/d^2$$

Equation 1: sample size determination; Fisher 1991

Where

n - Sample size to be calculated

p - Probability of occurrence

Z- 1.96 at 90% standard error

q - 1-p

d - design effect equals 1 (Githunguri Sub County)

d^2 - desired confidence of 0.1

And therefore N = 1.962X0.55 x0.45x1/0.12

= 95

Whereby the minimum number of respondents for the survey therefore must not be less than 95.

3.3. Data Analysis

The results of the field experiment where there was data on nutrients on different treatments and moisture content was tabulated and the total sum of squares analyzed with one way ANOVA using Genstat software. The data analysis focused on descriptive statistics (percentages and frequencies) and then the Sum of squares was analyzed for further inference of the means for the survey.

Genstat version 17 was used to assess the significance of the various treatments to the parameters that were being analyzed of moisture content and nutrients content for the different periods. LSD was used for separation of means. Values tabulated were used to plot the distribution and the associated probability (P) value which was then be used to test the hypothesis. The P value was significant at 0.09 for the 5th sampling which was significant for the moisture content for the plots having coffee and desmodium.

The research study was aimed at investigating if there is any significant relationship between soil, nutrition and moisture concentration when desmodium cover crop is used in coffee (mono crop) plantation and whether the fodder produced can be supplemental income for the farmers' as the fodder is used as a protein source in livestock production systems. The reduced weeding and fertilizer application can also be factored in relation to carbon sequestration and mitigation of greenhouse gases. The climatic variations that results in shortage of fodder for livestock farmers was also looked basing the perspective of the quantity achievable as an alternative sources of livestock fodder from the coffee plantations. There was need to investigate on the governance factors that has led to low adoption of the use of desmodium as a cover crop in coffee plantations with a view of contributing to the policy direction towards the adoption of agro-ecology in coffee production with the synergistic relationship to livestock production and improved production systems.

3.4. Hypothesis statement and the parameters

3.4.1 (a) Null hypothesis

i. There is no significant moisture conservation when desmodium legume fodder cover crop is used in coffee and therefore no value in adoption
ii. There is no significant crop nutrients fixation and weed control by desmodium cover crops when intercropped with coffee in the plantations
iii. There is insignificant fodder yields achievable when farmers intercrop desmodium with coffee
iv. There is no production difference in coffee production between the current farmer practices and adopting the desmodium legume fodder cover crop in coffee.

3.4.2 (b) Alternative hypothesis

i. There is significant moisture conservation when desmodium legume fodder cover crop is used in coffee and therefore farmers should embrace this legume fodder cover crop in a wider scale.

ii. There is significant crop nutrients fixation and weed control by desmodium legume cover crops when intercropped with coffee and should be the driving force for farmers accepting new adaptation methods.

iii. There is significant fodder yields and possibly the reason why farmers would like to use the cover crop as means of better crop husbandly

There is a considerable coffee yield difference when desmodium legume fodder cover crop is intercropped with coffee and the reason farmers should consider this climate smart approach.

3.4.3 The hypothesis testing parameters and deductions

Null hypothesis

i. There is no significant moisture conservation when desmodium legume fodder cover crop is used in coffee and therefore no value in adoption was tested with the t test and P value which was = 0.069 that means that the was outside the test area and thereby alteternative hypotheis accepted that there was significant moisture conservation when desmodium was used as a cover crop.

ii. There is no significant crop nutrients fixation and weed control by desmodium cover crops when intercropped with coffee in the plantations was tested with the presence or absence of weeds and the significant weeds that were assessed using the 1 metre quandrant indicated a higher abudance of weeds where hand weeding and herbicide treatment were used. Using the Shanon Weiner diversity comparison whereby the hand weeding and herbicide treatments had higher weed frequency, growth, diversity and overall need for repeat operations which were absent in the desmodium treatment. Thus the alternative hypothesis was accepted that since desmodium reduced the weed incidence.

iii. There is insignificant fodder yields achievable when farmers intercrop desmodium with Coffee at the period of harvesting the coffee, there was significant desmodium biomass yields as indicated by quadrangular quadrat method as indicated by ’t Mannetje, (2000), involving the harvesting of the fodder by cutting using 1 m x 1 m frame then after drying, extrapolating to estimated yields of fodder per heactare per year. The results of the data analysis indicated significant ability of farmers to harvest close to 17 tons per heactare while saving weeding costs which was a significant yield comparison absent in both the herbicide and hand weeding plots. The yield difference therefore strongly made the relevance of the alternative hypothesis to have a stronger score as indicated in the study.

iv. There is no production difference in coffee production between the current farmer practices and adopting the desmodium legume fodder cover crop in coffee which was tested by the Intercluster correlation (ICC) using regression method indicating that desmodium cover crop had 1.8 times higher production than herbicide treatment and 1.2 times higher than hand weeding. This indicated a significant difference allowing the decision criteria to favour alternative hypothesis.

CHAPTER FOUR

4.0 Optimization of Ecosystems Services for Sustainable Coffee Production under Changing Climate (East African Journal of Science, Technology and Innovation, Vol. 2; 2021(Special Issue)

4.1 Abstract

Although use of legume cover crops have previously been evaluated for green manure, weed control and soil moisture conservation, their evaluation as a source of biomass for protein fodder intended for feeding livestock has been missing. The focus of our research was to compare soil nutrients and moisture concentration at different times in the treatment plots in the coffee plantation after establishment of desmodium legume cover crop with quantification of the resulting biomass as fodder for livestock. This case study conducted at the University of Nairobi coffee plantation evaluating different weed control methods in coffee using hand weeding, glyphosate (1.0 kg ha-^{1} of acid equivalent) based herbicide and desmodium spp legume cover crop compared weeding costs and implications to farmers' incomes in coffee production. Using randomized complete block design 4 treatments replicated 3 times were analyzed for the annual weeding labour costs, soil nutrients, soil moisture and biomass production. Statistical analysis of soil moisture content and nutrients was evaluated among the treatments. The results indicated that soil in the coffee intercropped with desmodium had a higher moisture retention of 36 % on average being higher than other treatment and desmodium legume fresh biomass production was extrapolated to 17,000 kgs per hectare per year. Desmodium spp planted was able to establish providing groundcover (90%) 18 weeks after planting inhibiting weed growth thus reducing the frequency for weeding as well as conserve soil moisture. There was significant savings on the cost of manual weeding with additional earnings or savings of USD 750 from sales or utilization of the desmodium fodder per hectare. The study suggests that cover crops can enhance farmers' resilience to changing climate utilizing the same size of land without extra inputs and increase farm revenues. Our study indicated possibilities of additional biomass production of desmodium forage rich in crude protein (protein 18% DM), which can reduce the reliance on grains as a protein source for animal feeds. Policy makers' realignment of extension services introducing desmodium legume cover crops in coffee production for the reduction of high weeding labour costs and associated ecosystem benefits to farmers would assist in increasing farmers resilience.

Key words: Biomass, Desmodium, Legumes, sustainability, Weed control

4.2 Introduction

Cash crops are sensitive to extreme weather patterns which has become more unpredictable with climate change impacting on their productivity (IPCC, 2007), this disrupts national economies as a result of decline in export earning associated with coffee and other cash crops with extra impacts on related industries (Parker *et al*., 2019). Sub-Saharan Africa already experiencing food insecurity and is ill equipped to accommodate the predicted yield losses (IPCC, 2007). Data from the global coffee platform (GCP) indicates that there are 115,600 hectares under coffee in Kenya with more than 98 % being Arabica, while 97% of the produce is exported (GCP, 2018). In 2018, 41,000 metric tonnes were produced by an estimated 790,000 farmer's majority being smallholder farmers (GCP, 2018).

There is importance to focus on the smallholder farmers for the growth and development of agriculture in Africa through agricultural intensification (Kamara *et al*., 2019). Declining land holdings are heavily constraining the smallholder agricultural capacity in many African countries (The Montpellier Panel, 2013) coupled with continued decline in soil fertility thereby resulting low productivity (Tully *et al.*, 2015). The paths towards increasing food security in times of changing climate therefore calls for sustainable intensification of the small holder agriculture

(Snapp *et al*., 2010). Juma *et al*., (2013) studies undertaking on the need for intensification in agriculture points out on the need to ensure sustainability by producing more using the same or less land and water with prudent use of agricultural inputs.

Monocultural coffee production promoted during the green revolution (Pingali, 2012) saw the research for sun tolerant varieties, technological packages with scientific backup relying heavily on synthetic inputs aimed at increasing yields which were adopted. Pingali and Rosegrant, (1994), noticed that the green revolution, saw the focus of the time being promotion of monoculture of similar genotypes, that were often attacked by diseases and pests which made it necessary for widespread application of toxic pesticide that had significant impact on the biodiversity, soil and water systems. The term “soil sickness” derived from the progressive soil quality loss resulting from monocropping, has been associated with the aggressive response of bacterial populations in monoculture agro systems for the peanut production (Chen *et al.*, 2020).

The associated loss of beneficial biodiversity of bacterial populations while increasing the other non-beneficial genera, indicated the influence of monocropping to simplification of bacterial communities with loss of ecosystem services associated with plant growth promoting functions (Chen *et al*., 2020). The realization of the SDG 1 of ending poverty, is not achievable by coffee farmers with the continued depression of farm gate coffee prices, which has pushed farmers to further poverty (UN, 2020), thus denying them ability to achieve a decent livelihood. This is despite coffee being the raw material for the $ 200 billion dollar industry (ICO, 2019).

Solutions to significantly reduce poverty among the coffee farmers is critical for achievement of the SDGs in the coffee industry requiring innovative models such as intercropping with desmodium legume fodder crops to increase profitability among the producers and supporting social protection among the producers and farm workers (Place and Migot-Adholla, 1998).

Diversified coffee cropping has been assessed for the potential environmental impacts improving on carbon dynamics and resulting in higher outputs in terms of land use (Acosta-Alba *et al.*, 2020). Selection of synergistic species offering multiple benefits such as carbon sequestration among other ecosystem services are great innovations for the improved synchronization of nutrient release patterns for the different crop demands, especially under adverse conditions, they are important in the selection of complementarity traits that enhances resilience and functionality (Scholberg *et al.*, 2010).

Zeng, (2015) studies focusing on continuous cropping in particular monocultures like the open sun grown coffee have surprisingly found that plant growth is usually reduced with weakened plant resistance to diseases and lowered quality with an accumulation of soil borne diseases that can result to economic losses due to poor yields. Resulting soil conditions referred as continuous cropping obstacles results from the deterioration of physiochemical soil properties loss of ecosystem services (Zeng, 2015), build-up of crop related soil borne pathogens and other harmful plant substances due to disturbed microorganism ecosystems (Vargas *et al.*, 2009) . Fungal pathogens accumulation in the soil micro-biota, are thought to be responsible cause of the continuous cropping obstacle disease (Manici *et a*l., 2013; Xiong *et al.*, 2015). The relationship between long-term inorganic fertilizer applications with resulting decline in organic matter can be attributed to PH alteration in most coffee fields (Ladha *et al.*, 2005). Monocropped coffee, have been associated with production of own allelochemicals suspected to influence long term soil acidification (Ehrenfeld *et al.*, 2005).

Dunn *et al.*, (2016), gives definition of cover crops as plants intentionally grown to cover the soil with properties of soil protection from soil erosion, losses of nutrients during and between periods of regular crops production like those grown between vines and trees in orchards and vineyards, additionally includes cover crops provisioning of beneficial ecosystem services (Schipanski *et al*., 2014). Legume cover crops are ideal for fitting in the climate smart coffee practices especially those that develop quickly, those suited to the weather and soil conditions under coffee as evaluated while serving the role of weed control (Gachene and Wortmann , 2004). Coffee systems intensification have been documented to be more sustainable when integrated with other crop species to complement biodiversity, improve soil fertility, improve on moisture retention, aid in soil erosion reduction while additionally aiding in carbon sequestration (Jassogne *et al*., 2013).

Weed control in coffee is a major hurdle to farmers' productivity and profitability and therefore the need for regular weed control, despite increasing labour costs farmers still need to attend to the coffee to ensure weed competition is reduced (CBK, 2005; Mureithi *et al*., 2003). Continuous cropping in most of the coffee producing areas found in the hilly areas of central Kenya, have reduced in profitability per unit land area due to increased erosion (Kogo *et al*., 2021), this is further declining crop yields with smallholder coffee farmers producing as low as 200kg per hectare resulting in food insecurity and increasing poverty levels (CBK, 2005).

The best fit for weed control in coffee using cover crops have been shown to be legume cover which are ideal for intercropping, which has been defined as having effective ability to suppress weeds, control soil erosion with additional soil fertility improvement (CIAT, 2010; Gachene and Wortmann ,2004). Fodder legume intercropping have the advantages of resource optimization such as light, moisture and nutrients while also transferring nitrogen to the other crop with confirmed soil protection from erosion, weed and pest control (Voisin *et al*., 2014).

Weed management is an expensive undertaking which should be minimized or avoided (CRF, 2003). Adoption of desmodium cover crop which smother weeds and reduce competition with coffee for nutrients, sunlight and water with weeds, are suited to serve other biological systems such as releasing biochemical (allelochemicals) that either lead to less weed germination or entirely killing them (Lu *et al*., 2000; Midega *et al*., 2017). Additional production of high biomass diminish the ability of weeds to grow (Mwendwa, 2017). The current rise of super weeds with great resistance to herbicides is making the long term ecological use of herbicides a major challenge due to increased dosages aimed at extermination of the resistant weeds (Bain *et al*., 2017) .

Continuous cropping in low fertility soils have resulted in increased soil degradation with the constant nutrient extraction at a rate higher than replacement or natural regeneration (Olsson *et al*., 2019; IPCC, 2019) and additionally continuous tillage reduces the soil organic matter (SOM) content resulting in reduced soil absorption capacity thereby reducing water retention predisposing the soils to soil erosion with runoff water. Despite the benefits derived from soil organic matter such as binding soils resulting in greater stability thus reducing soil erosion potential, SOM acts as the provision source for energy and carbon for soil micro-organism while storing carbon (Wood, and Scherr, 2000).

Heavy downpours during the rainfall seasons in many tropical agricultural systems results in varied rates of soil erosion especially on sloping areas, runoff and increased soil evaporation (Kinama *et al.,* 2005a, 2007b). In many high elevations beyond 1200 metres above sea level where coffee is currently being grown on sloping grounds, soil erosion is a constant challenge especially due to reduced vegetation cover predisposing the areas to soil erosion of huge magnitudes where no soil erosion control measures are instituted (Acharya *et al*., 2008). Ehui and Pender, (2005) studies indicates that more than 40 tons per hectare of soil are lost in hilly areas from soil erosion annually, with resulting fertility resulting in poor soils in hilly areas where adoption of soil and water conservation measures are absent in Ethiopian highlands.

Kinama *et al*., (2007), while evaluating the most ideal control for soil erosion on steep slopes observed that hedge rows and mulch were able to reduce soil loss, reduced runoff and increased yields with sustainable and tolerable soil loss. Hedgerow intercropping and mulching was seen to reduce soil evaporation in a more economically important yield increasing advantage in comparison with sole cropping (Kinama *et al*., 2005a). As a result, soil nutrient depletion in these higher elevation areas in east Africa is much higher than in many other parts of sub-Saharan Africa attributable to soil erosion with consequent nutrient loss (Hazell and Wood, 2008) that makes it necessary to compensate with additional fertilizer usage.

Rugged topography is associated to soil erosion through slope steepness and slope lengths whereby the topography like in many coffee growing areas, results in high costs of physical conservation via construction of conservation structures such as terraces (Kinama , 1990). Studies done in Kenya using contour hedge rows and grass strips (Kinama *et al*., 2007b) found that the soil erosion was reduced and the crop productivity would sustainably be maintained with less soil and nutrient loss. Hedgerow intercropping increased plant growth promoting solar radiation interception and biomass formation in the experimental area showing the advantage of utilizing space more optimally (Kinama *et al*., 2011). Other benefits such as weed suppression, improvement of the efficiency of nutrient cycling while providing additional revenue are important considerations when choosing cover crops (Baligar and Fageria, 2007).

Adoption of cover crops however remain very low at estimated 4% with portioning of the field for some cover crop growing (Wade *et al*., 2015). Among the cited factors for low adoption rates being producer compatibility with the cover crop, or expected moisture competition, increased management cost, extra machinery requirement and incoherence in policy (Reimer *et al*., 2012). Roesch-McNally *et al*., (2018), while indicating the farmers' appreciation of the benefits of cover crops indicates that the need to have additional management requirements, possible changes in the nutrient application and possibly further equipment modification reduces farmers drive to adopt cover crops while market drivers and related economies in large scale operations are unfavorable. Reckling *et al*., (2016), further indicates that the agronomic risks of legumes which are more sensitive to moisture stress in comparison to cereals is a major consideration in Europe, this is absent in the tropics where no winter is experienced and therefore adoption of legume cover crops should be highly encouraged and promoted.

Improved soil health resulting from accumulation of organic matter especially with atmospheric nitrogen fixation from legumes have been seen to benefit recipient crops from the nitrogen transfer and improved water holding capacity (Lu et *al*., 2000). Rapid legume decomposition resulting from their low carbon to nitrogen ratio increases availability of nutrients (Lu *et al*., 2000). Overcoming the barriers to adoption of legume cover crops require better communication on precise speed of release and the quantification of the nitrogen available for the associated crop relationship, with equivalent reduction in the application of the synthetic fertilizers (Bergtold *et al.,* 2019).

Studies on biological nitrogen fixation have proven that forage legumes can transfer almost 90% of their nitrogen to the companion crops (Unathi *et al*., 2018) from atmospheric fixation whereas for grain legumes it’s only at 50% despite factors such as legume species, soil microbial status for mineralization and immobilization, management and age being determinants (Tu *et al*., 2006). Studies evaluating the performance of different legume cover crops on coffee for weed control and nutrient benefits, indicated desmodium as a suitable candidate for further evaluation (Gachene, and Wortmann, 2004; Jassogne *et al*., 2013) as a way of increasing sustainability in coffee production and reducing the excessive use of synthetic nitrogen fertilizers and herbicides in weed control. Szumigalski and Van-Acker, (2005) studies further looked at possibilities of eliminating chemical weed control using cover crops and concluded that they are suitable sustainability measures for soil improvement.

Challenges related to feed availability from fodder is projected to exponentially complicate farmers' livelihoods and agricultural sustainability therefore requiring urgent interventions to increase their resilience (Tucker *et al*., 2015). The important role played by livestock an integral part in smallholder farming practices cannot be ignored due to its central role in nutrient provision, income source, manure provision and sometimes draft power for farm operations (Millennium Ecosystem Assessment, 2005). Many smallholder coffee farmers in Kenya incorporate livestock in their farming systems and thus cover crop that can be harvested as forage for livestock has been seen to have more advantages and more profitable (Snapp *et al.*, 2005).

Njarui *et al*., (2016) further amplifies the urgency of alleviating the major constraint to the smallholder farmers of livestock feed scarcity due to the recurring seasonal rainfall fluctuations. Cover crops such as desmodium spp. (Gacheneand Wortmann, 2004), that increase moisture percolation during rains, reduce speed of run off, reduce soil erosion and retain nutrients are among the most feasible sustainability solutions for the Kenyan coffee production systems. Cover crops like desmodium spp possessing deep rooting systems (Kinyua *et al*., 2019) have been seen to reduce soil compaction common with frequent field operations while improving soil health and aiding in improving the soil carbon content and nutrient availability (Schipanski *et al*., 2014). Blanco- Canqui *et al*., (2020) have shown the great benefits of having cover crops harvested as source of livestock feed in addition to the provision of the associated ecosystem services.

The current approaches to weed control in coffee production are associated with negative environmental impacts such as soil erosion and loss of ecosystem services. Previous studies on using cover crops for weed control in coffee were on agronomic practices and not focused on the framework of sustainable agricultural intensification practices with provision of ecosystem services and biomass production potential of desmodium legume as livestock fodder. The objective of our study was for the evaluation of integrating ecosystem services from integrating desmodium legume cover crops in coffee production, by comparing soil nutrients and moisture concentration at different times in the treatment plots in the coffee plantation after establishment of desmodium legume cover crop and quantification of the resulting annual biomass as fodder for livestock.

4.3 Materials and methods

Study area description

The field experiment was carried out at the University of Nairobi field 7 station at Kabete Campus coffee plantation (figure 3) with coordinates of 1’15l’’ S and 36’ 44l’’ E selected for having desirable climatic attributes fitting coffee production areas in Kenya, the availability of land for the study, coffee production systems and fitting to the environmental conditions of adjacent Kiambu County a major coffee growing area. The elevation is an altitude of 1940 m above sea level with similar climatic conditions of the high attitude coffee growing zone part of Central Kenya coffee highlands.

The soils comprise well-drained, dark red to dark reddish brown friable clay loams defined as very deep (> 30 m) (Mwendwa *et al.,* 2020). The main soil composition is the humic Nitisols as classified by (Karuku *et al.,* 2012) don’t experience sealing or crusting at the surface although percentage of clay may increase with depth (Gachene and Wortmann, 2004). The location experiences 2 rainfall seasons with long rains between Mid-March- May and short rains in Mid-October to December giving a characteristic of semi humid area with an annual rainfall of 1006 mm (Sombroek *et al*., 1980). The land is relatively gentle sloping basing on the Kenya Soil Survey agro climatic zonation methodology (Mwendwa *et al*., 2020).

The climatic conditions of Kabete coffee field station closely mirrors the same climatic conditions as the surrounding coffee growing areas in Kiambu County that is gradually reducing its coffee production due to the reduced returns from coffee production (CIAT, 2010). The coffee variety planted is SL 28, recommended for the medium to high altitudes less prone to coffee leaf rust with a recommended spacing of 2.74 x 2.74 m giving an average of 1330 trees per hectare (CRF, 2005).

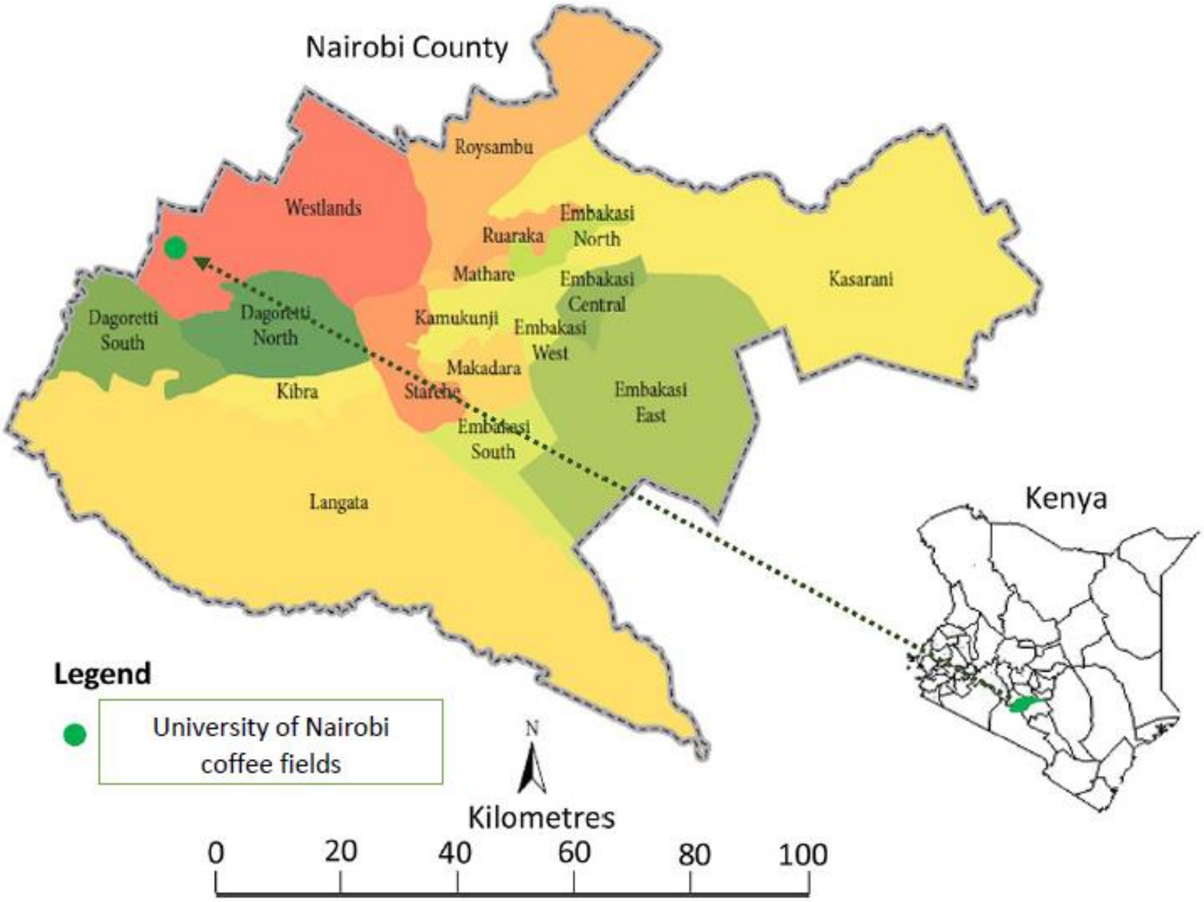

Figure 3; Map of the study area (University of Nairobi, Kabete coffee field plantation)
(Source, extracted from Google maps)

Research design and treatments

The study consisted of 4 treatments; the treatments were coffee + desmodium legume cover crop, coffee + hand weeding, Coffee + glyphosate salt herbicide (1.0 kg ha-^{1} of acid equivalent) and sole desmodium separately. The factorial set up for the treatments which comprised desmodium intercropped with coffee for weed control, manual weeding with hand hoes, herbicide treatment using and sole desmodium. The treatments plots were replicated 3 times with each plot measuring 6 m x 12 m. The different treatments relating to common coffee farmer production practices were setup for comparison. The set up using randomized complete block design of 4 treatments replicated 3 times in plots measuring 6 x 12 metres. The treatments plots each measuring 6 m x 12 m each containing 9 coffee bushes (except the sole desmodium planted adjacent to the coffee area) were selected in August 2019.

At the onset of the experiment in September 2019, all the plots were manually weeded and all weeds cleared. Desmodium spp was planted inside the coffee plantation for the 3 treatment plots (A1, B3 and C3) and 3 other separate sole desmodium plots. After the short rains, glyphosate herbicide was applied in 8th November 2019 on the treatment plots A3, B2 and C1, while hand weeding was done on the treatment plots A2, B1 and C2. Monthly, soil samples were taken from a depth of 30cm with 9 cores (Houba *et al*., 2000) taken from each treatment plot, using a soil auger. The soil samples from each treatment plot were thoroughly mixed and 1 kg sample taken which was later delivered to the University laboratory for soil moisture analysis.

A total of 12, (1 kg) samples were delivered each time for analysis. Soil samples for nutrients evaluation were taken after every 3 months with the baseline sample taken in October 2019. The glyphosate herbicide application and hand weeding continued every 4 months. Fresh desmodium biomass was harvested from the treatment plot measuring 6 m x 12 m and weighed at the intervals of every 4 months from the date of planting.

A baseline weed population and diversity was done at the start of the experiment and then every 3 months to describe the most dominant and aggressive species. Weed samples were pulled out from 1m x 1m subplots inside the main experimental plots and classified according to their category with their diversity and abundance recorded.

Data collection

Soil samples were taken regularly on a monthly basis for purposes of moisture monitoring from a depth of 0 -30 cm using a soil auger from each of the 12 experimental plots using a zigzag way to obtain 9 cores from each plot (Houba *et al.*, 2000). The soil samples from the 9 cores were thoroughly mixed and a sample of 1 kg taken as a representative for each experimental plot. Samples for moisture content analysis were taken every month for each plot for 6 months. The 1st /baseline sample was taken in October 2019 and every other month for 6 months respectively for moisture analysis. The soil samples for nutrient analysis were taken from each experimental plot with a soil auger for the 0-30 cm, using 9 cores for each experimental plot and the soil thoroughly mixed. 1 Kg sample for each of the experimental plot was clearly labeled for further lab analysis. The clearly labeled soil samples were collected and delivered to the University of Nairobi soil science laboratory at Kabete within 2 hours of collection.

Desmodium harvesting started 19 weeks after planting on each plot measuring 6 m x 12m. The fresh weight of the harvested desmodium was weighed for each experimental plot and recorded for tallying to get the annual yields. Every 3 months, desmodium fodder from each experimental plot was weighed and weight recorded. The final weight after the 4th harvest was presumed to be the final weight for 1 year. The Desmodium legume fodder biomass harvested after every 3 months, from the area of 1 square meter was dried and weighed. The weight of the biomass was determined then multiplied to the equivalent of 1 hectare for extrapolating the potential yield per hectare using the't Mannetje (2000) method which uses the 1 square metre as the baseline for the determination of fodder yields per hectare.

Data analysis:

Descriptive statistics for the soil nutrients and soil moisture concentration was summarized using Ms excel and data further evaluated using GenStat 14.1, using the GenStat Procedure Library Release PL22.1. The data was run for bivariate correlation among the sampling times per each parameter to understand their interaction trends with time. Then significant correlations among the parameters across the four sampling times were compared. Analysis of variance (ANOVA) for each parameter across the four sampling times was run to show the influence of the each treatment on the soil moisture at different sampling times. For the biomass production and weeding costs, the data was collected and summarized in a spreadsheet grouping different items in the list of similarity of sampling treatment and time, then extrapolated to show the biomass production and cost of weeding per hectare.

4.4 Results and discussion

Coffee production systems are faced with challenges of weed control and moisture losses during the dry weather, while the recommended spacing of varieties such (Scottish Laboratory variety)

SL 28 of 2.74 mx 2.74 m makes weeds become a major challenge (CRF, 2003). The spaces between plants and rows allow for adequate sunlight to support their photosynthesis.

Weed population and diversity

All the individual emerged weeds at the stage of 20 cm were uprooted and grouped for identification for the subplot with 1 m x 1 m frame using the Shannon Weiner (1960) method of weed diversity desciption for each individual plots where weeds were present especially for the hand weeding section. The emerged uprooted weeds were then grouped into annuals and perennials. The most common weeds that we observed with a population of more than 30 emerged plants attaining a height of 20 cm in the 1m x 1 m sampling subplots were Amaranthus spp (pig weed), Bidens pilosa (black jack), Oxygonum sinuatum (Double Thorn), and Tegetes minuta (Mexican marigold) for the broad leaved annual weeds.

The perennial weeds observed with high occurrence frequency based on the Shannon Weiner (1960) diversity index were Commelina benghalensis (Wondering Jew), Cynondon dactylon (Stargrass), Cyperus rotundus L. (Nut grass), Digitaria abyssinica (Couch grass) and Oxalis latifolia (Wood sorrel). The creeping habit of some of the perennial weeds makes them challenging once established, while the production of numerous seeds from the annuals makes their abundance a challenge to control (Odhiambo *et al.*, 2015). From our observations, we found that desmodium legume cover crop after establishment was able to achieve complete weed suppression due to its creeping habit thereby completely covering the ground, preventing weeds from emergence. This is in line with findings by Gachene and Wortmann, (2004), which indicated that at 29 weeks after planting, Desmodium was able to completely cover the grounds preventing weed emergence.

The efforts by farmers to control weeds using either chemical or manual weed control comprises a major cost in their operations and reduces the revenue from coffee production (CRF, 2003).

Despite herbicides and tillage dominating the main weed control practices, both have been evidenced as having environmental impacts especially amplified by increased weed herbicide resistance, thereby calling for an agro-ecosystem based approach to weed control (MacLaren *et al.*, 2020). While manual weeding is widely practiced by smallholder farmers using implements such as hoes, jembes and pangas, soil degradation impacts have been observed such as predisposing the soil to erosion (Thierfelder and Wall, 2009).

Different classes of weeds such as annuals, biennials and perennials affect coffee plants in different ways mainly competition for water and nutrients, while maturing more quickly and could also harbor pests (Hakansson, 2003). CRF, (2003) have indicated that weeds could reduce yields by up to 50 % and the most prevalent and troublesome weeds in Kenya coffee systems are Amaranthus spp, Bidens pilosa (black jack), Commelina benghalensis (Wondering Jew), Cynondon dactylon (Stargrass), Cyperus rotundus L. (Nut grass), Digitaria abbisinica (Couch grass), Oxalis latifolia (Wood sorrel), Pennisetum clandestinum (Kikuyu grass) Tagetes minuta among others.

Intensive tillage which results in declining soil organic matter increases soil compaction thereby reducing water absorption and retention, with consequent increase in soil moisture loss from rapid run off, wind and sun evaporation with resulting water quality effects from soil erosion (Bruinsma and FAO, 2003; Thierfelder and Wall, 2009). We found out that using desmodium legume fodder cover crop reduces soil compaction since there are limited tillage operations on the farm. Continuous tillage affects soil microorganism diversity, population and ability in nutrient cycling is highly diminished reducing their ability to provide the ecosystem services (Millennium Ecosystem Assessment (Program), 2005).

Some observations on the tolerance or slow response of the black jack weed to the glyphosate based herbicide could be supported by the observation that continuous usage of glyphosate based herbicides to control weeds in coffee plantation in Kiambu is already being reported to have resulted in some weeds being reported to developing resistance/ tolerance (Migwi *et al*., 2017). The abundance of this weed species after glyphosate herbicide weeding operations being indicated either as tolerant or resistant and bidens pilosa (black jack) was found to be most abundant after herbicide weed control operations (Migwi *et al*., 2017). This is becoming a global problem that has been noted in the United States of America of the challenges of resistant weeds compelling farmers to increase dosages of toxic herbicides which are increasing the environmental harm associated with excessive herbicide usage (Carvalho, 2017).

Soil moisture retention.

Table 2: Soil moisture trends accross the treatments for the 6 months sampling at the University of Nairobi, Kabete coffee field plantation

Treatment/ Moisture content %	**30 days after set up**	**60 days after set up**	**90 days after set up**	**120 days after set up**	**150 days after set up**	**180 days after set up**
Coffee+Herbicide	24.84 %	22.79 %	36.07 %	29.03 %	40.27 %	38.52 %
Sole Desmodium	36.54 %	24.79 %	32.87 %	27.42 %	36.54 %	45.59 %
Coffee+Hand weeding	27.11 %	23.76 %	35.5 %	28.86 %	38.55 %	50.55 %
Coffee+Desmodium	22.11 %	27.25 %	41.4 %	32.52 %	35.46 %	57.66 %

The observations on the moisture was based on the sampling periods whereby timing was on montly basis. During the periods of dry weather after establishment of the sole desmodium, there was a better moisture retention as shown in table 4, and this could be attributed to the lower competiion since the plot didn't have any coffee bushes within the plot.

The significant moisture differences in the treatments were observed during from the 4th and 6th sampling when the desmodium treatment in the plots with the coffee coffee bushes had considerably better soil moisture contnent than the treatements of hand and herbicide weeding in the same location where competition between the coffee and desmodium was evident. The 5th sampling had desmodium showing slightly lower soil msoiture content as it was during the extrermly dry period.

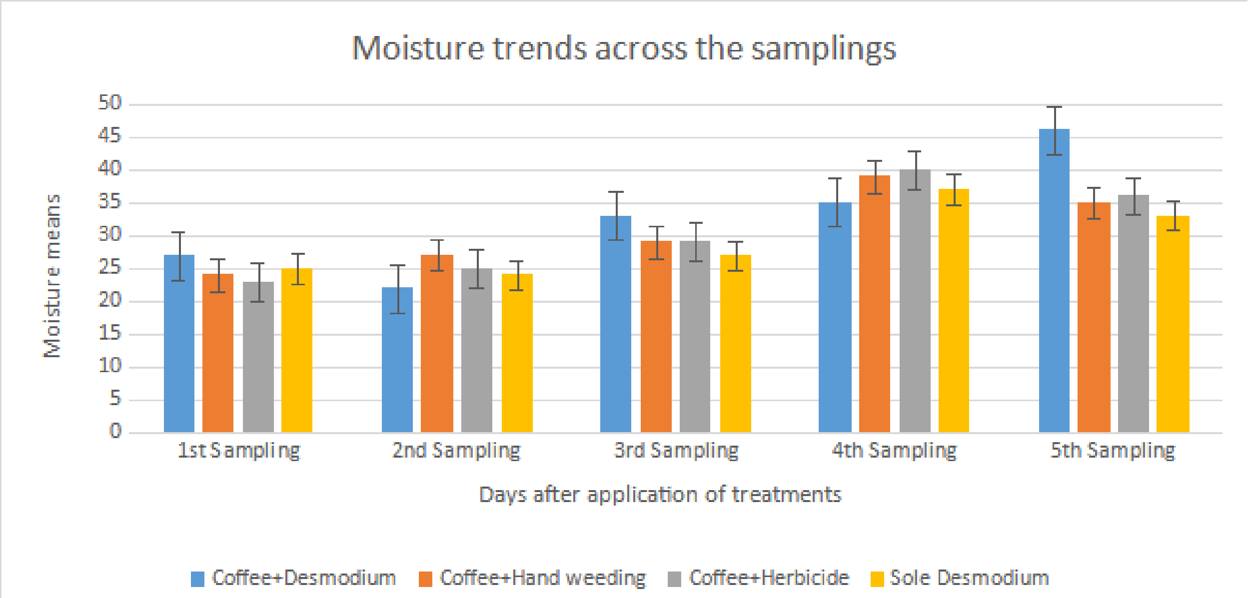

Figure 4: Moisture percentage trends accross the sampling times at the University of Nairobi coffee plantation

Legend: Error bars represent the standard deviation.

From figure 4, Moisture was lowest in 2nd sampling (24%) and highest at 4th and 5th sampling (38%). 1st sampling correlates with 2nd sampling (r = 0.626, p-value = 0.029) at 0.05 while it correlates with 3rd and 5th sampling (r = 0.733, p-value = 0.007 and r = -0.710, p-value = 0.01) at the 0.01 level. 2nd sampling correlates with 3rd sampling (r = 0.899, p-value = 0.000). The low moisture indication was during the dry period when there had been no rains for the month during the sampling.

The study found out that after establishment of desmodium, there was a better moisture retention in the presence of a cover crop, which could also be related to better rainfall percolation which would also be indicative of better control of runoff. The moisture retention was more enhanced as the desmodium continued its establishment indicative of better soil coverage and reduction of runoff from the rains. The treatments that had desmodium cover crop indicated higher moisture retention than the hand weeding and herbicide application possibly because for the other treatments, the ground was left bare allowing more soil evaporation while desmodium provided ground coverage reducing moisture loss.

The monthly soil sampling was collected from the site for analysis as per the results indicated that showed that the cover crop was able to have a high moisture retention in comparison with the other treatments. Kinyua *et al.*, (2019) analysis of the benefits associated with selection of the right cover crop indicates their nature of being deeply rooted and ease of management, while being viable economically having multiple uses and their ability to conserve soil moisture as an important attribute in cover crop selection.

Climate change impacts of increased land surface temperatures have a corresponding increase in soil evaporation termed as the “unproductive soil moisture loss” responsible for lowering crop and land productivity, affecting soil water balance leading to soil water unavailability to crops and subsequent lower crop productivity (Bhatt and Hossain, 2019). Since soil moisture holding capacity have a direct influence on crop productivity and duration of production and on non-irrigated land, results in shortened plant lifespan (Bhatt and Hossain, 2019), our results on the coffee + desmodium showing sustained higher moisture holding is supported by these findings.

The treatment that had coffee + desmodium cover crop retained higher moisture content across the sampling period indicating that adoption of cover crops would help farmers achieve enjoy the benefits of soil moisture conservation, soil erosion control and reduced chemical runoff while increasing crop yields as also reported by (Bergtold *et al*., 2019). Other studies on the program from scaling-up and dissemination of climate resilient push-pull pest and weed control technology, (Midega *et al*., 2017) using desmodium species to suppress the parasitic striga weed while realizing higher grain yields and had appreciably good amounts of biomass indicated the drought tolerance of desmodium indicating that it does not use a lot of water in its growth.

Soil nutrients trends across the treatments.

For the analysis of Nitrogen (% N), Coffee + desmodium showed slightly higher % N as shown by 3rd sampling (figure 8). While the other treatments didn't have very significant difference in % N across all the treatments. In terms of percentage nitrogen, sole desmodium had the lowest and statistically significant (p-value = 0.009). The results on the analysis of Nitrogen (% N), Coffee + desmodium showed slightly higher % N as shown by 3rd sampling. While the other treatments didn't have very significant difference in % N across all the treatments. In terms of percentage nitrogen, sole desmodium had the lowest and statistically significant (p-value = 0.009).

Table 3 : Nutrient trends accross ithe treatments for the sampling period at the University of Nairobi Kabete coffee field plantation

Treatment Units	PH	%OC	%N	K cmol/kg	Ca cmol/kg	Mgcmol/kg	P ppm

Coffee+Hand weeding	5.341	2.602	0.2842	1.285	8.117	1.773	34.06
Coffee+Desmodium	5.413	2.516	0.2858	1.446	8.027	1.669	37.74
Coffee+Herbicide	5.533	2.505	0.2775	1.432	8.363	1.737	29.8
Sole Desmodium	5.856	1.875	0.2258	1.29	8.115	1.692	36.69

Soil nutrients serve a key role plant nutrition with associated productivity leading to the revenue generation and this research was to compare the effects on soil nutrients from the different treatments to evaluate any considerable variations which could be attributable to higher nutrient use by the desmodium cover crop. Other than the lower organic carbon observed in the sole desmodium, all the other treatments had no significant differences in the soil organic carbon and other nutrients evaluated.

Therefore the use of desmodium cover crop fits well in the companionship with coffee as noted by Mubiru and Coyne (2009) during their evaluation on the impact of cover crops on soil physiochemical properties using different legumes cover crops made the observations that legumes can significantly improve the degraded soils improve their properties even though with more than two cropping seasons needed.

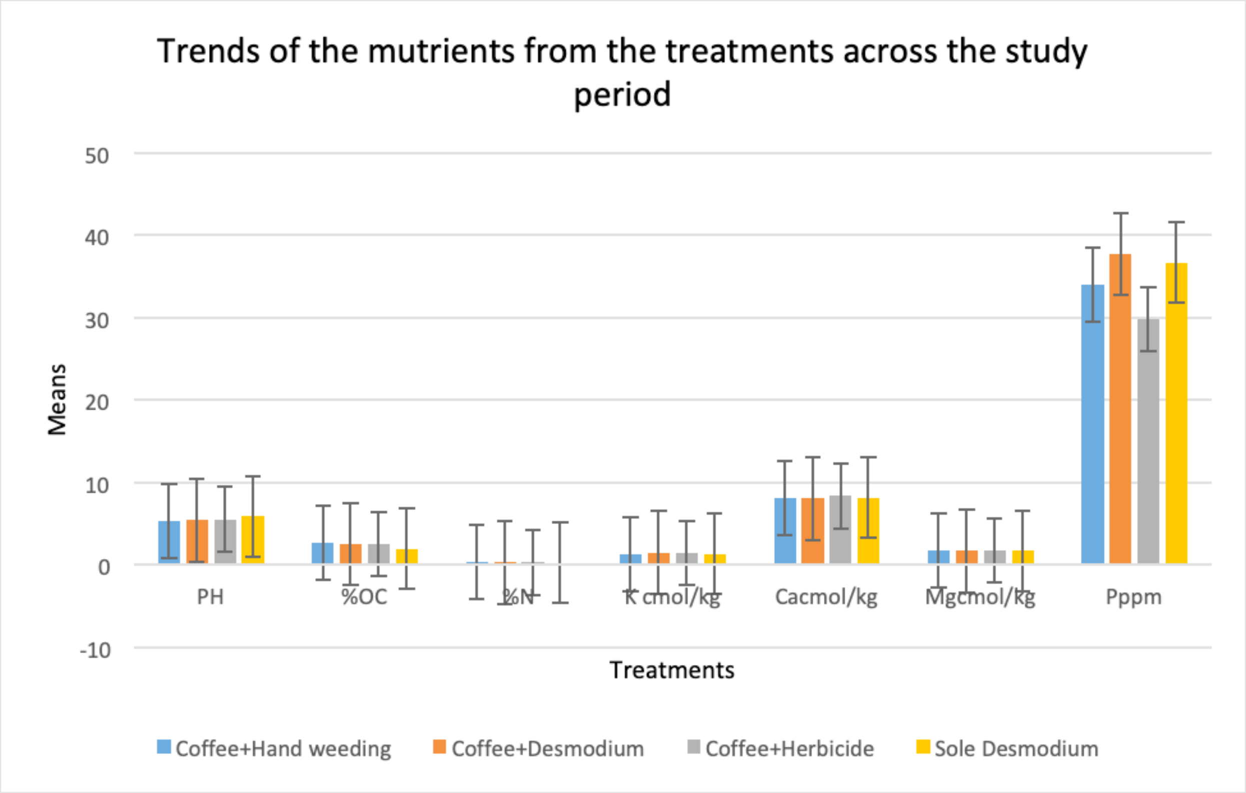

Figure 5: Trends in the nutrients accross the treatments for the 2019 season

The findings (fig. 5) are in line with (Kinyua *et al*., 2019) who appraised the benefits of green manure from cover crops with their soil health improving ability, affordability, ease of establishment, attainment of rapid growth to attain ground cover, ability to produce high amounts of biomass while resisting diseases without being a host to pest and diseases.

The findings are in line with Kinyua *et al.*, (2019) who appraised the benefits of green manure from cover crops with their soil health improving ability, affordability, ease of establishment, attainment of rapid growth to attain ground cover, ability to produce high amounts of biomass while resisting diseases without being a host to pest and diseases.

Crop Nutrients and cover crop relationship

Both macro and micro nutrients serve a key role plant nutrition with associated productivity and this research was to compare the effects on soil nutrients from the different treatments to evaluate any considerable variations which could be attributable to higher nutrient use by the desmodium cover crop. There was lower organic carbon observed in the sole desmodium (fig 9) which could relate to the previous crop grown, while calcium was lower in the herbicide treated plot soil sample.

Studies on the relationship of glyphosate residues and micronutrients have shown possibilities of formation of chelates or complexes with the metal ions in solution related to pH levels (Duke *et al*., 2012). Most evidence has pointed to the possibilities of forming strong complexes with glyphosate of copper and zinc while relatively lesser degree has been associated with Iron, Calcium, Magnesium and Manganese (Duke *et al*., 2012; Mertens *et al*., 2018). The formation of the complexes affects plant uptake which could be attributable to more availability where glyphosate has been used. The other mineral elements among the treatments had no significant differences in the soil organic carbon and other nutrients evaluated.

Therefore the use of desmodium cover crop fits well in the companionship with coffee as noted by Mubiru and Coyne, (2009) during their evaluation on the impact of cover crops on soil physiochemical properties using different legumes cover crops made the observations that legumes can significantly improve the degraded soils improve their properties even though with more than two cropping seasons needed.

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Desmodium herbage and Biomass

The destructive method of determining the yield of the desmodium biomass following the quadrangular quadrat method as indicated by (’t Mannetje, 2000), which involves making a 1 m x 1 m frame and cutting the fodder, then weighing the fresh weight. The fodder weight obtained from these subsamples was then used to calculate the quantity equivalent to 1 hectare and multiplied by the number of times is harvested to get the annual yield estimates. The desmodium was harvested every 3 months after full establishment 29 weeks after planting and the yields were dependent on the rainfall during the growing period.

The results from the harvesting of desmodium done 4 times per year yielded a fresh biomass of 17,000 kgs per hectare for the plots intercropped with coffee while the sole cropped desmodium was extrapolated to 18,500 kgs per year. This closely related to the potential indicated by (ILRI, 2013) of harvesting 19 tons / hectare of desmodium fresh forage when intensively planted as a sole crop with an estimated crude protein of 18 % (Heuzé *et al.*, 2017) makes it an important inclusion in farmer’s ability to get more yields from the same area of land and mitigate against livestock feed challenges. Livestock feed shortages are occasioned by changing climate as indicted by Ayantunde *et al.*, (2005) mainly exacerbated during spells of the dry season and often magnified during drought.

Returns to labour on different weed control treatments in the coffee management practices

Table 4: Returns on labour for the different treatments per hectare at the University of Nairobi Kabete Coffee field plantation

Treatment	Cost of labour per ha (US $)	Frequency of labour (US $)	Total costs per year (US $)	Extra Returns on labour (US $)
Coffee + cover crop	56	3	168	750
Coffee + hand weeding	56	4	224	-
Coffee + herbicide	41	3	123	-

Note: herbicide costs US $ 20/ litre; labour costs US $ 7 /person day. Person day paid at eight hours an adult per day. Forage sales @ 3 US $ per bale. 1 $ US is equivalent to 100/= Ksh.

The initial cost of desmodium establishment is spread out for 1 year although the life of the crop is 5 years. The price for selling desmodium dry hay at 300/= Ksh (3 $ US) per bale of dry hay. Annual yield of 250 bales (table 6) of 30 kg bales per hectare would be equivalent to 75,000/= Ksh per hectare extra income from the sale of the biomass annually. Desmodium fodder is also consumed fresh by livestock. With 115,600 hectares under coffee production in Kenya today, the potential fodder production from desmodium cover crop could be estimated at 115,600 x 30 kgs x 250 bales = 867 million kgs of desmodium hay with an economic value estimate of 8,670,000,000/= Ksh (86.7 $ US million). This would save many mixed crop farmers cost of buying some part of the protein based animal feeds and possibly be a great saving to the country on the cost of importing grains for animal feeds competing with human food security and their associated carbon foot print.

The sales or saving of this magnitude in livestock feed is important since as (Lukuyu *et al*., 2011) while looking at the reason why optimal livestock feeding which comprises 60-70% of the associated total costs indicated reliance on commercial feeds with unpredictable global inflation, makes smallholder dairy livestock production uneconomical. Climate smart options of incorporating biological nitrogen fixing legume fodder in cropping systems with reduction of external nitrogen needs and associated negative environmental footprint with provision of livestock fodder is an important consideration (Medeiros *et al*., 2019; Santos *et al*., 2016)

Observations

Soil evaporation is an inescapable outcome to harvest the end-product in all cropping systems (Kinama *et al*., 2005), addition of the cover crop reduces the area exposed to direct sun radiation and reduces the surface temperatures which could lower rates of soil evaporation. The average, potential evapotranspiration often exceeds total rainfall received with the exception for the months of November and April when more rain is received than the potential evapotranspiration (Kinama, , 1990). During hot periods, in the presence of mulch or cover crops, soil temperature was found to reduce due to reduced solar energy reaching the soil (Liu *et al*., 2014).

The reasons for the low nitrogen content in the sole desmodium could be due the low soil PH which could reduce the activity of the biological nitrogen fixation, leading to lower soil mineralization of the biomass. Nitrogen analysis could give varying units due to the confirmation of direct nitrogen transfer to adjacent non legume crop through mycelial Arbuscular fungal network as reported by (Koorem *et al*., 2020). Mendonça *et al*., (2017) studies on quantification of Nitrogen fixation through biological nitrogen fixation with analysis on the Nitrogen levels in the coffee leaves while intercropped with legumes observed that Cajanus Cajan had 55.8% nitrogen contribution, and this could be possibly due to longer duration of the intercropping.

Climate smart sustainable crop production demands the integration of ecosystem services derived from micro-organisms serving as bio fertilizers (Biological Nitrogen Fixation) as well as bio-pesticides to reduce or cancel the ecological footprint resulting from agricultural activities usage of synthetic chemicals (Mendes *et al*., 2013; Mitter *et al*., 2016). Planted crops benefits from the ecological composition of the soil microbiota ecosystems colonizing the rhizospere (root zone) which as well recruit plants as their habitat (Mendes *et al*., 2013).

Kawasaki *et al*., (2016) observed that some root zone communities were influenced by root exudates from plants which could alter some of their composition despite the bulk of the soil population remaining stable. Plant root exudate metabolites including amino acids, fatty acids, sugars and vitamins directly affect composition of the microbes around the roots (Hu *et al*., 2018). Therefore, the establishment of desmodium cover crop in the coffee plantations is expected to create new microbial relationships between the coffee and the legume fodder that will aid in creating synergistic relationship that will create strong ecosystem services especially with the isotopic exchange of nitrogen fixed biologically by the legume fodder cover crop (Rose and Kearney, 2019).

Limitations of the study

The study looked at short term gains from the adoption of desmodium legume cover crops for providing ecosystem services to cropping systems. Desmodium being a perennial and having a longer life than 1 year, needs further social economic evaluation for its entire lifespan and the related interrelationship with coffee production should be evaluated further.

Implications of the findings

The results indicate that adoption of legume cover crops confer many ecosystem benefits to crop production while reducing the need to increase more land for production of livestock fodder therefore reducing the need for land use change associated with negative environmental impacts. Livestock feeding challenges in Kenya have been associated with migration of pastoralists and conflict in search of pasture. Climate-smart agriculture should embrace integration of desmodium legume fodder crops in coffee production and other tree crops to benefit from the ecosystem services.

4.5 Recommendations for future research and practical applications

Evaluation of quantities of nitrogen fixed in the soil and transferred to the coffee annually and the impacts on long term coffee productivity.

Comparison of the soil micro-organisms composition between manual weeding, herbicide and desmodium legume cover crop incorporation. Comparison of other shade tolerant creeping legume cover crops for their provision of similar ecosystem benefits.

Relationship between coffee grade and taste and the different weed control methods (desmodium legume cover crop, herbicide and manual weeding).

4.6 Conclusion

There is an opportunity to address the environmental challenges associated with the current coffee weeding practices which exposes the soil to environmental challenges and loss of ecosystem services. Intercropping coffee with desmodium can increase the benefits of ecosystem services of better moisture retention and better nutrient availability for coffee. Associated desmodium biomass serving as livestock fodder plays a role in reducing land pressure for livestock feed production in competition with human food associated with increased encroachment to forests and other fragile ecosystems.

Current weed control methods in coffee production are associated with undesirable environmental impacts which are being amplified by climate change thus facing sustainability challenges. The adoption of desmodium legume fodder cover crops will help coffee farmers sustainably manage weeds, maintain soil character (ecosystem services) and support sustainable coffee production, while obtaining biomass as livestock fodder.

CHAPTER FIVE

5.0 **Evaluating Cover Crop Ecosystem Services for Buffering Coffee against Changing Climate** (Journal of Biodiversity and Environmental Sciences) J Bio. Env. Sci. 19(4), 16-36.

5.1 Abstract

Conventional coffee production systems relies heavily on broad-spectrum glyphosate herbicide applications and intensive tillage practices for weed control practices oblivious of the risks associated with loss of supportive ecosystems services. Agroecological alternatives integrating legume cover crops for weed control benefiting the soil ecology and optimistically enhancing ecosystem services has been missing in coffee production. This study compared low input coffee production weed control practices using conventional tillage and glyphosate herbicide application with desmodium legume cover crop as an agroecological alternative. The study having three treatments replicated 3 times was carried out at the University of Nairobi coffee plantation at Kabete considered agro climatic zone III mirroring other Kenyan coffee production areas. Total coffee yields were compared among the three weed control practices after 15 months. Regression analysis of the yields was compared to give the differences in the yields associated with each practice. Climate predictions have indicated that coffee production systems will face climate change related challenges and farmers need to adapt resilience measures to adapt to the related environmental impacts. Results showed that desmodium legume cover crops had 1.6 times higher production per coffee bush than herbicide weed control and 1.2 times higher than hand weeding. These positive results on coffee production adaptation resulting from agroecological modifications enhancing ecosystem services benefits should be demonstrated to farmers to enhance their understanding on the need to embrace agroecology in their coffee production systems.

Key words

Climate change, desmodium, ecosystem services, herbicides, Legume cover crops

5.2 Introduction

The projected need for doubling food production in the next 50 years (Hatfield and Walthall, 2015) will put a great strain on natural resources despite the challenges associated with changing climate. Vulnerability of African agriculture and its high exposure to climate change with its related low response capacity, is exacerbated by increasing temperatures amplifying water stress piling additional pressure on agricultural systems with the associated irregularity in precipitation witnessed to have detrimental effects to both crops and livestock (Pereira, 2017). Vulnerability is considered as the susceptibility of a system or its inability to cope with climatic change adversity and related extremes of variability (IPCC, 2014).

Environmental impacts associated with increased agricultural production with concomitant reliance on chemical weed control have been attributed to negatively affect the soil and water quality (Smith *et al*., 2015). The reliance on synthetic inputs that have dominated modern industrial agriculture due to the great need for increased food production for an increasing population, which has increased by more than 8 times since 1961 (Lu and Tian, 2017). Labour challenges has increased the reliance on herbicides for weed control in plantation crops with a 20 fold global increase since 1980 (Oerke, 2006).

There has been emergence of herbicide resistance globally with over 400 cases of weed species (Heap, 2014). There has also been a reduction in new herbicide chemistries making the challenges of multiple weed resistance a major challenge to economic weed control in coffee production systems (Heap, 2014). Over reliance on agrochemicals in agriculture has resulted in accumulation of agrochemical residues in the environment, and this is becoming a great concern with increased awareness on the implications to biodiversity (Vázquez *et al*., 2018b). Intensive tillage practices such as manual weeding has been attributed to accelerated loss of soil and nutrients leading to accelerated land degradation and loss of soil ability to provide ecosystem services (Beniston *et al*., 2015; Gao *et al*., 2016)

The major factors limiting coffee production have recently been seen as unfavorable weather and recurrent drought, which are being predicted to be exacerbated by changing climate (DaMatta and Ramalho, 2006). Coffee plant sensitivity to extreme temperature makes it susceptible to oxidative stress during drought conditions and high temperatures while low temperatures negatively affect flower production and fruiting resulting in yield decline and weakened plants (DaMatta and Ramalho, 2006). These impacts related to environmental factors that negatively affect coffee production requires adaptation mechanisms that will enable farmers buffer the coffee production systems to sustain production in times of uncertainty (DaMatta and Ramalho, 2006).

The alignment of sustainable agriculture to the Aichi biodiversity goals which aim to address causes of biodiversity loss and reducing direct pressure on biodiversity requires reorientation (Perino *et al*., 2021). This calls for adoption of sustainable agricultural intensification, improving status of biodiversity through safeguarding ecosystems to enhance the benefits from of ecosystem services by addressing participatory planning, knowledge management and capacity building especially in the framework of coffee production (FAO, 2016).

Ecosystem services have been defined as the collective benefits associated with processes through which natural ecosystems with their connected species sustain and fulfil human life in the dynamic complex of plant, animal and microorganism communities and their entire non-living environment interact as a functional unit (Millennium Ecosystem Assessment, 2005). Regulating services such as pollination and pest control have not been fully appreciated and promoted in coffee production with the additional climate regulation services. Supporting soil formation processes focusing on its ability to provide habitat for diverse species, which will ensure continued supply and provisioning of the ecosystem services, calls for judicious use of the natural resources to ensure successful coexistence with nature as an improved ecological foundation in agriculture (FAO, 2016; Kihara *et al*., 2020).

The maintenance of soil quality, services of nitrogen fixation, pest control and pollination services, are among the important biological diversification processes that maintains and regenerates ecosystems services vital for success in sustainable agriculture which is a necessity in coffee production(Kremen and Miles, 2012). Diversified ecologically focused farming systems benefit from multiple ecosystems services reducing the need for intensive use of synthetic inputs associated with externalities to sustainable ecological balance (Kremen and Miles, 2012).

A summation of the ecosystem services derived from Agro-biodiversity are biological nutrient management, community biodiversity services such as pollination, carbon sequestration, enhanced crop productivity, improved water holding capacity, weed suppression, disease and pest management and the overall resistance and resilience to climate change impacts (Kremen and Miles, 2012). Agroecosystems ability to derive full benefits of regulatory and supporting ecosystem services is dependent on the system design in order to provide soil regulation services, reduce soil degradation by soil erosion control, provide habitat for pollinators and predators for pest control (Kaye and Quemada, 2017).

Adaptation to the challenges of the 21st century of increased uncertainty resulting from changing climate have related to offering farmers the best fit options for optimization of sustainable production systems that reduce the strain on water resources and reduction on the emissions of anthropogenic gases associated with global warming. Adoption of legume cover crops in coffee production for nutrition management through nutrient cycling shows ability to have 8 – 14 times higher nitrogen accumulation than where its absent (Delgado *et al*., 2021a). Adoption of cover crops helps in soil erosion control leading to less nutrient leaching promising ability of the coffee cropping system to sustain yields and fit in climate mitigation (Delgado *et al*., 2021a).

The social ecological Resilience theory relating to the holistic approach is required in understanding the interactions, interdependence and interconnectedness between the biophysical and human components of the agro-ecologic systems due their complexity (Cabell and Oelofse, 2012). Due to the dynamic nature of natural systems there is the requirement of resilience becoming transformative with flexibility for learning from past exposures and adoption of measures to reduce impacts and shocks (Cabell and Oelofse, 2012). There is an urgent need for attention to increase relevance on the governance systems of the inter-disciplinary linkages related to social-ecological systems in relation to their sustainability and resilience (Folke *et al*., 2016). Coping mechanisms haves temporal dimensions often with short term trade-offs that may impact on the long-term resilience (Cabell and Oelofse, 2012).

The resilience of a farming system can be seen as its ability to continue provision of its functions despite the increasing complexity of environmental, economic, social and institutional stresses and related shocks by building robust adaptability that enables it to transform its performance despite the negative forces (Manevska-Tasevska *et al*., 2021). Environmental Challenges associated with farming systems include extreme weather events (droughts, excessive rainfall, hails storms, frost and floods), epidemics in terms of pests, disease and weed outbreaks which has not been focused on in the framework of how to benefit from agroecological applications (Manevska-Tasevska *et al*., 2021). The long term stresses in agriculture relating to soil erosion leading to degraded soil (deterioration of soils), decline in pollinators, antimicrobial resistance, loss of habitats for certain species, gradual settlement of invasive species and rising salinity needs sustainable solutions (Potts *et al*., 2016; Ray *et al*., 2015)

Resilience described as the ability of a system to maintain its productivity of nutritious and sufficient food in the face of intense and continuous environmental disruptions is the basis for this article (Potts *et al*., 2016; Rahn *et al.*, 2014). Previous studies integrating desmodium intortum and desmodium incunum in maize production have had positive results even under low moisture conditions suppressing parasitic weeds and increasing yields while aiding in biological nitrogen fixation (Midega *et al*., 2017). This article looks at integration of agro-ecology in coffee production using Desmodium intortum legume cover crops as a mechanism for assisting smallholder farmers to increase their economic, social and ecological resilience in the agro-ecosystem and help them reduce vulnerability in coffee production systems.

5.3 Materials and Methods

Description of the study site

The field experiment was undertaken at the University of Nairobi Kabete Campus, coffee plantation field number 7 (fig. 6). The field has coordinates of 1’15l’’ S and 36’ 44l’’ E and an elevation of 1940 m above sea level, located on the western part of the Nairobi County bordering Kiambu County which has coffee among the cash crops. The site was selected due to its history of growing coffee with conventional methods of weed control being dominated by tillage and alternated with herbicide utilization.

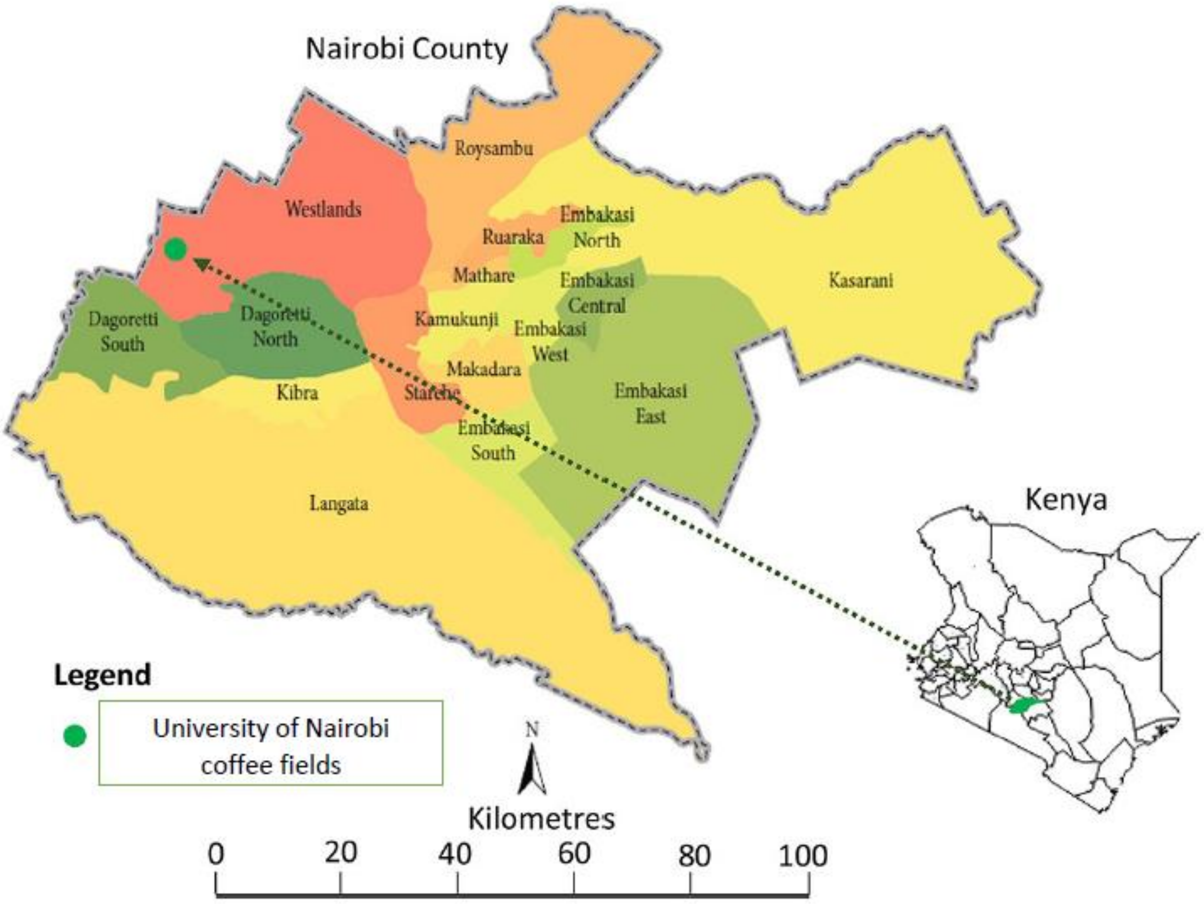


Figure 6: Map of the study area (University of Nairobi, Kabete coffee field plantation)
(Source- extracted from Google map)

The location lies in the upper midlands classified as agro ecological zone III that normally experiences 2 rainfall seasons. There is the long rains season experienced between Mid-March-May, traditionally interspaced by a period of low temperatures in June and July, with dry periods of August and September and the short rains experienced in Mid-October to December. Annual rainfall is normally in the range of 1006 mm considered a sub humid zone (Kabubo-Mariara and Mulwa, 2019).

Methodology

The study comprised of 3 treatments replicated 3 times of low input coffee where no fertilizers or fungicides were applied. An extra sole desmodium sections with 3 plots for comparison on soil relationship with the test parameters was set in adjacent plot without coffee. The treatments were coffee + desmodium legume cover crop, coffee + hand weeding, Coffee + glyphosate salt herbicide (1.0 kg ha-^{1} of acid equivalent). The treatments were in a factorial setup comprising desmodium intercropped with coffee for weed control, manual weeding with hand hoes and glyphosate herbicide treatment.

The treatments plots were measuring 6 m x 12 m replicated 3 times. The set up was related to the common coffee farmer production practices to compare the outcomes of each practice. The treatments were in a randomized complete block design of 3 the treatments replicated 3 times in the plots. The uniform treatments plots contained 9 coffee bushes were selected in August 2019. The experiment started on start of September 2019, when all the plots were manually weeded. Desmodium spp was planted inside the 3 coffee treatment plots (A1, B3 and C3). Glyphosate herbicide was applied in 8th November 2019 for the treatment plots A3, B2 and C1. Hand weeding was carried out on the treatment plots A2, B1 and C2 on the 8th November 2019.

A baseline soil sample for both moisture and nutrient analysis was taken on the first week of September 2019. From the month of October, on a monthly basis for 6 months, soil samples were taken from a depth of 30cm with 9 cores (Houba *et al*., 2000) taken from each treatment plot, using a soil auger. The different soil samples from each treatment weighing approximately 1 kg were taken to the University laboratory for soil moisture analysis monthly. Every 3 months, soil samples taken from a depth of 30 cm were delivered to the university laboratory for nutrients evaluation. The weeding exercise using glyphosate herbicide application and hand weeding were done every 4 months to keep the coffee plots weed free. Weed diversity was recorded using a wooden frame measuring 1x1m. After the initial clear weeding, newly emerged weeds were sampled, grouped and recorded in November after the rain season and in April after the main rain season. Weather data was collected form the Kabete weather station on a monthly basis with minimum and maximum temperatures, rainfall, humidity and evaporation recorded. This was done from the onset of the experiment in October 2019 until the end in December 2020.

Weather data

The weather data (table 5) was collected at the end of every month (compiled from the daily records) from the onset of the experiment in October 2019 until the end of the harvesting period in December 2020. The data weather recorded was monthly rainfall, the minimum and maximum temperatures, relative humidity and evaporation (Table 5 and Figure 7.)

The weather recording was aimed at having the optimal coffee production temperature and rainfall comparison with the experimental site actual data records for the period of the experiment.

Table 5: Weather data for the period (Oct 2019- Dec 2020) at the University of Nairobi, Kabete field weather station.

month	Temp. min	Temp Max	Rainfall mm	RH %	Evaporation (mm)
2019 Oct	14.6	21.6	214.3	64	110.8
2019 Nov	14.2	21.6	256	67	106
2019 Dec	14.4	21.8	256	62	102
2020 Jan	14.8	23.4	267.7	64.5	104
2020 Feb	14.8	24.4	89.4	55.7	123.5
2020 Mar	15.6	24.7	157.1	63	121.2
2020 Apr	15.9	24.1	284	41.9	161.3
2020 May	15.1	23.1	156.7	58.6	96.8
2020 Jun	12.9	22.4	130.5	60.4	82.5
2020 Jul	12.3	21.2	6.8	61.2	69.9
2020 Aug	12.5	22.7	4.4	53.4	93.4
2020 Sept	13.1	28.1	96.5	82.9	105.1
2020 Oct	13.8	22.7	81.2	78.8	116.2
2020 Nov	14.8	22.9	175.1	87.7	103.1
2020 Dec	13.8	23.9	40.9	76.6	141.5
			1490.3		

Source: University of Nairobi, Kabete weather station

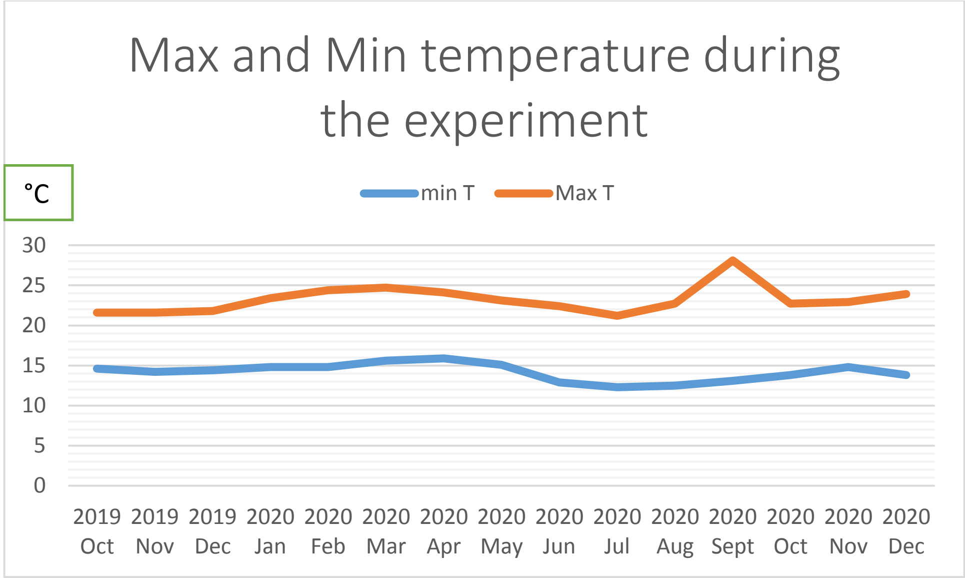


Figure 7: Graphical presentation of the monthly average minimum and maximum temperature during the peiod of expereiment. Data Source: University of Nairobi, Kabete weather station.

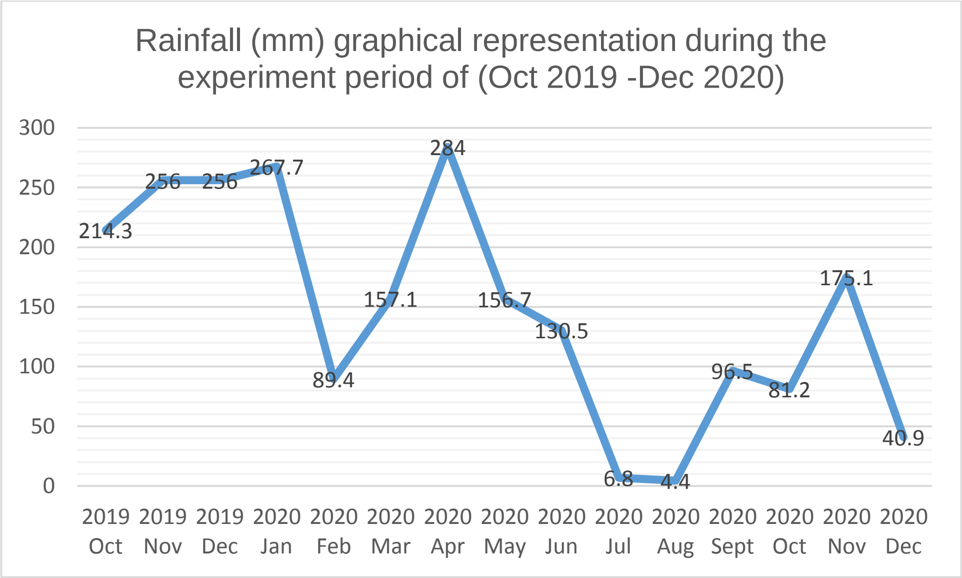


Figure 8: Graphical presentation of rainfall in mm during the period of experiment

Data Source: University of Nairobi, Kabete weather station.

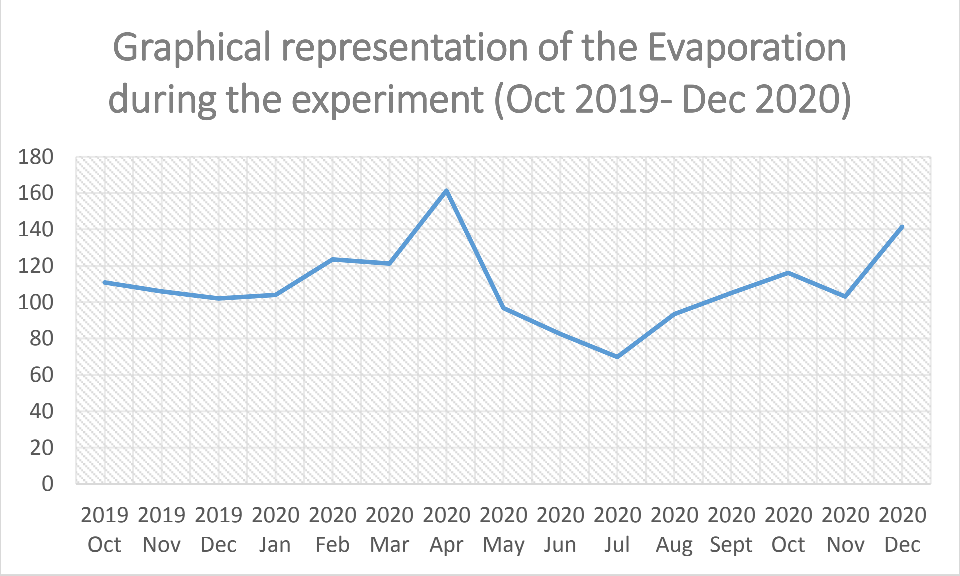


Figure 9: Graphical presentation of evaporation in mm during the period of the experiment

Data Source: University of Nairobi, Kabete weather station.

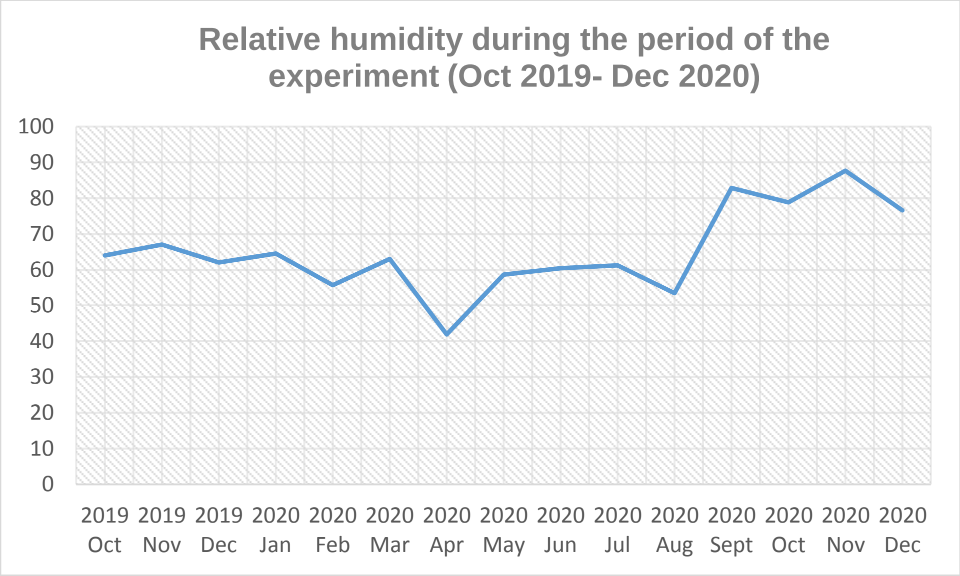


Figure 10: Graphical presentation of the monthly average relative humidity in % during the period of experiment at the the university of Nairobi, Kabete coffee field plantation

Data Source: University of Nairobi, Kabete weather station.

Data Analysis

The coffee harvest data was arranged in Microsoft Excel 2016 and then imported into the statistical software R version 3.5.2 for analysis. The values for harvest per kg were tested for normality using Shapiro-Wilk test on the R statistical software. The data was then fitted into a mixed effect linear regression model using the lme4 package. In the model, harvest per kg was predicted by treatment (hand weeding used as the comparator for either Desmodium spp or herbicides) as the fixed effect, while the bush number and harvest period were the random effects. Model outputs were summarised using the jtools computer package for statistical analysis.

5.4 Results

Weed diversity in the experimental plots comprising hand weeding and herbicide treatment were recorded during the experiment. The weeds were noted to have emerged 2 weeks after the rains in October 2019. For identification purposes, weeds attaining 20 cm height were uprooted and grouped. A wooden frame of 1 m x 1 m was used to measure a subplot from the main experimental plot where weeds were dense.

The emerged weeds comprising of annuals and perennials were uprooted and grouped. The frequency of occurrence indicated the most common weeds having a population of more than 30 plants having attained a height of 20 cm in the 1m x 1 m sampling subplots. The most commonly occurring weeds were pig weed (Amaranthus spp), black jack (Bidens pilosa), Double Thorn (Oxygonum sinuatum), and Mexican marigold (Tegetes minuta) for the broad leaved annual weeds. The main perennial weeds found with high occurrence were Wondering Jew (Commelina benghalensis), Star grass (Cynondon dactylon), Nut grass (Cyperus rotundus L.), Couch grass (Digitaria abyssinica) and Wood sorrel (Oxalis latifolia).

Soil moisture comparisons from soil samples analyzed in the lab indicated higher moisture content in the treatment containing desmodium. This was an indication that there was better moisture retention and or percolation from the rainfall where desmodium served as a cover crop among the treatments. During the onset of flowering before desmodium was harvested as fodder for livestock, there was an increase in foraging bee population in the plots that had been planted with desmodium spp. The moisture trends are indicated below (Table 6) showing the trends between the treatments over time. Coffee and herbicide had the lowest moisture content results possibly because of higher evaporation rates from the bare soil surface and or higher ground water runoff.

Table 6: Soil moisture % trends based on the treatments during the period of 6 months (November 2019- April 2020) at a soil depth of 30 cm.

Treatment / Moisture content %	**30 days after treatment**	**60 days after treatment**	**90 days after treatment**	**120 days after treatment**	**150 days after treatment**	**180 days after treatment**
Coffee + Herbicide	24.84	22.79	36.07	29.03	40.27	38.52
Sole Desmodium	36.54	24.79	32.87	27.42	36.54	45.59
Coffee + Hand weeding	27.11	23.76	35.5	28.86	38.55	50.55
Coffee + Desmodium	22.11	27.25	41.4	32.52	35.46	57.66

Coffee harvesting started on the 11th of November and a second harvesting was done on the 1st of November while the third and final harvest was done 17th December 2020. The recording of the harvest was done per coffee bush/tree and weighed and recorded separately according to the respective treatment. After the 3rd and final harvest, the total weight was summed up per tree/ bush and summed up to show the total reduction for each treatment as the table (Table 7.)

Table 7: Coffee yeilds in Kilograms (kgs) for the different treatments per bush/tree and the total per treatment

Replicate	Treatment	no of (bushes) trees	Yield (kgs)	Yield (kgs)	Yield (kgs)	Yield (kgs)	Yield (kgs)	Yield (kgs)	Yield (kgs)	Yield (kgs)	Yield (kgs)	Plot total Yield (kgs)
		tree	1	2	3	4	5	6	7	8	9	
A1	Desmodium	8	4.9	5.5	5.7	5.6	6.2	5.2	5.2	5.7	-	44
B3	desmodium	9	6.3	4.9	4.8	4.05	4.95	5.4	5.85	4.75	5	46
C3	Desmodium	9	4.6	7.4	4.6	5.7	5.15	5.65	3.95	3.95	4.45	45.45
A2	hand weeding	7	4.6	6.2	3.3	2.9	3.8	4.6	5.1	-	-	30.5
B1	hand weeding	9	3.3	4.25	2.7	3.3	2.75	5	4.6	2.8	5.1	33.8
C2	hand weeding	9	3.05	3.25	2.95	3.5	3.35	3	3.6	3.35	3.5	29.55
A3	herbicide	9	3.9	2.6	3	2.1	1.7	3.4	2.25	3.9	2.5	25.35
B2	herbicide	8	3.3	4.3	2.85	3.05	2.75	2.5	3.95	4.1		26.8
C1	herbicide	9	2.3	2.95	3.1	3.7	2.75	3.5	3.65	3.4	3.75	29.1

At the end of the experiment end in December 2020, the tally of the harvest data was summarized in excel data sheet and then plotted to show the effects of each treatment on the coffee yields. The results indicated that the data was normally distributed (W = 0.92079, p-value = 0.000000002822) validating the use of a mixed effect linear regression model. From the outputs of the model there was an indication on the log odds of the possibility of achieving higher coffee yields when desmodium was used as a cover crop translating to 0.51 This led to a deduction that there is a possibility of yield increase by 1.6 times in the desmodium treated plots when compared with plots where hand weeding was the treatment (Table 5 and Figure 11). The yields obtained from the plot where herbicides treatment were used indicated an even lower yield than the hand weeding treatment. The difference in the coffee yields comparison between hand weeding treatment and herbicide weeding treatment indicated log odds of 0.19. The yield differences translated to an indication that herbicide treatment had a lower harvest by 1.2 times compared to hand weeding (Table 8 and Figure 11). Inter cluster correlation (ICC) of the random effects was below 0.5 indicating low variability between the groups, i.e., different harvest periods and bush number (Table 8).

Table 8: Linear regression model for the diffrent weed control methods

	Est.	S.E.	t val.	d.f.	p
(Intercept-hand-weeding)	1.24	0.13	9.50	2.68	0.00
Treatment Desmodium	0.51	0.07	7.43	201.52	0.00
Treatment herbicide	-0.19	0.07	-2.79	201.52	0.01

AIC = 257.24, BIC = 277.41

Pseudo-R² (fixed effects) = 0.30

Pseudo-R² (total) = 0.45

Where: AIC- Akaike information criterion

BIC- Bayesian information criterion

Table 9: Intercluster correlation (ICC) between the groups in the random variables

Group	Number of groups	ICC
Bush_number	8	0.02
Harvest_Period	3	0.19

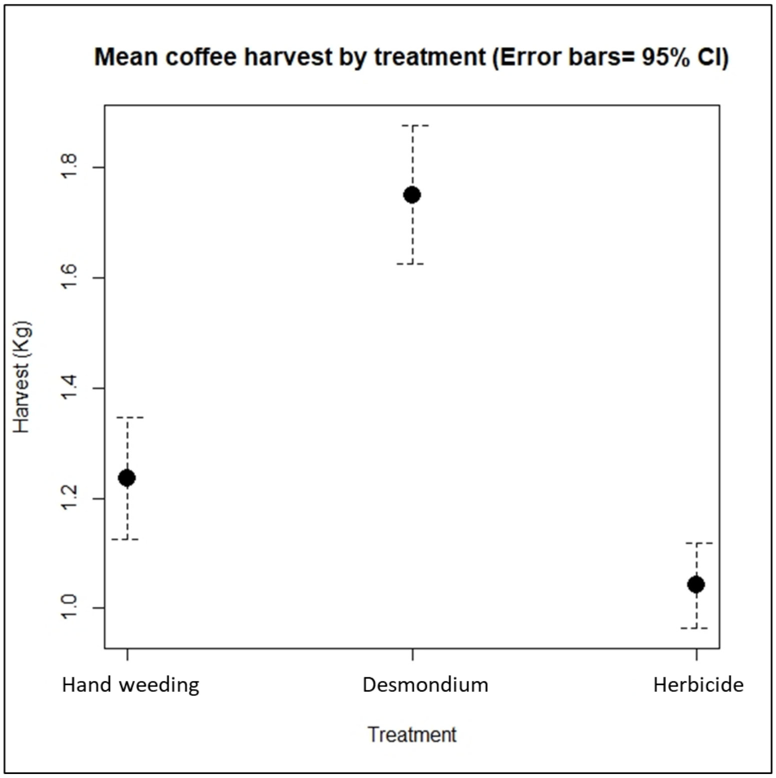


Figure 11: Graph showing comparison of coffee yeilds in relation to weeding method at the University of Nairobi, Kabete coffee field

Legend; Error bars represent the standard deviation.

There was an insignificant variance in the total number of bushes for each treatment, and the harvesting period remained the same thus having no significant effect on the harvest per bush. Harvesting was done at the same time periodically at the intervals of 3 weeks to 1 month depending on coffee maturity and the recordings in excel sheet tabulated with the final sum showing the grand total per tree/bush and treatment.

5.5 Discussion

The minimum temperatures experienced during the experiment averaged at 13.3° C while the maximum temperatures average was 21.8° C. There were few incidences of very low night temperatures in June and July going when temperatures were below 12° C, although not so much extended to show significant impact on the coffee growth. The optimal range of temperature for coffee production are in the range of 18° – 22° C with minimal seasonal fluctuations, the temperature tolerance is between a low of 15° C and a maximum of 25° C according to research done in 2010 by (Camargo, 2010). The increasing incidences of the very low night temperatures may therefore impact the coffee negatively if extended for longer durations. Climatic changes are expected to face Kenyan coffee farmers which has already been predicted by among others, the global climate risk Index (2017) placing Kenya among the countries expected to be faced with significant climate change impacts in coffee production.

Adaptation to this phenomena is important because as shown in our study, the very low night temperatures affect coffee production especially in relation to flowering and fruit set. This is in correspondence with impact studies on quantitative production in the northern Tanzanian highlands which have indicated the possibility of a relationship between night temperatures and diminishing yields of Arabica coffee between 1961 and 2012 (Craparo *et al*., 2015). The future climate change projections indicates that every rise of 1 °C of minimum night temperatures may result in coffee yield losses in the range of 137 ± 16.87 kg ha by 2060 which is important to Kenyan coffee farmers as this will affect sustainability (Craparo *et al*., 2015). There are striking similarities in the highland coffee growing zones of Kenya with our experimental site at the University of Nairobi in Kabete, indicating the need for adaptation strategies aimed at addressing the minimum temperature challenges in relation to reduction in coffee productivity (Craparo *et al*., 2015).

The cyclic weather as witnessed in our study site showing with more heavier rainfall in January 2020 and absence in December 2020 when its needed to facilitate harvesting, increases unreliability that has been predicted to worsen with the predicted 2- 4 degrees C temperature increase in the tropics where coffee is grown (Camargo, 2010). In relation to temperatures, our site recorded some low night temperatures of below 13°C, but the maximum mean temperatures remained optimal except a brief slight increase in September 2020. The concern on high temperatures during coffee flowering have been associated with flower abortion while ripening of cherries when temperatures are higher than 30 degrees C lead to poor quality due to accelerated ripening which is a reality that farmers must face (Camargo, 2010; Venancio *et al*., 2020).

The annual rainfall recorded during the experiment was 1490 mm with unusually high rainfall received in January 2020 at 267 mm and low rainfall experienced between June 2020 and September 2020 which is part of the period coffee flowering occurs. The reduction of rainfall during harvest in December 2020 with only 40.9 mm had implications in harvesting since coffee cherry ripening is affected by inadequate rainfall (DaMatta and Ramalho, 2006). Therefore the changing climatic patterns that are being associated with extreme events of either heavy rainfall downpours or unpredictable droughts will continue to burden farmers with negative implications to the coffee production systems as indicated by (Camargo, 2010). Previous studies have shown the optimal rainfall for Arabica coffee to be in the range between 1200 – 1800 mm annually, with a dry period preferred in the middle for flowering and our site achieved 1490 mm which shows its suitability in line with previous studies (DaMatta and Ramalho, 2006).

Previous observations in Kenya which were also witnessed during the period of the study have shown seasonal rainfall shifts with increased total annual precipitation in some areas. This has also been witnessed in other areas like Mt Kilimanjaro coffee growing region, with the poor distribution making farmers experience drought during certain period in their coffee production

(Wagner *et al*., 2021). In our study, there was no delayed onset of the rainfall season which have been seen to affect coffee flowering but the 2020 short rain season were lower than expected which affected coffee maturation and harvesting cycles with slower rate of cherry ripening resulting in reduced yields which has also been shown by (Wagner *et al*., 2021).

During the periods of July and August when only 6.8 and 4.4 mm of rainfall was received which was indicative of drought conditions, extreme drought affect coffee leaves water potential which is associated with up to 90% decrease in leaf hydraulic conductance associated with negative impact on yields (Martins *et al.*, 2019). Reasons for lower coffee production during drought are related to physiological responses and interactions of the coffee species to drought. Drought is associated with elevated heat stress when there is inadequate water supply and interventions related to water supply during drought may prevent yield reduction which is among the impacts of climate change as seen by (DaMatta *et al*., 2018).

Greater variability of the rainfall distribution has been seen to have a great impact on maturity of Arabica coffee with drought implications at maturity resulting in poor cherry maturity and affecting harvesting predictability. This was witnessed during our experiment when the rainfall in December 2020 was very low resulting in poor cherry ripening and delayed harvesting especially in plots with herbicide treatment which in agreement with studies by (Wagner *et al.,* 2021). Arabica coffee production reduction has been predicted to decline by almost 50 % due to impacts of climate suitability in business as usual scenario (Ovalle-Rivera *et al*., 2015) which is the reason why new ways of adaptation such as legume cover crops could help farmers adjust to the new environmental challenges as shown by our study. These challenges require adaptation mechanisms to safeguard the source of income for more than 750,000 farmers in Kenya (GCP, 2018) engaged in coffee production with interventions such as adoption of legume cover crops.

The low rainfall like the one that we experienced during the study in July and August (6.8 and 4.4 mm) has been associated by earlier studies to affect coffee bean size and result in some defects. The absence of defects and average bean size are the major determinants of quality and price and their dependence on the right climatic conditions indicates that low rainfall during fruit formation (July-September) may increase the risk by 80% of getting small sized beans as also indicated by (Kath, *et al*., 2021). While the harvesting period during our experiment experienced dry weather, the opposite of having excessively high rainfall during harvest (October – December) has been associated with increased risk by 75 % of bigger bean size and molds resulting in price penalties which the other extreme of climate change as per the studies by (Kath *et al*., 2021). Our study therefore recommend coffee farmers to introduce interventions such as the adoption of legume cover crops which reduce the soil moisture stress during dry weather to reduce yield penalties associated with weather variability.

Cover cropping benefits

During our experiment, which we started in September 2019, we realized desmodium full cover establishment covering the entire ground area between the coffee plants after 18 weeks, thereby establishing a good soil cover and preventing weed emergence. Cover crops have been defined as closely growing crops offering soil protection with associated soil improvement during and between periods of normal crop production (Treadwell *et al*., 2008). During our experiment, manual weeding and herbicide weeding ensured the entire plots were weed free with zero cover on the soil throughout the cropping period, which left the soil the unprotected soil and could result in some level of soil erosion during heavy rainfall. Soil erosion has been associated with nutrient runoff during heavy rains resulting soil depletion perpetuating a cycle of soil degradation as observed by (Kaspar and Singer, 2015). Introduction of legume cover crops in perennial tree crop types like coffee has been proposed as an ecological alterative when appropriately selected and our choice of desmodium legume cover crop satisfies a multi- criteria evaluation grid to arrive at an optimal cover crop as advised by (Jannoyer *et al.*, 2011). In selection of cover crops, the important considerations are related to their agronomic potential and range ecological services they provide such as weed control, ability to control runoff and soil erosion (Jannoyer *et al.*, 2011).

The choice of a suitable cover crop like desmodium spp. in coffee based on agro ecological approaches should increase yields through facilitation and resource partitioning which is a strategic intercrop that increases yields of the associated crop while improving soil health as discussed by (Bybee-Finley and Ryan, 2018).

Ecosystem services of weed control by cover crops

During our experiment, due to the continued rainfall especially during the rainy season, weed emergence was very rapid. This required the urgent need for the weeding either manually or herbicide application which was done every 3 months. Weed competition for nutrients effect on coffee yields losses have been estimated at 50 % (CRF, 2003) in Kenyan coffee production systems. As per our observation, there were many rapidly growing weed species comprising both annual and perennial weeds with a short growing cycle enabling them to produce numerous seeds. Abundance of weed seeds make their control a challenge with the additional creeping habit of most perennials making them most challenging to control once established as observed by (Odhiambo *et al.*, 2015).

We observed that desmodium legume cover crop established within 12 weeks covering the ground with its creeping habit with its complete weed suppression observed from week 18 onwards possibly due to adequate rainfall with no further weed emergence observed in the plots planted with desmodium spp. This is in line with studies by Gachene and Wortmann (2004) who found complete suppression while using desmodium spp at 29 weeks after planting possibly due to rainfall variation during their study.

The cost of manual weeding and herbicide weed control in our experimental coffee plots was almost double annually in comparison with desmodium cover crop once established in concurrence with studies by the (CRF, (2003). The study by the CRF concluded that weed control comprises a major cost in farmers operations declining their coffee earnings. During our experiment, we observed that black jack (Bidens pilosa) was not being affected by the glyphosate herbicide which could be associated with increasing weed resistance to the regular usage of herbicide which is routine at the university farm. The emergence of weed herbicide resistance has been noted globally with several weed species having developed resistance to continuous herbicide applications (Heap, 2014). In the plots that manual weeding was practiced, we found the soil to be much loosened predisposing it to water erosion during heavy rainfall confirming similar results by studies done by (Thierfelder and Wall, 2009). It has been equally observed by Bruinsma and FAO, (2003), that intensive tillage practices that leaves the soil bare are associated with declining soil organic matter that also increases soil compaction resulting in reduction of rain water infiltration and retention. Our experiment also indicated better soil moisture trends in the experimental plots that had desmodium cover crop and this has been shown that bare soil suffers continuous moisture losses from sun evaporation and suffers the risk of increased soil erosion from speed of runoff water (Thierfelder and Wall, 2009).

We observed the creeping habit of desmodium spp having the ability to suppress weeds ecologically which is great method of weed control, other studies have also associated the root exudates from desmodium having ability to suppress some parasitic nematodes reducing nematode reproduction) (Lawley *et al*., 2011; Robyn *et al*., 2018).

Ecosystem services of soil improvement from Cover Crops

During the soil sampling in our experiment we observed that the soils where the desmodium legume cover crop was planted had become less compacted and the probe for soil sampling could penetrate more easily. We attributed the softening of the soil where desmodium was present to rain water absorption improvement and reduced evaporation. This is supported by studies done by Blanco- Canqui *et al*., (2015) which indicated that cover crops directly help maintaining and improving soil physical properties through aggregation by the roots and formation of pores that improve moisture absorption, while the decomposition of the plant residues indirectly improve the soil properties. Other weed control methods like manual weeding and herbicide usage have been associated with soil compaction and loss of other important soil properties being left open to the effects of the sun (Thierfelder and Wall, 2009).

Studies by Blanco-Canqui *et al*., (2014) further amplify the value of the cover crops like desmodium du to their ability to improve the soil aggregate stability protecting the soil from the impacts of raindrops, with the belowground and above ground biomass contributing to the increase in soil organic carbon that enhances and promotes microbial activity. Desmodium Legume cover crops are associated with deep rooting ability and their roots penetrate compacted soil layers thereby reducing soil compaction(Blanco- Canqui *et al*., 2015). Our choice of the cover crop being desmodium spp, possess a deep rooting system having soil binding properties through the belowground root systems and the above ground cover preventing soil from being carried by either wind or water erosion energy reducing soil erosion (Blanco-Canqui *et al*., 2014).

Ecosystem services of Soil quality improvement associated with cover crops

From our understanding, there is a consensus among scientist that soils biological, chemical and physical components plays an essential function for the promotion of healthy crop growth (fig 16) for attaining high yields as emphasized by Tully and McAskill, 2020). The presence of a legume cover crop promotes the biological, chemical and physical soil elements which are the essential components for optimal soil functionality having ability to support growth of healthy and high yielding crops termed as healthy soil (fig 16) in agreement with studies by (Bunemann *et al*., 2018).

Gruver and Weil, (2007) have further elaborated on the need to change unhealthy soils to healthy by deliberately enhancing the functionality of the biological systems with the incorporation of cover crops in cropping systems. Since we used the desmodium legume cover crop, we expected nitrogen fixation by the associated symbiotic bacteria which was also evident in the formation of root nodules from the desmodium plants we pulled out in agreement with (Mus *et al*., 2016) indicator of soil health and quality. In our study, we related the aspects of a healthy soil with its ability to sustain biological activity, diversity, and productivity, ability to filter, buffer and help in decomposition of inorganic matter, regulation of water flow, ability to store and cycle nutrients while providing support and physical stability in line with (Tahat *et al*., 2020).

Relating our studies to those by Begum et al., (2019) relating to the Arbuscular mycorrhizal fungi (AMF), we used the legume cover crop to provide habitat for the AMF which in turn would provide ecosystem services to the coffee crop by acting as bio fertilizers helping plants tolerate different kinds abiotic stresses like heat, drought and extreme temperatures. Our choice of desmodium legume cover crop was to encourage the synergy between rhizobia bacteria interactions with AMF, which has been seen to increase the beneficial soil microorganisms' relationship in the roots of legume crops playing a key role in maintenance of soil fertility

(Giovannini *et al*., 2020). Studies by de Novais *et al*., (2020), further amplify the need of legume cover crops to support a wide network of fungal mycelium associated with AMF that aid in nutrient translocation and providing habitat for the nitrogen fixing rhizobia bacteria. The value of adding desmodium legume cover crop in coffee can be expected to enjoy similar benefits as indicated by the results of de Novais *et al*., (2020) with promotion of nodulation of up to 40% and subsequent nitrogen fixation in the relationship with host legume soya beans (Glycine max).

Impacts of Glyphosate based ingredients on ecosystem service provision in the soil

During our experiment, we searched literature on the impacts of glyphosate, which is a popular and widely used herbicide in coffee farms weed control programs and side effects on non-target soil organisms. Studies by Zaller *et al*., (2015) found that ecosystems services were decreased by the impact of glyphosate (and/or its metabolite AMPA) metabolites because they resulted to a decrease of up to 40% of the spore biomass of the mycorrhizal fungi and resulted in 30% decreased rainfall infiltration in the soil.

Tillage impact of ecosystem services provision by soil micro biome community

While using manual tillage in our experiment, we looked at the studies by Alguacil *et al*., (2008) indicating that continuous cropping results in lower AMF diversity while less tilled systems had increased AMF diversity and density. The conclusion is that tillage system influence the abundance AMF whereby increased soil disturbance are thought to disrupt the AMF hyphal network, dilute propagule rich topsoil and increase root decomposition with dispersal and exposure of the spore to less conducive growing conditions (Alguacil *et al.*, 2008).

Ecosystem services from cover crops on soil chemical properties

Observations from our experiment indicating increase in underground biomass from increased roots from desmodium legume fodder cover crop and some leaves. Incorporation of cover crops in cropping systems have been attributed to their ability to facilitate biomass decomposition helping in the scavenging and release of soil nutrients. The action of holding the soil together prevents nutrient loss through leaching and soil erosion as well as reducing the speed of water runoff during periods of normal crop growth (Kinama *et al*., 2007; Krstić *et al*., 2018; Oliveira *et al*., 2017).

Studies by Abdalla *et al*., (2019) have attributed the losses of nitrogen in the form of nitrate (NO3-), reducing availability and fertilizer use efficiency thereby increasing non-point source pollution to water bodies where the rainfall directs flow. Other observations by Malone *et al*., (2014) have associated the effects of cover crops reducing speed of rainfall water flow while increasing soil water holding capacity reducing this nitrogen loss. Biological nitrogen fixation from the atmosphere associated with legume cover crops leads to enhanced nitrogen availability (Blanco-Canqui *et al.*, 2015). Some cover crops are associated with improved potassium availability to the associated plants which could be attributed to the improvement of the cation exchange capacity of the soils associated with cover crops (Hallama *et al*., 2019; Nascente and Crusciol, 2015)

Ecosystems services of better soil biological processes influenced by cover crops.

When comparing the different treatments in our experiment in relation to soil coverage, we found the desmodium cover crop having long term soil coverage where there were more beneficial insects such as spiders hiding and they serve as predators to some coffee pests. The ability of the cover crops to provide shade and hiding place for beneficial insects could provide a habitat to a diverse community of insects and micro-organism which work on the organic matter and thereby safeguard biodiversity which is also discussed by Alyokhin, and Brown, (2020) and Vukicevich *et al*., (2016). Another observation that we made was on the increase in soil organic carbon concentrations due to the biomass input in both above ground where they trap dead coffee leaves and below ground sphere where roots form a mesh as observed by (Poeplau and Don, 2015). Longer living legume cover crops like desmodium are well fitted to crops such as coffee which are perennial which allocate sizeable resources to belowground productivity in comparison with annuals which helps in the accumulation of soil carbon with more nutrient retention to aid in hydraulic conductivity (McKenna *et al*., 2020). Coffee being a perennial crop has been seen to develop long term interactions of with the soil microbial community due to their longevity which help them develop unique ecosystems within the soil micro-biome especially useful are the mutualistic species (McKenna *et al*., 2020). Findings by Vukicevich *et al*., (2016) have associated the productivity of perennial crops such as coffee with having long-term relationship with Arbuscular mycorrhizal fungi which doesn't adequately develop in cases of continuous soil disturbance. Therefore their studies indicate the need to promote long term legume cover crops in the reduction of tillage practices to promote the AMF (Vukicevich *et al*., 2016).

Ecosystem services from cover crop relationship with crop production

There was a significant coffee harvest difference observed during the experiment indicated by a 1.6 higher production in the plots with desmodium legume cover crop, which was superior to hand weeding and herbicide weeded plots in the same environment. Resource competition studies focusing on water use, have indicated that cover crop adoption in areas receiving more than 800 mm of rainfall annually benefit from increased water storage in the soil and better crop production than pure stand crops (Blanco-Canqui *et al.*, 2014).

Since our study site had rainfall amounting to 1490 mm, it can be concluded that the potentiality of cover crops increasing coffee yields is relevant since there is absence water resource competition which could result in a penalty on the yields as observed by Balkcom and Reeves

(2005). Our study can therefore be used to indicate that in areas of higher precipitation, where weed growth in coffee is also a major challenge, adoption of desmodium legume cover crops will actually improve on the yields. The complementarity of the cover crops may not be so evident in semi-arid areas due to moisture competition and could possibly result on yields penalties (Blanco-Canqui *et al*., 2014; Balkcom and Reeves, 2005).

Kremen and Miles, (2012) studies concluded that intensive conventional farming in most monocultures weed control challenge as a key feature necessitating intensive control methods which could be attributed to lower arthropod population resulting in bigger pest problems. The intensive weed control systems are also seen to have lower soil nutritional status, insufficient nutrient cycling systems and may suffer lack of pollination services, resulting to a higher negative environmental footprint (Kremen and Miles, 2012). From our study results we can hypothesize that in coffee growing zones where rainfall is above 800 mm annually, the integration of desmodium legume cover crops is an ideal way of increasing benefits of ecosystem services in the production system.

Ecosystems services loss associated with glyphosate herbicide formulations

We made observations during the period of the experiment on the richness of insect diversity present in the different experimental plots and confirmed that the plots with desmodium cover crop had higher beneficial insect population such as bees during flowering foraging for pollen. Some relevant studies on the effects of climate change leading to geographic range shift for pollinators and leading to the absence of the ecosystem services have been indicated result in negative implications on food security due to the important role served by bees in the pollination processes (Imbach *et al*., 2017).

Studies related to coffee production have indicated that reduction in bee population and richness has been predicted to reduce coffee growing suitability by 10-22% which will be amplified with changing climate impacts already showing reduced suitability of coffee growing areas (Imbach *et al*., 2017) Studies done in the coffee rich area of Brazil indicated that 68 % of the 53 major foods were dependent on animal pollination and loss of pollination services would lead to reduction of the Brazilian GDP by 6.46%± 19.36%, and would be more prevalent among smallholder farmers representing 74.4% of the Brazilian agricultural labour force (Novais *et al*., 2016).

Bee pollination is an important factor in coffee production because coffee bean formation is highly dependent on insect assisted pollination for the fruit formation. Klein e*t al*., (2003) have amplified the importance of honeybee (Apis mellifera) in the cross pollination of coffee to offset the self-sterility and help in better fruit set since wind or self-pollination has success rate of 10 % in fruit setting. Our experiment can therefore be used to deduce that practices that promote the abundance of bee population such as cover crops is a key important feature in the success of coffee pollination and successful fruit set. The important role played by bees as part of the ecosystem services calls for the prudent use of pesticides to ensure the successful coexistence of bees with farmers so that the ecosystem services of pollination are achieved which are otherwise lost by farmers low knowledge in the use of pesticides leading to poisoning of the bees from toxic pesticides and loss of entire swarms (Fikadu, 2020). Continuous exposure of honey bees to toxic agricultural chemicals has been associated with their increasing decline (Vázquez *et al*., 2018b). Studies by Vázquez *et al*., (2018) on glyphosate formulations a popular herbicide globally, which also used in our experiment, detected glyphosate residues in honey and bee pollen baskets. The glyphosate residue traces found in the honey bee food have been associated with delayed larvae moulting and reduced weight of the bees (Vázquez *et al*., 2018b).

Other studies by Farina *et al.*, (2019) have indicated the negative ecological impacts of glyphosate residues on bees being the disruption of the associative social learning processes employed in the foraging, slow development of the cognitive and sensory abilities of young hive bees and related delays in brood development impacting on the entire swarm survival (Farina *et al*., 2019b).

Glyphosate working mechanisms targeting specific receptor sites of weeds have also been seen to affect micro-organisms that have symbiotic relationships such as bacteria and some insects living near the agricultural sites of application (Motta and Moran, 2018; Wilkes *et al*., 2020). Micro-biota found in the gut of the honeybee responsible for weight gain promotion and resistance to pathogens has been found to be susceptible to the herbicide (Motta *et al*., 2018). Other relevant studies by Motta *et al*., (2018), relate to the abundance and dominance of gut micro-biota species in the bees exposed to glyphosate at different concentrations, whereby higher concentrations was associated with their increased mortality from the opportunistic pathogens signaling the danger of disappearance of these great pollinators. Worker bees acquire the micro-biota from their nest mates in their early life where other bee foragers coming into contact with glyphosate introduce it in the feeding system. Since honeybees depend on their gut micro-biota to regulate their immune system, disruption of their normal development cycles makes them vulnerable to opportunistic infections (Motta and Moran, 2020).

Our study confirms the urgency of discontinuation of glyphosate formulations in coffee weed control and adoption of agroecological practices in weed control using desmodium legume cover crops to safeguard the native bee population which serve the critical ecosystem services role of pollination. Additionally coffee farmers should replace intensive tillage for weed control with desmodium legume cover crops for its agro-ecological value of enhancing benefits of ecosystems services which will build their resilience to climate change while aiming to reduce negative environmental impacts associated conventional weed control practices. Desmodium fits among the suitable coffee legume cover species due to its ability to smother weeds, reduce soil erosion, aid in biological nitrogen fixation and with improvement of yields. Livestock farmers have extra benefits of having biomass suitable as livestock feeds.

Limitations of the study

The focus of the study was on coffee yields relationship with coffee production and the interactions on the conventional weeding systems in comparison with adoption of the desmodium legume cover crop. Since both desmodium and coffee are perennial crops, longer term studies on the interactions may show further implications on the intercropping

Recommendations for future research and practical applications

Demonstrations are needed as part of the extension services provision package for making farmers understand the practicability and for them to experience the multiple ecosystem benefits associated with incorporating desmodium legume cover in their coffee production. Comparison of different species for different environments maybe needed to help farmers select the species combination that best fits their environmental conditions and help them make appropriate decisions on the species selection fitting their needs including availability of planting materials.

Inclusion of the ecosystem services in agricultural production systems should focus on the ability to use legume cover crops for weed control to assist in the reduction of the intensive agrochemicals aimed at intensive crop production ignoring the long term impacts on the soil fertility and nutrient cycling dynamics.

In relation to the Aichi targets on inclusion of biodiversity inclusion in sustainable agriculture should also look at the biological, chemical and physical attributes of the soil in relation to increasing agricultural production and increasing farmers' resilience to climate change impacts.

5.6 Conclusion

There was marked increase of 1.6 time's higher coffee yields per bush when desmodium legume cover crop treatment was compared with herbicide weed control in the coffee production plots during the experiment. There was 1.2 times higher coffee yields where desmodium was used as cover crop in comparison with manual weeding. This strongly indicates that coffee production systems adopting desmodium legume fodder cover crop in areas receiving more than 800 mm of rainfall will increase their ability to withstand climate change impacts by benefiting from the ecosystem services that sustainably increases the yields. Our objective of indicating the value of integrating legume cover crops in the cropping system for the provision of the ecosystem services of weed control, soil protection and yield improvement was achieved.

The benefits associated with desmodium legume cover crop will be highly beneficial I areas receiving more than 800 mm of rainfall annually where weed control in coffee production systems is a challenge without any negative tradeoffs in terms of moisture competition being experienced. Although the performance of cover crops to large extent is dependent on soil type, existing weather conditions, compatibility with crop species, and the cropping system, the need for communication to farmers for their understanding of the benefits associated with ecosystem services provision is needed urgently in the face of changing climate. The long term benefits of integrating legume cover crops in coffee production need to be understood by farmers so that they can increase their profitability.

CHAPTER SIX

6.0 Ecosystem Services Knowledge, Attitude and Practices of Farmers in Githunguri in Relation to Using Legume Cover Crops. Agroecosystems. Ecosphere Volume13, Issue 4; E4046

6.1 ABSTRACT

Farmers' adoption of Sustainable Agricultural Intensification Practices (SAIP) that deliver ecosystem services and increase farmers' resilience capacity in changing climate while supporting farmers' livelihoods referred as climate-smart are being promoted. This study on ecosystem services Knowledge, Attitude and Practices was conducted in Gewa ward, Githuguri Constituency in Kiambu County using a face to face questionnaire interview with coffee farmers who also keep dairy animals to gauge level of adoption of SAIP. The objective was to find out the level of adoption of desmodium legume fodder cover crops in coffee with associated ecosystem services benefits and fodder for livestock. A logistic regression model was used to make the relationship between commercial feeds and milk production. The findings were significantly important as an indicator on the reliance on commercial feeds for the success in milk production. 92% of the farmers have low knowledge on use of desmodium legume cover crops for the ecosystem benefits as intercrops either with napier grass (Pennisetum purpureum) or coffee. 90 % of the coffee and livestock farmers reported weather variability exacerbating feed scarcity increasing dependence on commercial livestock feed purchases thereby reducing their profitability of milk production. Milk production being a major economic focus in the areas is mainly supported by purchase of commercial feeds, which increases when rainfall is inadequate or delayed. Commercial feeds and milk production are strongly correlated with the average price per litre contributed by commercial feeds estimated at ksh. 19 (USD 0.2) per litre of milk produced. Majority of the farmers are concerned due to the impact on reduction of the milk income associated with intensive reliance on commercial feeds and seeking alternatives in Napier (Pennisetum purpureum) production which is inadequate. Our findings indicate that adoption of legume fodder cover crops in coffee which are rich in proteins would reduce farmers' reliance on commercial feeds and increase incomes while benefiting from ecosystem services when adopting sustainable agricultural intensification with climate change remaining a major concern.

Key words: ecosystem services, legume fodder cover crops, milk production, resilience, sustainable agricultural intensification.

6.2 Introduction

There is evidence of the devastating impacts from changing climate on farmers' livelihoods which have been predicted to intensify in the sub-Saharan Africa region accelerated mainly from land use change, land degradation and resource scarcity (Gomiero, 2016; IPCC, 2014). Climate change impacts are intensifying at more rapid rate never seen before affecting farming communities with increased uncertainty on predictability putting food security and livelihoods of farming families at great risk (FAO, 2016). Unpredictable weather is resulting in unpredictable yields affecting most of the coffee varieties and farming practices increasing coffee farmers vulnerability to diseases and pests further depressing yields and increasing production costs (Bunn 2019; Ovalle-Rivera *et al*., 2015).

There is an increased frequency of drought occurrence to more than once every 5 years causing irreversible significant impacts on the livestock sector as well (Thornton, 2010). Increasing evapotranspiration associated with more regular intensive droughts is likely in most of sub-Saharan Africa where rain fed crop production accounts for more than 90% of crop production *(*Bhaga *et al*., 2020). Predictions of increased climate variability influenced by changing climate (IPCC, 2014), requires farmers to look for diversification strategies to increase their resilience against the ever increasing risk of failed seasons which are becoming increasingly more frequent due to the heavy reliance on rain-fed agriculture (Thornton *et al*., 2011). Promotion of agricultural technologies that help farmers resilience to climate change have been indicated as the most sustainable ways of helping farmers in adoption of “climate-smart agriculture” (Sabrina *et al.*, 2015; Lipper *et al*., 2014). Smallholder farmers, defined as owning two hectares or less (Wiggins and Keats, 2013), represent about 80% of the productive land sector in sub-Saharan Africa and contributing to almost 90% of the agricultural production.

Despite the challenges predicted by changing climate, smallholder farmers are still expected to continue playing their significant role in food security in the developing countries (Wiggins and Keats , 2013) . Climate change vulnerability requires farmers to adapt to the uncertain turn of events, as a response to the expected or observed climatic stimuli (IPCC, 2007). Farmers can mitigate risks by utilizing available opportunities associated with environmental changes with a set of actions, decisions, attitudes and activities which help an individual cope with the changes with an expectation of improved wellbeing (Koorem *et al*., 2020). Behavioral and cognitive predisposition influences the perceptions of the threat level associated with changing climatic conditions (Quiroga *et al*., 2020). New technologies and practices that farmers may be willing to adopt for improving their adaptive capacity has some associated risks that create mental constraints related to ease of adoption or cognitive ability to accept and access such as crop diversification to reduce climate change impacts vulnerability (Roesch-McNally *et al*., 2018).

The increasing vulnerability of the farmers to climate change impacts have been predicted to significantly increase missed seasons or declined yield production leading to impacted livelihoods. This has been documented for the coffee farmers and livestock farmers with their inability to sustainably cope with the climate change impacts of reduced capacity for rain fed food production (Pretty *et al*., 2011). Adoption of agricultural innovations with potential impact to change livelihoods has been slow especially in relation to adoption of cover crops (Mukasa, 2016).

Utilization of legume cover crops have been demonstrated offering unique ecosystem services among them being increased crop yields and additional incomes (Garrity *et al*., 2010; Turnbull *et al*., 2016). Adaptive farmers have increased their resilience to climate change impacts associated with yield stability and increased efficiency of rainfall use (Isbell *et al*., 2017). Nitrogen fixation resulting from adoption of legume cover crops among the ecosystems services resulting increase yields of associated crops while increasing resilience to changing rainfall patterns (Sheppard *et al*., 2020).

Increasing adaptive capacity equally equated to increasing resilience is reflected by the capacity of a system to absorb disturbance, without conditionally changing elementary interactions that characterize the system (Baggio *et al*., 2015). Successful mitigation and adaptation strategies are best tailored to regional and local conditions persisting in differentiated regionalism (Rosenzweig and Tubiello, 2007). Crops grown under monoculture system like coffee having ecological homogeneity have been found vulnerable to climate change related to biotic stresses that renders their productivity precarious and unpredictable (Raza *et al*., 2019). Increasing temperatures relating to the specific coffee optimal temperature requirement for growth and reproduction is a narrow range affecting suitability, whereby if warming exceeds coffee’s optimum temperatures, yields decline results (Agesa *et al*., 2019).

Adaptations to climate change through adaptations such as climate-smart agriculture through ecosystems based adaptations has increased the transformations and reorientation of agricultural systems approaches that helps in the dynamics of changing climate (HLPE, 2016; Lipper *et al*., 2014). Climate smart adaptations aim to increase the synergies among the varying crop production practices that are expected to reduce emission of greenhouse gases while increasing farmers’ productivity and positively enhancing their resilience to climate change (Lipper *et al*., 2014). Studies by Shikuku *et al*., (2017) on provision of climate information indicated that farmers readiness to invest in climate-smart adaptation such as crop diversification and adoption of climate resilient farming systems which promoted better land, soil and water management strategies was influenced by provision of timely climate information.

While looking at the aspects of soil health, (Gunstone *et al*., 2021) analysis of cover cropping in relation to soil health improvement, affirms the important characteristics for sustaining plant productivity being good soil tilth, sufficient root depth, reduced population of pathogens and insect pests, better nutrient supply, resistance to degradation and freedom from chemicals and toxins harmful to the crops, these properties have been attributed to being provided by the selection of the right cover crop.

Meijer *et al*., (2015a) studies on knowledge, attitudes and perceptions have indicated the challenges related to the adoption of agroforestry in Sub-Sahara Africa, the benefits and the challenges of any technology adoption is relative to the key role played by the farmers characteristics and economic variables in the decision making process. A farmer's decision to adopt a technology as influenced by knowledge, attitude and perception relates to the general attitudes people have in relation to the said technology and relevance to the local environmental conditions (Meijer *et al*., 2015b). Adoption constraints such as agronomic challenges, land shortage and associated low multipurpose value have been cited as among the mental cognitive challenges to adoption despite perceived positive contributions (Meijer *et al*., 2015b).

Our study was aimed at the evaluating the ecosystem services knowledge, attitude and practices of coffee farmers associated with legume fodder cover crops among mixed farmers (coffee and livestock) in Githunguri aims at analyzing the KAPS related to ecosystems services associated with intercropping coffee with legumes.

6.3 Materials and Methods

The study was carried out in the month of January 2021, in Gewa ward, Githuguri Constituency in Kiambu County (fig 12) in central Kenya (S 1° 3' 31.0824", E 36° 46' 40.4796"). The community is comprised of farm families growing coffee and keeping dairy animals. The area is located in a high elevation zone of 1979 m above sea level considered upper highlands with land characterized by high elevations plains, hills and plateaus comprising of slopping areas with moderately deep valleys. The area has reddish volcanic fertile soils, that are well drained The annual mean temperatures are 23 degrees C and bimodal rainfall with precipitation occurring mainly from March to May and October to December, giving an annual average of 2,000 mm (GoK , 2018).

A cross sectional survey comprising 97 farmers selected based on the set criteria of having coffee and dairy animals in combination with other crops was undertaken. The respondents were selected through snowball sampling (Kirchherr and Charles, 2018). This sampling method was chosen since the participants were referrals made amongst a community sharing and possessing similar characteristics of research interest (Kirchherr and Charles, 2018). A research permit was granted by the National Council for Science and Technology and Innovation (NACOSTI), License No. NACOSTI/P/20/5946. The farmers were selected based on guidance from the Gititu Coffee factory Githunguri, based on the criteria of a farmer having coffee and dairy animals.

Ethical considerations were put in place in relation to respect of the culture and lifestyle and questions to farmers were presented in a transparent manner after explaining the purpose of the study. The questionnaire was structured into 3 parts, part 1 was to capture the farmer’s farm size, coffee and milk production and related factors affecting milk production. Part 2, was related to the farm dynamics and part 3, and was in relation to knowledge, attitude and practices related to the ecosystems services associated with intercropping. Each participant was interviewed individually after consenting to the interview. The time taken for each interview was approximately 45 minutes. Data was collected using the Arch Gis tool Survey 123, which summarized data into a CV file compatible with Ms excel.

Map of study area.

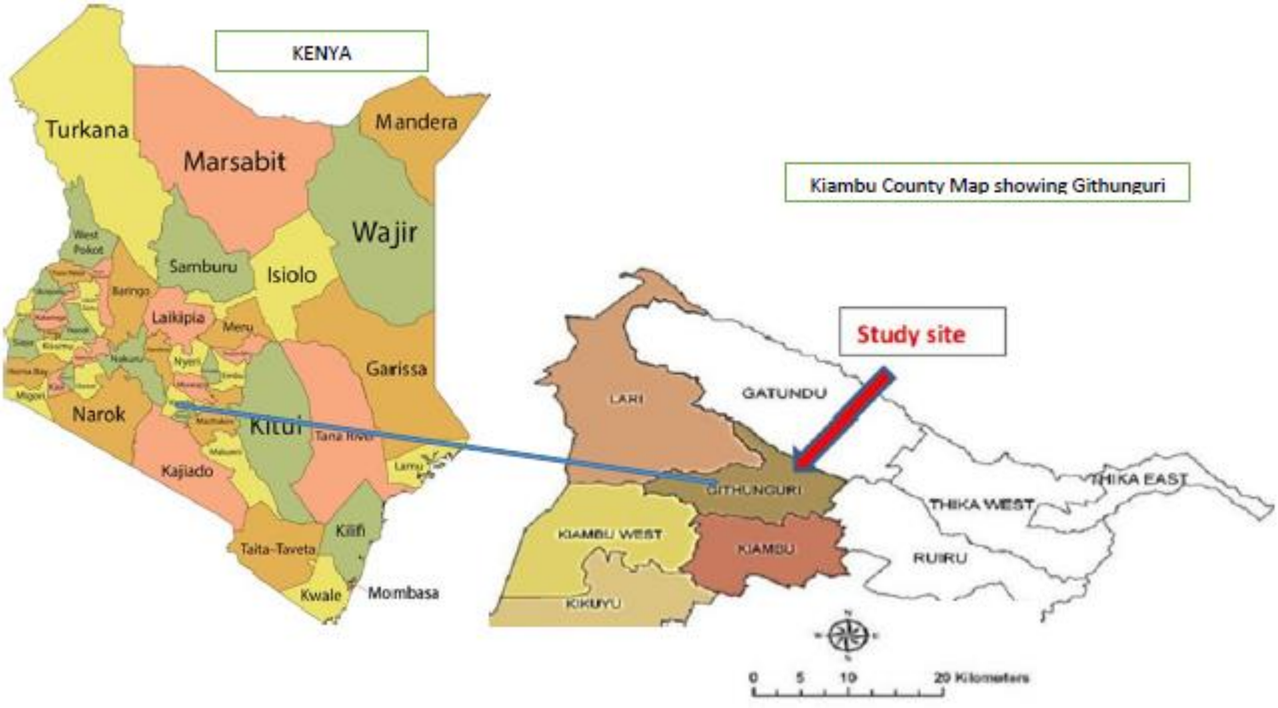


Figure 12: Map of the study area, Githunguri sub County in Kiambu County
(Source- extracted from google maps).

6.4 Results

The average land holding was noted to be 1.1 acres (0.44 ha), which is an indication of the extent of increased land subdivision arising from increasing population, with land registration being 100% in the name of the male household head. Specific farmers were identified through the contacts from the local coffee pulping station known as Gititu coffee factory. All the farmers identified grew coffee and kept dairy cows which were supplied with some fodder grown locally dominated by napier grass (Pennisetum purpureum) and supplemented with commercial feeds from the Githunguri Dairy cooperative society, which also collects milk for processing and marketing. Diverse crops are grown by the farmers with almost 60% farmers having bananas, 30 % have avocados and others have macadamia trees. The main trees grown being Grivellia Robusta and Eucalyptus spp. Around 98 % of the farmers had part of their plots planted with napier grass which enables them to substitute on the dairy cow feeding cost. On average, the farmers get commercial feed advances of 20 Ksh (USD $ 0.2) per litre of milk which translates to an extra cost per litre of milk delivered.

The most common land tillage practice is manual weeding mostly done 4 times per year during the rain seasons. The main tools for weeding are hand hoe, fork jembe and machete, while minority of the famers (10%) are still using herbicides for coffee weed control. The landscape is comprised of several valleys where the sloping is around 55% to 75 % for the steep areas, making the tilled soils susceptible to soil erosion. The population density being over 600 persons per km² with an indicative fertility rate of 4.3 giving an average household of 6 persons with an average life expectancy of 75 years 2 (KNBS, 2019). The most commonly used coffee fertilizer is NPK 17:17:17 which increases coffee yields when applied. For soil erosion control measures, 80 % of the farmers have constructed bench terraces across contours (fanya juu- Swahili word used for making bench terraces introduced in the 1970’s and 1980’s) where some bench edges have been planted with napier grass. The ownership of dairy animals is based on personal ability with many households having at least one animal but others have more animals. The animal manure is an important part of the farmer’s production system since they extensively use the manure to improve soil fertility in their farms.

1. Intercropping in coffee.

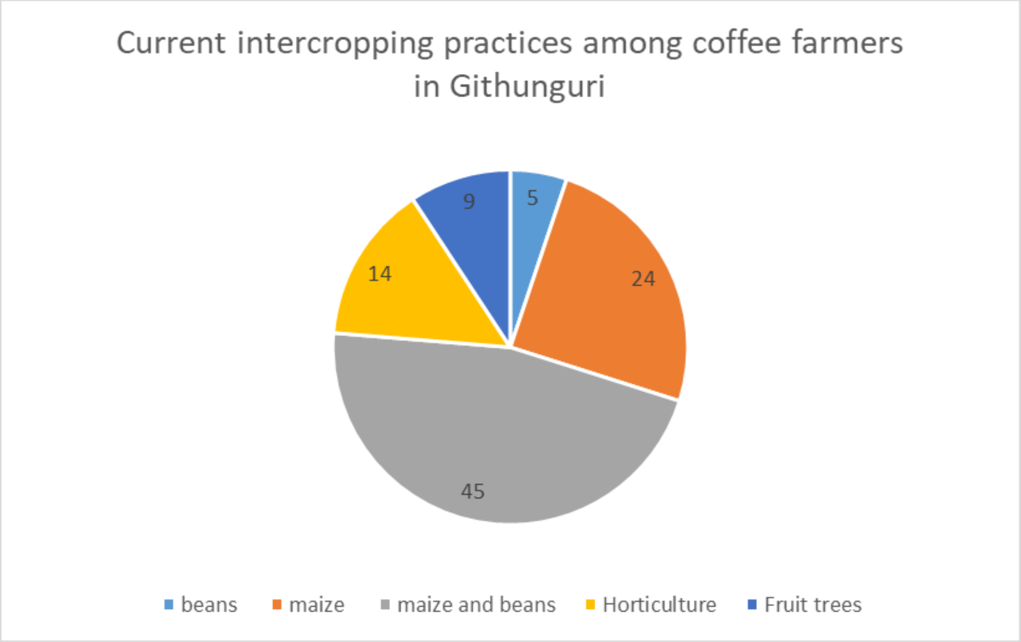


Figure 13: Intercropping patterns among coffee farmers

All the farmers interviewed have been intercropping their coffee (fig. 14) with different crops and their concerns are not on the synergistic relationship between the crops but on their food security. The results of the different intercropping patterns have resulted in lower coffee productivity due to nutrient competition. The ideal intercropping regimes in agronomy and sustainable agricultural intensification are aimed at synergy between the crops such as nitrogen fixation by legumes, soil erosion control and moisture conservation with the intended benefits of the companionship. Since the early years of introduction of coffee from the 1960's to 1990's, the coffee act Cap 333 was strongly followed and intercropping was not allowed in coffee, which was aimed at production intensification and was characterized with high input usage which resulted in high yields. Following the collapse of the international coffee agreement which had coffee quotas, there was a crash of the coffee prices in July 1989 (ICO, 2019). Since then, many farmers have been discouraged by the low prices and some farmers didn’t receive any money from their coffee deliveries’ as it was being deducted against input advanced. Further delayed payment and lowered prices have made farmers to result to intercropping coffee with different crops. Our study found that 45 % of the farmers intercropped maize and beans with coffee, 24 % maize alone, 14% had horticulture (cabbages, spinach, tomatoes, capsicums etc.) in the coffee, 9 % had fruit trees intercropped with coffee and 5% had only beans in the coffee intercrop (fig 2). Many farmers intercropping was aimed at supporting household food security and the absence of extension service provision made them unaware of complementarity of intercropping.

2. Demographics

Table 10: Sample characteristics of the survey

Variable	**Means**	**%**
Male	73	75
Age (years)	63	65%
Education level	Primary	60%
Years in coffee	25	52 %
average coffee farm size	0.44 acres	51 %
Average production per farmer (acre)	857 kgs	60 %

Our survey revealed that 45% of the population were aged between 50 – 65 years (mature) while 38 % were retired (over 65 years), with 15 % being between 35 – 49 years and only 2% (35 years and below) being in the youth bracket (fig 15 and table 11). The male population was dominant since they own the land and are responsible for decision making while female led households had some of their husbands working elsewhere. The bulk of the population had basic education level having gone through primary school. The study revealed that majority of the decision makers were above the age of 50 years.

Figure 14: Age distribution of the respondents.

3. Average coffee yields

The average coffee yields were 400 kgs per year for small farms (0- 0.5 acre), 450 kgs for small to medium farms (0.5 – 0.75 acre), 980 kgs per year for medium farms (1-1.25 acre) and 1550 for large farms (more than 1.3 acres) (fig 16). The size of the farm was somehow related to the efforts made by the farmer to improve on production since the larger farms were showing better production than smaller farms. With an average of 532 plants per acre (CRF, 2005) for the SL 28 variety which is most common, the yields are low since this translates to 1.8 kgs per stem, while the optimal coffee yield per stem should be on average 10 kg per stem.

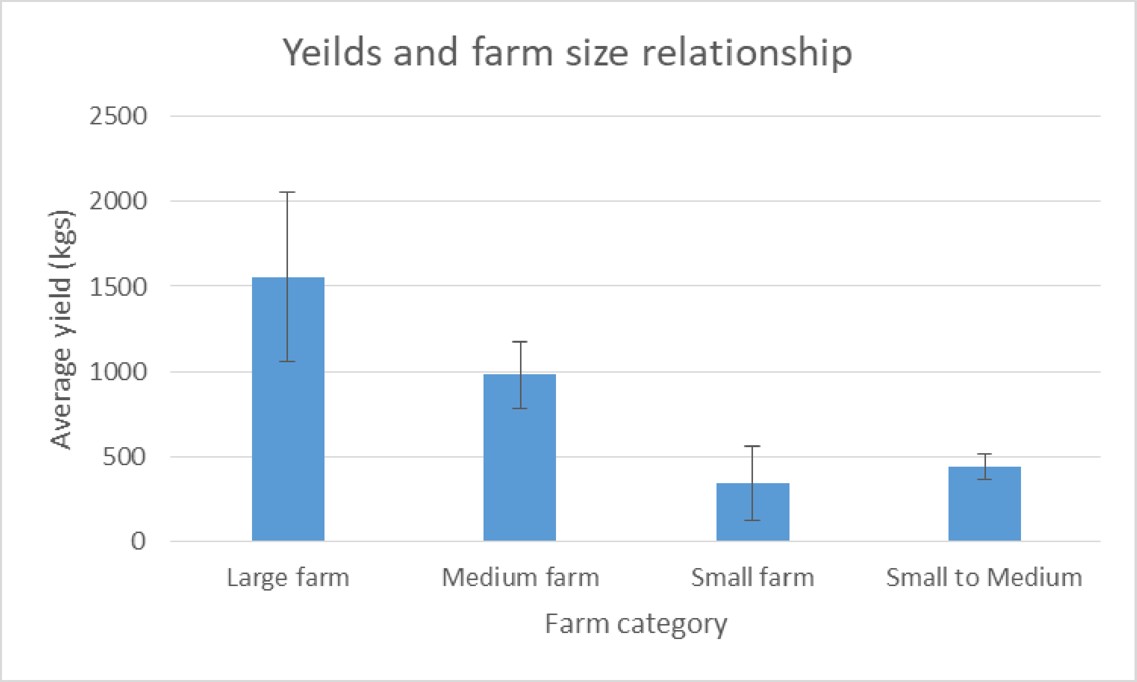


Figure 15: Average coffee yeild and farm size relationship

Legend; error bars indicate the range of the standard deviation.

Large farms had higher production related to size and more focus from the owners due to the higher incomes from the farms. Farm sizes are dependent mainly on inheritance from parents where bigger families lead to smaller farms eventually after subdivision. There is an increasing trend of farm size reduction as more children inherit the farms from their parents.

4. Coffee production related factors

Farmers had different factors expressed related to the coffee production with most farmers relating timing of payment and unfavorable weather as having significant impact on their yields. Figures 17-19 below shows the different factors classified as primary, secondary or tertiary affecting farmers in the coffee production.

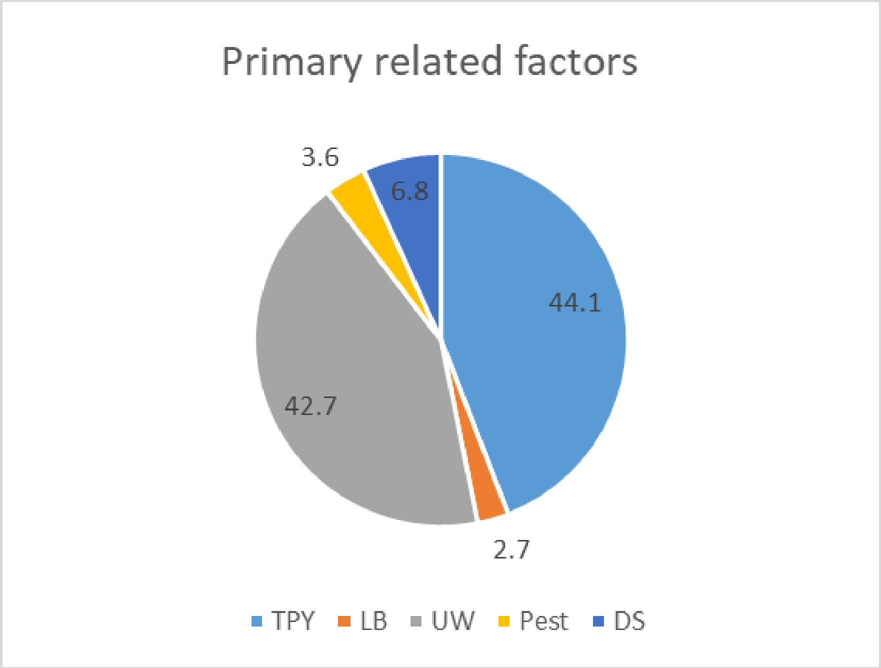


Figure 16: Primary coffee production related factors

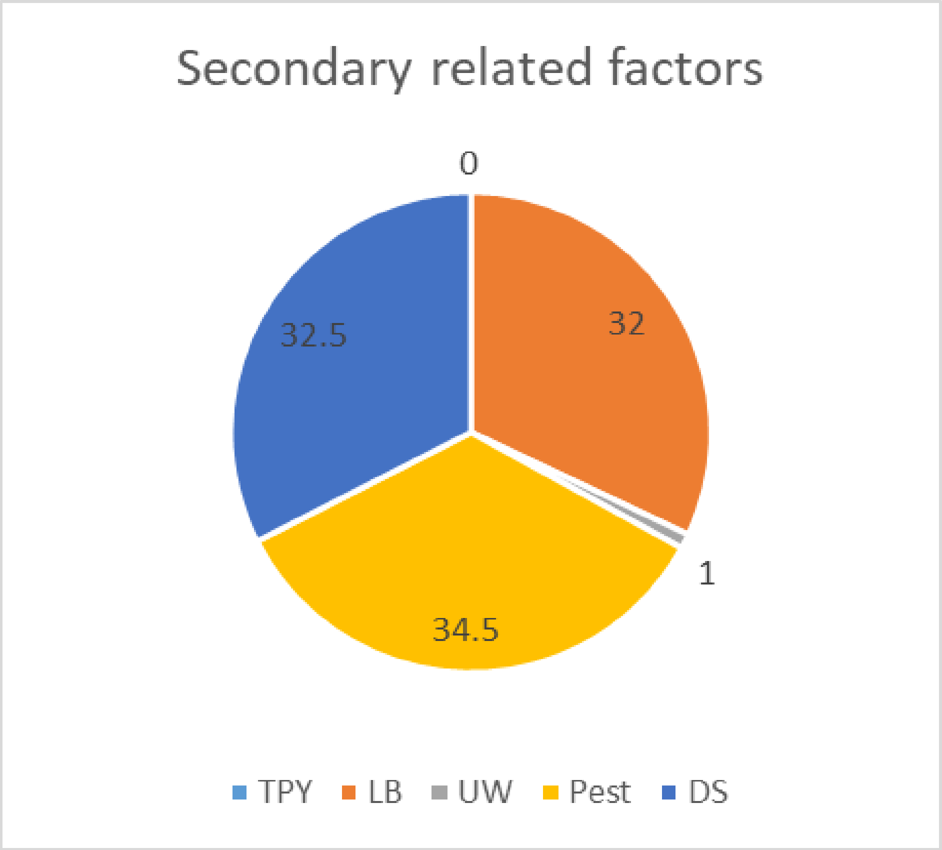


Figure 17: Secondary coffee production related factors

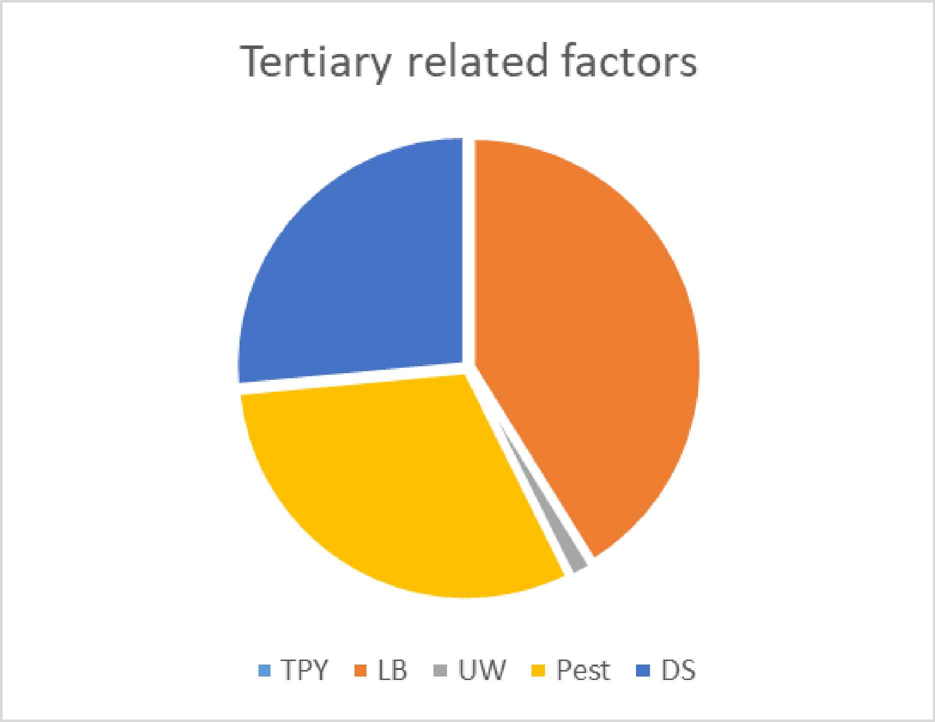


Figure 18: Tertiary coffee production related factors

Legend: TPY = timing of payment, LB – Labour cost, UW- unfavorable weather, DS- Coffee Diseases and Pest – Coffee pests

Most of the farmers had the timing of payment (44%) figures 17, 18 and 19) as a primary factor (beyond farmers control) related to declining coffee yields followed by 43 % unfavorable weather while labour and diseases were not considered as primary factors causing decline in coffee yields. Most of the farmers had observed inadequate rainfall resulting in irregular flowering and less fruiting, while harvesting was affected by continued drought during maturity making cherry not to ripen during the expected peak period of November and December. Secondary factors associated with coffee yields decline were 34.5 % increase in pests which was making it more expensive to maintain, 32.5 % timing of payment, while 32% associated the labour costs reducing profitability among factor of coffee production decline.

Tertiary factors associated with coffee production challenges were 40% labour related, 31% pests and 26.5 % diseases associated with coffee production.

5. Milk production costs

The majority of the farmers knew that milk production was related to the type of diet fed to the dairy cow and that some types of fodder or mixes of some fodders would show an increase in milk production. A linear regression plotted to compare the effect of commercial feeds on milk production found the p value to be 0.69 (fig 20) which is considered to be significantly important indicator of the reliance on commercial feeds for the success in milk production.

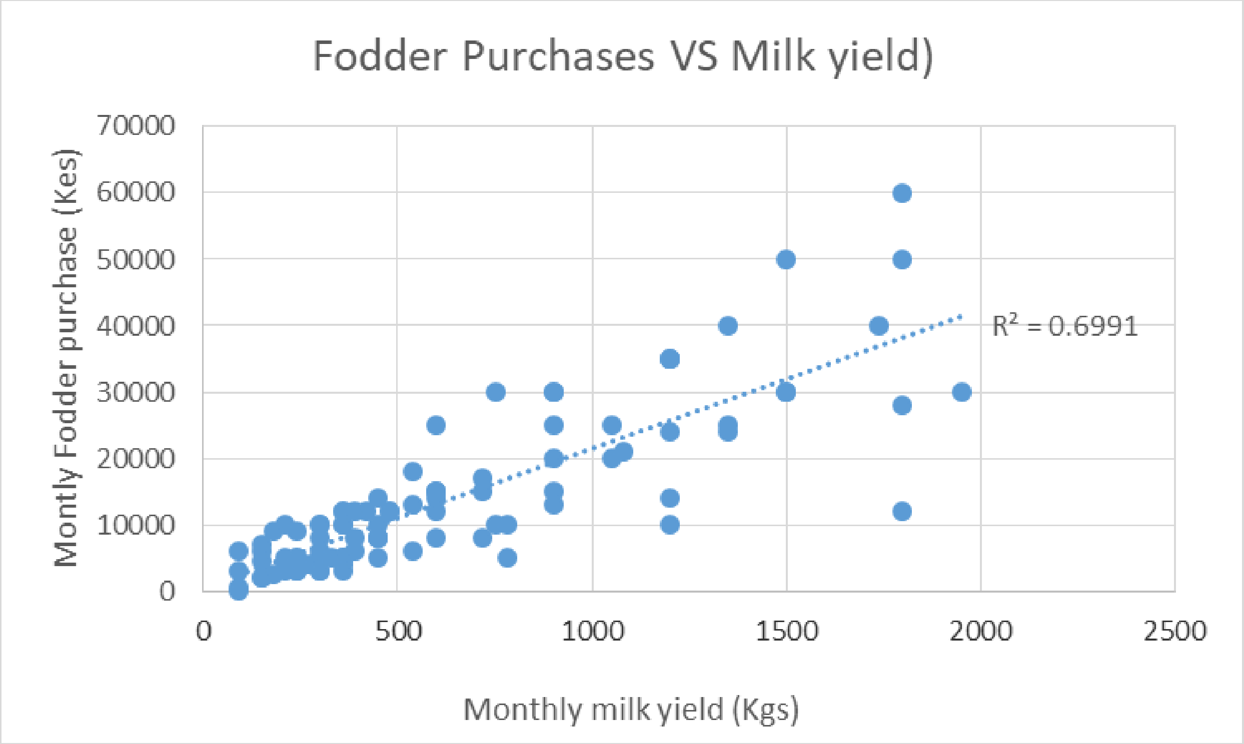
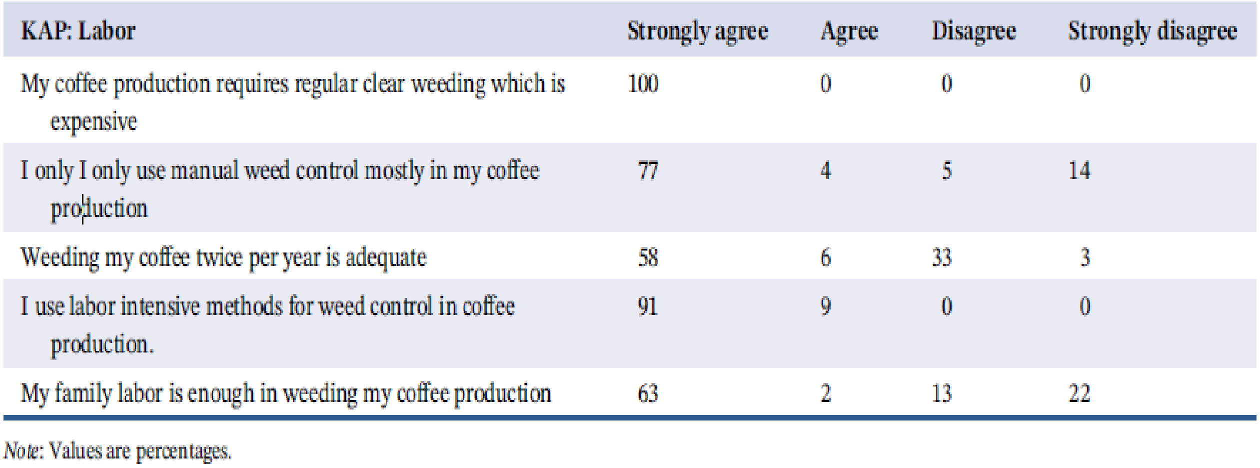


Figure 19: Commercial fodder purcahses versus milk production

The monthly commercial feed purchases were significant and the farmers who sold more milk had purchased more commercial feeds showing the significant relationship between commercial feed supply and increase in milk production. The average cost of milk production was positively correlated to Ksh 20 (USD 0.2) of purchased commercial feeds for every litre of milk produced. For the farmers to increase the milk production while relying of grown fodder, they didn’t know the exact quantity required and the ratios, feeding dairy animals is dependent on availability and ease of access the fodder for the animal. The Githunguri farmers’ dairy cooperative society have been conducting different trainings related to dairy production giving a variety of the types of the legume fodder that can help farmers increase milk production such as desmodium, Lucerne, vetch, calliadra, tricandra among those that can be mixed with napier grass to supply crude protein for better milk production. Some of the farmers who had been trained, had already started incorporating desmodium with napier grass as intercropping but the majority fear that desmodium could smother napier grass and reduce its vigorous growth and thus reduce number of cuttings and productive years.

KAPS (knowledge, attitude, and practices) Analysis

Table 11: KAPS (Knwoledge, attitude and practices) Analysis

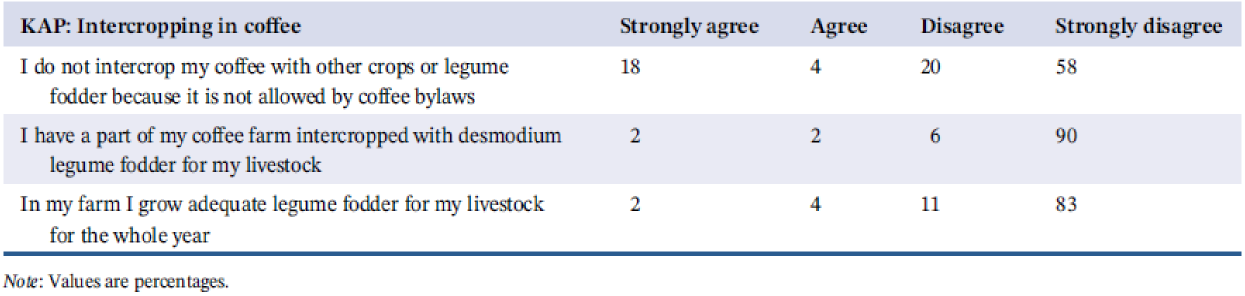


KAP: Labor	Strongly agree	Agree	Disagree	Strongly disagree
My coffee production requires regular clear weeding which is expensive	100	0	0	0
I only I only use manual weed control mostly in my coffee production	77	4	5	14
Weeding my coffee twice per year is adequate	58	6	33	3
I use labor intensive methods for weed control in coffee production.	91	9	0	0
My family labor is enough in weeding my coffee production	63	2	13	22

Note: Values are percentages.

Labour for different coffee production operations differed from the family being able to supply enough labour at 65% to having 22 % relying on outside labour for their coffee production operations which was more critical during harvesting. The larger farms had more labour challenges which could not be supplied by the family household and relied on paid labour for the coffee operations. Since manual weeding is the most commonly practiced, 91% attributed it to being most intensive and expensive.

Table 12: KAPS on intercropping



KAP: Intercropping in coffee	Strongly agree	Agree	Disagree	Strongly disagree
I do not intercrop my coffee with other crops or legume fodder because it is not allowed by coffee bylaws	18	4	20	58
I have a part of my coffee farm intercropped with desmodium legume fodder for my livestock	2	2	6	90
In my farm I grow adequate legume fodder for my livestock for the whole year	2	4	11	83

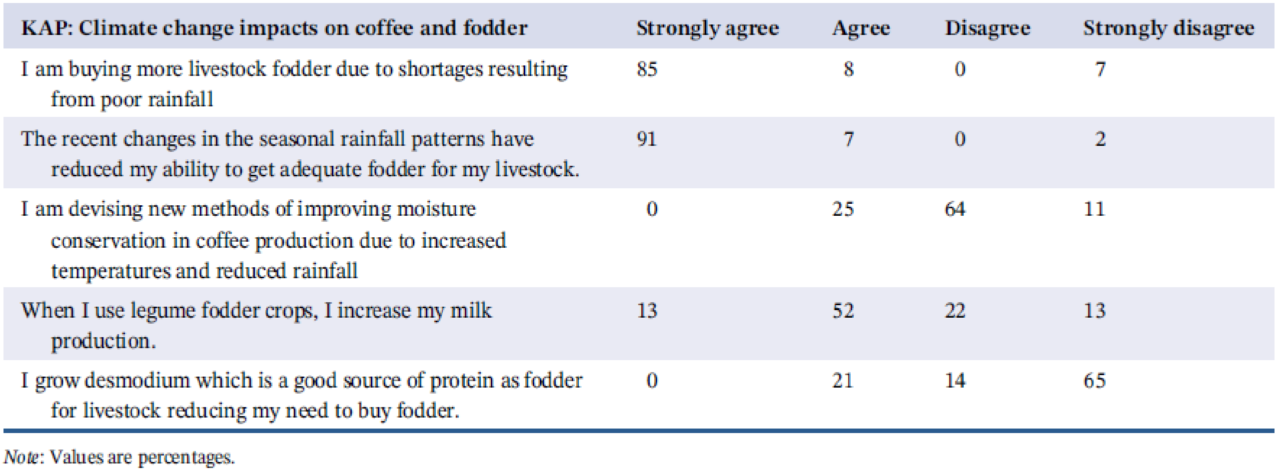
Note: Values are percentages.

Farmers liberally intercrop coffee with different crops as shown and there is little knowledge on the interactions between the different crops and coffee. This intercropping results in competition with the main crop and could be attributed to the declining yields. There is little knowledge on the value of complementarity among the intercrops as farmers are influenced by food security concerns.

In the early years of coffee establishment, Cap 333 (the coffee Act 1963) had prohibitions related to coffee production, and had expressly declared that coffee was to be mono-cropped with no allowance of intercropping. The act had prohibitions that made farmers who opted to grow coffee sign confirmation of maintaining the crop and ensuring no intercropping including cover crops.

Many farmers face challenges in providing adequate nutritious fodder to their livestock and 85 % of the respondents indicated being forced by circumstances to buy commercial feeds to sustain the milk productivity with reducing land sizes leading to reduced capacity for fodder production. Increasing weather variability has resulted in decreased capacity for most farmers to produce adequate fodder for their livestock and with 91% reporting facing fodder shortage related challenges (table 13). There is absence of adoption of desmodium legume cover crop in coffee due to lack of extension services to advice on the adaptation to changing climate.

Table 13: KAP (Knowledge, attitude and practices) responses on climate change impacts



KAP: Climate change impacts on coffee and fodder	Strongly agree	Agree	Disagree	Strongly disagree
I am buying more livestock fodder due to shortages resulting from poor rainfall	85	8	0	7
The recent changes in the seasonal rainfall patterns have reduced my ability to get adequate fodder for my livestock.	91	7	0	2
I am devising new methods of improving moisture conservation in coffee production due to increased temperatures and reduced rainfall	0	25	64	11
When I use legume fodder crops, I increase my milk production.	13	52	22	13
I grow desmodium which is a good source of protein as fodder for livestock reducing my need to buy fodder.	0	21	14	65

Note: Values are percentages.

There is notable absence of training on the adoption of cover crop adoption and intercropping in coffee due to absence of extension services and many farmers don't know the relationship between different crops used in intercropping with coffee. There is absence of the knowledge of ecosystems services related to cover cropping as witnessed by the responses of farmers not having experimented cover crop usage in their coffee (table 14).

Table 14: KAPS on ecosystem benefits from cover crops

KAP: Cover crop ecosystem benefits	**Strongly agree**	**Agree**	**Disagree**	**Strongly disagree**
I am not motivated to use legume cover crops for my coffee weed control	4	3	62	31
Using legume cover crop in my coffee farm for moisture conservation is not very encouraging since the returns are low.	5	5	72	18
Using desmodium legume fodder cover crop for my livestock fodder intercropped in coffee has not given me better returns	2	7	67	24
I am not very enthusiastic to use desmodium to reduce my use of fertilizers in my coffee farming	3	6	66	25
I have low Motivation for looking for desmodium planting material to use as legume fodder cover crop in my coffee farm.	2	7	59	32

Note: Values are percentages.

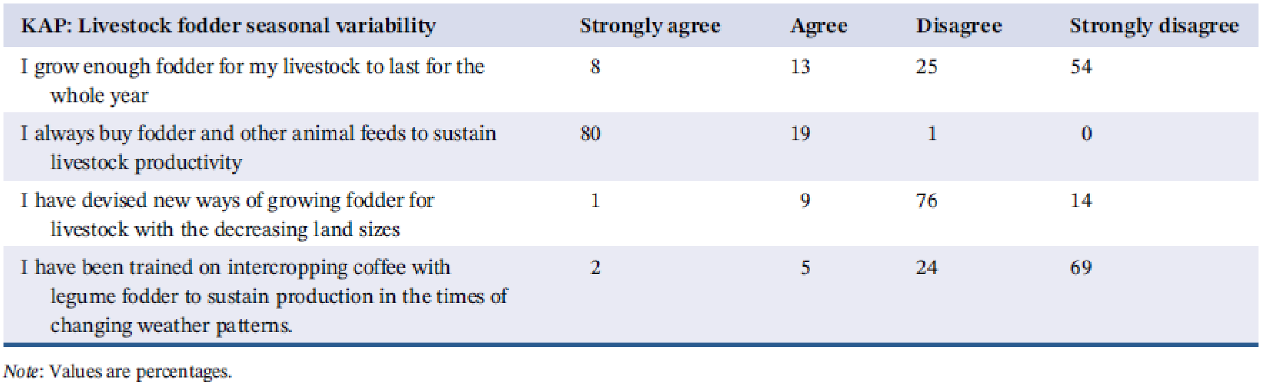
Table 15: KAPS on ecosystem services knowledge

KAP: Ecosystems services from cover crops	**Strongly agree**	**Agree**	**Disagree**	**Strongly disagree**
I have not realized any significant savings from using legume fodder cover crop in my coffee production	9	14	52	25
I have not seen any reduction on my animal fodder purchase even when I have desmodium legume cover crop in my coffee farm.	9	8	60	23
I have realized enough production from my livestock even when not using desmodium legume fodder.	1	4	78	17
I do not see the big benefit of controlling soil erosion using desmodium legume cover crop in my coffee farm.	1	10	71	18
I have no interest in intercropping desmodium legume cover crop in my coffee farm since it is a lot of work.	4	9	58	29

Note: Values are percentages.

Most farmers have not internalized the ecosystem services that can be realized with use of legume cover crops and still use manual weeding for their coffee despite the predisposition of the soil to erosion and not benefiting from the intensification of their farming activities.

Table 16: KAPS on livestock fodder

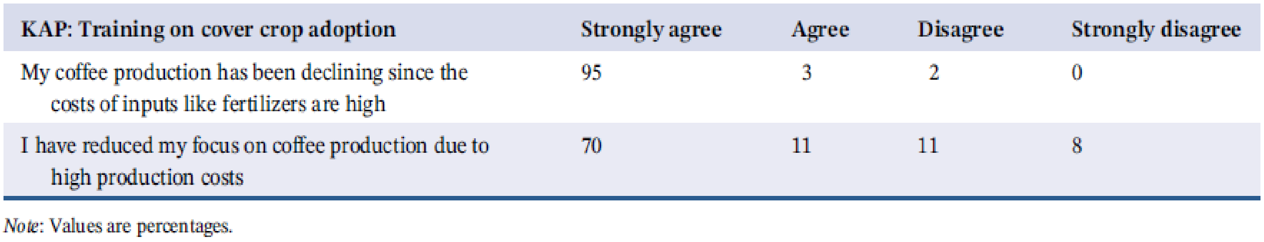


KAP: Livestock fodder seasonal variability	Strongly agree	Agree	Disagree	Strongly disagree
I grow enough fodder for my livestock to last for the whole year	8	13	25	54
I always buy fodder and other animal feeds to sustain livestock productivity	80	19	1	0
I have devised new ways of growing fodder for livestock with the decreasing land sizes	1	9	76	14
I have been trained on intercropping coffee with legume fodder to sustain production in the times of changing weather patterns.	2	5	24	69

Note: Values are percentages.

80 % of the farmers interviewed are always buying commercial feeds and fodder to sustain milk production. This is despite the possibility of using cover crops to bridge the fodder shortage since they have not been trained on use of legume cover crops in coffee. 79 % of the farmers do not grow enough fodder for their livestock despite having some areas left for growing napier grass.

Table 17: KAPs on training of cover crop production



KAP: Training on cover crop adoption	Strongly agree	Agree	Disagree	Strongly disagree
My coffee production has been declining since the costs of inputs like fertilizers are high	95	3	2	0
I have reduced my focus on coffee production due to high production costs	70	11	11	8

Note: Values are percentages.

There has been a notable decline in coffee production with 95% of the farmers attributing it to absence of extension services. 81 % of the farmers interviewed attributed the diminished focus on coffee production to increasing costs of production including labour.

6.5 Discussion

Our findings showed that the average age of the farmers interviewed was 63 years, with most having only primary education and more than 25 years in coffee production (table 11). The reliance of farmers on income from milk has been considerably impacted by shortage of fodder leading to over dependence on commercial feeds despite their high significance in the overall cost of milk production (fig 20). The findings support our research gap of the value of adaptation to climate change by farmers in relation to adoption of measures to compliment livestock fodder to sustain their resilience.

Adaptations to climate change.

In our study, we found that farmers are intercropping coffee with other crops (fig 14), which can be considered as a measure of adapting to the decline in coffee prices and lower productivity. However, the kind of the intercropping mix lacks optimality in that competitive species are grown which doesn't compliment coffee production. The practice of increasing species diversity have been realized to result in better resource use efficiency in agro-ecosystems with microhabitat differentiation allowing species to grow in their ideally suited environment suited to species unique requirements (Bybee-Finley and Ryan, 2018). Evaluation of intercropping systems based on land use value is best indicated by the Land Equivalent ration (LER), which provides the yield comparison between a sole crop (mono culture) and combination of two or more crops in the same area (Amanullah, 2016) and this seems to be missing among the farmers choice of the crop type to intercrop with coffee in our study. While LER increases the ability to analyses the advantages of using legume cover crop mixture by providing the combined yield advantage (Sebetha, 2018), most of the farmers use short season annual crops in competition with the coffee. The advantages of the combined yields expressed in LER is great way to measure the reverse competition (Morales-Rosales and Franco-Mora, 2009). Net biodiversity effect (NE)(Clark *et al*., 2019) aims at evaluating the total biomass production of the mixture, which is a great way to measure the net effect of the optimal legume cover crop mixtures.

While the farmers in our study are engaged in intercropping as a way of adaptation, adaptability can be expressed in the adjustment capacity to unpredictable changing circumstances causing disruptions and the development of new action plans, engaging in new actions or modifying behavior to enable better coping or recovery from the unfamiliar conditions (Solorzano and Cárdenes , 2019). Correct choice of adaptation measure advocates for development of flexibility and ability to apply existing resources to new applications of multiplicity of roles for the same thing. (Solorzano and Cárdenes , 2019) describes resilience or vulnerability as depending on the actual adaptive capacity dependent on multiple factors including access to assets and related services supportive of resilience. Adaptive capacity in a way is a measurement of the outcomes of the resilience practices adopted (Dazé and Dekens, 2016). Gerber and FAO, (2013) looks at climate smart adaptations in relation to landscape approaches that embrace sustainable agriculture principles that result in the reduction of competition in land use in addition to enhanced integration of planning and management practices that maintains ecosystem services such as clean air, water, better food and ensuring reduction of land degradation in the production processes. Additionally Livestock management practices that improve feeding strategies that reduce or cancel methane production, fodder crops that reduce reliance on grains for animal feeds with enhanced manure treatment where possible to produce domestic energy (FAO, 2016).

Proposed Governance measures in adaptation

Our studies indicated low presence of extension service providers and therefore the training of the farmers to adopt adaptive measures to increase their resilience to climate change impacts is low or absent (table 14). The arguments on good governance strongly indicate the importance of bringing positive results aimed at raising ability of the people to attain their productive function in a sustainable way reducing marginalization and giving everyone equal opportunity to thrive (Argyriades, 2006). Better attainment of the SDGs by developing countries has been seen through alignment with good policies and supportive institutions (Go and Quijada, 2012). The absence of a collaborative governance in the coffee sector has seen challenges associated with absence or low presence of extension service providers, delayed payment and often reduced earnings by farmers indicating low stakeholder engagement for the collective decision making, consensus and deliberative policy implementation in terms of coffee deliveries payments (Ulibarri, 2019).

Weeding operations have been seen to be among the major challenges to farming families with 100% indicating the intensity especially those who engage in manual weeding (table 12). Addition of legume cover crops in the coffee systems reduce intensity of soil operations thus improving on soil moisture conservation, reduced soil erosion, aids in nutrient cycling while reducing overall weed competitiveness (Tadesse, 2018). Weeds in coffee production have been associated with loss in crop productivity while their control increases cost of production, they create competition for space, light, moisture and nutrients, with other releasing their natural substances that have capacity to inhibit growth of other crops (allelopathy), with binding weeds physically smothering the growing crop (morning glory and bind weeds) (Fasih *et al*., 2019). Other weeds serve as host to fungal pathogens while hosting pests injurious to the main crop (Tadesse *et al*., 2016). Reducing weed competitiveness while enhancing crop growth requires choice of vigorously growing locally adopted legume cover crop varieties with ability to smother weeds, but also maintain healthy and living soil and where possible increase nutrient cycling such as the biological nitrogen fixation (Vitousek *et al*., 2013).

Ecosystem services related to cover crops

Adoption of cover crops is low due to famers' low level of understanding the role of legume cover crops in providing beneficial ecosystem services (table 15). The main purpose of addition cover cropping system in farming, is for provision of agronomic and ecological services such as weed suppression (Brust *et al*., 2011), soil water management (Sastre *et al*., 2018) and nutrient cycling through biological nitrogen fixation (Mendonça *et al*., 2017). Ecosystem services, defined as conditions and processes supporting natural ecosystems with their species makeup sustaining and fulfilling’s human life with provision of food, fiber and fuels (Swinton *et al.,* 2007). The provisioning, supporting and regulating services from cover crops (improvement of soil fertility “nitrogen fixation and organic carbon”, suppression of pest and diseases and weed control), other environmental and cultural benefits such as carbon sequestration and biodiversity conservation could be added as other ecosystem services (Damour *et al*., 2015; Ramirez-García *et al*., 2015; Tardy *et al*., 2015).

Selection of species that combine these different functional traits while having compatibility with the main crop makes the overall performance of the selected cover crop important especially if it has less competition with the main crop and characteristics such as adaptation to under story growth (Holmes *et al*., 2017; Kramberger *et al*., 2012). This niche differentiation in terms of resource partitioning (light competition) results in competition avoidance which is among the most important cover crop traits (Tilman *et al*., 2006).

Cover crops can as well be defined as “service crops” since they are grown to support the main crop for the provision of non-marketed ecosystem services such as organic carbon improvement, control of soil erosion, maintenance of soil fertility, biological nitrogen fixation and weed suppression (Elhakeem *et al*., 2019; Garcia *et al*., 2018). Positive impact often result in other associated ecosystem services such as pest and disease regulation, improvement of soil percolation and improvement of soil biodiversity (Elhakeem *et al*., 2019). The correct selection of a service crop that has less competition for soil resources with the main crop is required to maintain the desired balance of main crop production and benefits of the ecosystem services (Shackelford *et al*., 2019).

Arabica coffee is grown in the highlands often in sloping areas prone to soil erosion (Garcia *et al*., 2018), while continuous cropping reduce organic carbon levels (Coll *et al*., 2011; Salomé *et al*., 2016), steep slopes accelerate run-off during heavy rain periods which could be mitigated with cover crops. Salomé *et al*., (2016), highlights on the expected benefits of cover crops as improvement of soil organic matter, biodiversity, soil erosion control and reduction of soil compaction.

Associated disservices of ecosystem services from cover crops have been on water and nitrogen (Celette and Gary, 2013; Ruiz-Colmenero *et al*., 2013b), which makes the species selection important to optimize ecosystem services and cancel out this “disservice” (Shao *et al*., 2021; Zhang *et al*., 2017). For the achievement of adequate balance between ecosystem services and disservices, there is need for flexibility in the adaptive management (Schipanski *et al*., 2014) which makes desmodium a suitable candidate in terms of timescale since it can be cut during times when there are coffee operations and it regenerates later. Soils rich in organic matter are associated with ecosystem services resulting from symbiotic mycorrhizal fungi which are associated with drought resistance of host plants due to improvement of plant water relations (Garg and Chandel, 2010).

Shackelford *et al.*, (2019), review on the benefits associated with cover crops ecosystem services showed that organic matter was 9 % higher in presence of cover crops, 41% more microbial soil biomass, weed incidence was 27% lower with more carbon stores in the organic matter. In relation to yields, legume cover crops resulted in 16% higher cash crops yields with 53% less nitrate leaching, (Shackelford *et al*., 2019) nevertheless disservices associated with cover crops concluded that moisture competition indicated 13% disadvantage to in comparison with no cover crops (Shackelford *et al*., 2019).

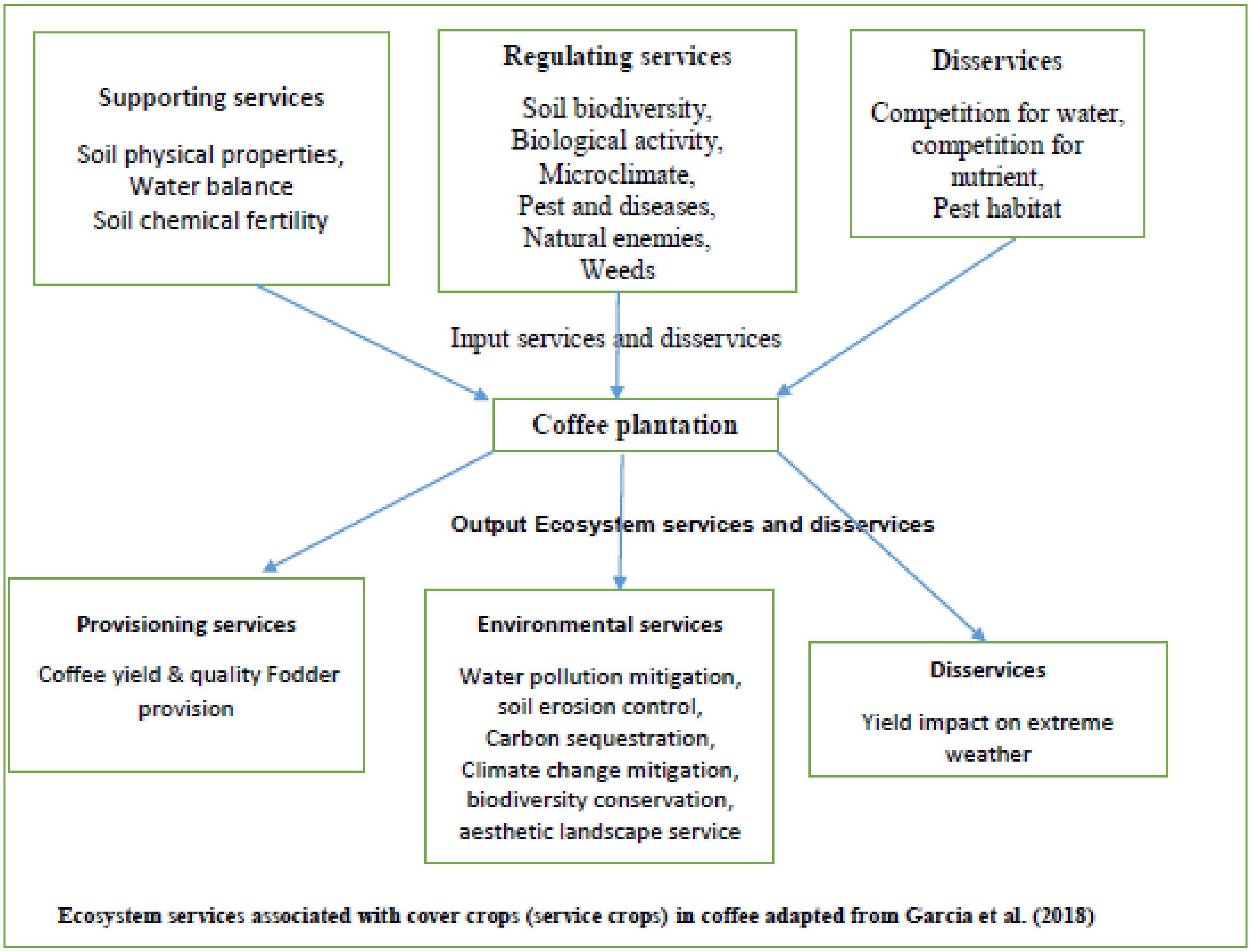


Figure 20: Ecosystem services associated with cover crops

Ecosystem goods

Many farmers are aware of the challenges associated with inadequacy of livestock fodder and usually depend commercial feeds during times of low rainfall when napier grass is inadequate (table 7). Studies on the ability of Desmodium legume fodder cover crops (table 15 and fig 20) are yet to be appreciated by coffee farmers, this is despite studies like done by (Tadesse *et al*., 2016) evaluating the use of desmodium cover crop in Arabica coffee. The study demonstrated the benefits of moisture conservation and weed control when the desmodium was harvested twice a year and carried away from the coffee farm. Development of the Push-Pull technology by scientist at ICIPE have already shown the benefits associated with inclusion of desmodium cover crop in maize crop mix leading to more than 20% yields associated with soil fertility improvement with biological nitrogen fixation from the legume, suppression of parasitic weed Striga, reduced insect attacks, and production of biomass for livestock fodder (Midega *et al*,. 2017).This is in line with (Mijatovic *et al*. 2013) indicating that various adjustments that contributes to resilience combining diversification of farming systems, adjustments in cultivation practices, adoption of stress tolerant species, agroforestry and sustainable use of natural resources will the best adaptation strategy by farmers.

Simplified agro-ecosystems have been found to remove some functional groups that in effect leads to a shift in balance from desirable to less desirable states that alter their responsive capacity to changes and ability to generate ecosystem services (Folke *et al*., 2004). Agro-ecosystem diversity (table 16) have been shown to increase resilience to a great degree to various environmental shocks (DuVal *et al*., 2019). Perception of climate change among households have been seen to be influenced by access to extension services or external reliable communication, which influences in turn adaptation actions (Opiyo *et al*., 2016). Household or community livelihood resilience as influenced by adaptation planning helps to evaluate the important factors which can be self-assessed to measure resilience capacity (Choptiany *et al*., 2017). The adoption of the practices of agro-ecology aimed at transforming food systems (Wezel *et al*., 2009) is aimed at emancipation of farmers to empower them have control over their production system broadening access to food and embracing environmentally friendly practices (Béné *et al*., 2018).

Species Complementary and diversity

Although many farmers intercrop coffee with diverse species, the knowledge of complementary is lacking (table 14), the low Species diversity does not act as adequate buffers against failure associated with dynamics of environmental fluctuations accelerated by changing climate. Complementarity and compensatory capacity of the entire agro-ecosystem plays a role in increasing resilience, since if one species fails, the other can play a role resulting to a better predictable aggregate community response or enhance ecosystem communal assets (Altieri *et al*., 2015).

Service crops (cover crops) protects soil aggregates from impacts of heavy rains thereby reducing aggregate breakdown and soil detachment that renders soil prone to erosion (Ghimire *et al*., 2019) while at the same time preventing soil from sealing and crusting (Luo *et al*., 2020). The reduction of surface runoff is dependent on the rate of the coverage by the cover crop, with the additional maintenance of favorable soil structure for promoting porosity (Capello *et al*., 2019). This results in the provision of water infiltration service as well as the reserve filling during the period of the rains (Bois *et al*., 2020). The increased surface roughness associated with cover crop vegetation improves on infiltration while the root system is associated with a better soil macro-porosity (Lopez-Vicente *et al*., 2020), which additionally improve on soil surface hydraulic conductivity (Levavasseur *et al*., 2015) .

Soil moisture retention associated with improved soil structure and increase in soil organic matter associated with cover crops is improved (Mohammed *et al*., 2020). In areas with heavy rainfall occurrence at different times, enhanced soil water storage is important which is associated with rainfall infiltration which is made available to the associated crops for longer periods (Gaudin *et al*., 2010). The mulching effect of the cover crop, reduces soil evaporation, reduce rate of runoff and enhances water uptake by the associated crop (Prosdocimi *et al*., 2016).

Cover crops are associated with provision of a better habitat for fauna and flora therefore impacting on the abundance and biodiversity (Rahman *et al*., 2009), including abundance of earthworms (Coll *et al*., 2011). Decreased soil disturbance is associated with maintenance of higher trophic levels in the soil (Sánchez-Moreno *et al*., 2009). Arbuscular mycorrhiza fungi development is enhanced with its associated formation of mutualistic symbiosis with many crops thereby enhancing biological activity (Cheng and Baumgartner, 2006; Ingels *et al.*, 2005; Steenwerth and Belina, 2008).

Cover crops help in the provision of habitat for natural enemies that could act as the biological pest control of some pests in coffee (Woltz *et al*., 2012). The provision of alternative food or flowering at different times for cover crops may provide alternative forage for bees which provide pollination services for coffee (Fiedler *et al*., 2008). While some pests like nematodes and some soil borne pathogens maybe favored by grass cover crops, other perennial plants suppress nematodes through hosting predatory nematodes by supporting better food web structure (Thoden *et al*.,2011; Zhang *et al*., 2017). Khan *et al*., (2010) while working on the push-pull technology using desmodium observed the cover crop emitting biological chemicals that deterred the laying of eggs by moths which develop into stem borers on maize. Studies on the impact of desmodium cover crops used as rotation in bean production have already shown its ability to reduce nematode populations and could be more preferred than grass species (Kimenju *et al*., 2008).

The ability of cover crops to control weeds therefore reduces the high cost of manual labor as well as reducing the reliance on herbicides (Tworkoski and Glenn, 2012). Desmodium have already been shown to have the ability to inhibit the development of the Striga weed a parasite that greatly affects maize yields (Khan *et al*., 2008). Lou *et al*., (2016) further amplifies the role played by allelochemical compounds released by decomposing residues that suppress weeds by inhibiting weed seed germination. Cover crops coverage of the soil surface is associated with low soil disturbance reducing the exposure of dormant weed seeds to favorable conditions for their emergence thereby leading to continued weed suppression in crop production (Tardy *et al*., 2015).

Attempts to qualify agricultural systems to fit adaptation for increasing farmers' resilience in the face of climate change (table 14) evaluating different technologies have concluded that utilization of cover crops will greatly help in mitigation of climate change (Kaye and Quemada, 2017; Mwangi *et al*., 2015). The adoption of legume cover crops to aid in reduction on the reliance on synthetic fertilizers will result in reduction of greenhouse gas emissions, cover crop also help in reducing heat absorption by the soil, aid in increasing soil carbon storage while reducing greenhouse gases emissions associated with bare soils (Kaye and Quemada, 2017).

Cover crops are also associated with better sequestration of carbon and reduced greenhouse emissions from the soil since they remain covered for longer durations (Basche *et al*., 2014; Poeplau and Don, 2015). Therefore legume cover crops ability to fix atmospheric nitrogen which could lead to reduction on reliance on synthetic nitrogen sources associated with nitrous oxides which as powerful greenhouse gases, while increasing sinks for greenhouse gases into the soil (Ramirez-García *et al*., 2015).

6.6 Conclusion

Many farmers are advanced in age and are used to manual weeding and herbicides, while complementarity in intercropping has not been realized. Adoption of legume fodder cover crops which has the best optimal land equivalent ratio should be promoted to enhance farmers' resilience to climate change. Milk production is made expensive by lack of alternative fodder despite opportunities in in adoption of legume fodder cover crops. Farmers' knowledge attitude and practices related to the ecosystem services provided by adoption cover crops is still very low and concerted efforts need to be put in place to make farmers appreciate the comparative advantage of adoption of legume fodder cover crops especially in areas where crop livestock mix is prevalent.

Table 18: Comparative significance of different coffee weeding methods

Parameter	Hand weeding	Cover crop	Herbicide
Cost implications	*	******	******
Time requirement	******	***	*
Yield impact	***	******	***
Crop safety	*	******	******
Soil erosion	*	******	*
Soil nutrient benefit (nitrogen fixation)	*	******	*
Weed competition	*	******	***
Sustainability rank	***	******	*

Key = *low significance *** Medium Significance ****** high significance

Sustainability ranking of the different methods of weeding coffee in relation to the associated ecosystem services should be promoted by policy makers and extension services providers. The right type of legume fodder cover crop needs to be understood by the farmers in terms of ranking them (table 19) in relation to the range of ecosystem services expected from such kind of selection of the optimal mix.

CHAPTER SEVEN

7.0 CONCLUSION AND RECOMEDATIONS.

Coffee production plays an important role for many smallholder farmers and the entire Kenyan economy, which has been impacted by the continuous population growth reducing available land for coffee production. Climate change impacts have been documented to have varying economic impacts on the agricultural sector further increasing coffee farmer's production challenges and therefore urgent policy guidelines for advising farmers on the best adaptation alternatives focusing on climate smart agriculture. The climate-smart agriculture focusing on increasing adaptation and building farmers' resilience to climate change while increasing agricultural productivity and incomes while possibly leading to reduction of emissions from agriculture with the adoption of the better land management practices should be encouraged. This calls for sustainable agricultural intensification where adoption of legume fodder cover crops in different mono-cropping systems particularly in coffee which reduces or eliminates the intensive tillage practices while increasing land productivity in terms of land equivalent ratio needs to be promoted.

The coffee farmers challenges associated with increasing weeding costs and increasing input prices while exposing the soil to erosion agents have accelerated land degradation, thus reducing land productivity and reducing farmers' incomes and therefore engaging farmers to adopt desmodium legume fodder cover crop should aim at reducing production costs and protecting the soil from agents of erosion associated with degradation while sustaining productivity.

This climate-smart research in coffee production comparing three different weed control methods of continuous tillage, herbicide application and incorporation of desmodium legume cover crop found out there is a great potential of incorporating legume fodder cover crop in coffee systems to support farmers with climate smart practices that help them in adaptation and increase resilience to climate change impacts. The additional study in Githunguri, where farmers grow coffee and keep dairy animals undertook a knowledge, attitude and practices survey among small holder coffee farmers who also keep livestock in relation to adoption of climate smart agriculture.

The study results diagnosed the misconceptions surrounding the incorporation of desmodium legume cover crops in coffee production through a hypothetical analysis and provided a convincing contribution in advancing the urgency in the adoption of desmodium legume cover crop in weed control in coffee production systems.

The study concluded that desmodium legume fodder cover crop have the ability to convey the various ecosystem benefits in areas receiving more than 800 mm of rainfall annually through controlling weeds which we found reduced farmers labor cost significantly. The study results further showed that desmodium legume fodder cover crop once established was able to sustain a longer duration when the soil moisture was higher than conventional hand weeding and herbicide application. The results obtained from the production of extra biomass estimated at 17 tons per hectare per year greatly needed in livestock production and therefore supported the need for sustainable agriculture intensification where the same size of land produces more.

The study conclusion is that, our four objectives were positively achieved which were of showing ability of desmodium legume fodder cover crop to control weeds was achieved. Our objective of indicating that there are moisture conservation benefits of adoption of desmodium legume cover crop was achieved. Our objective of comparing coffee yields between conventional weed control methods of hand weeding and herbicide with desmodium legume fodder cover crop indicated that desmodium had 1.8 times higher production than herbicide and 1.2 times higher than hand weeding. Further results of the desmodium fodder biomass harvest of 17 tons per hectare per year indicated the great potential of increasing the land equivalent ratio positively needed for climate change adaptation.

Recommendations

i. Existing extension services provision to farmers should embrace integrating climate-smart coffee production practices where desmodium legume fodder cover crop should be promoted to increase farmer's ability to increase resilience and adaptation to climate change.

ii. Coffee farmers should be encouraged to adapt their production systems with desmodium legume fodder cover crop to enjoy the savings from using the legume fodder for livestock, the labor saving from reduced weeding costs and the associated ecosystem benefits.

iii. In the face of increasing cyclic seasonal weather oscillations which may affect coffee yields, farmers should take advantage of incorporating desmodium legume fodder cover crops which enables the soil retain moisture longer and thereby supporting better coffee production outcomes.

iv. Policy makers should embrace the climate-smart agricultural adaptation where the incorporation of desmodium legume fodder cover crop should be promoted among the climate-smart interventions that gives farmers multiple adaptation benefits to increase their resilience to climate change.

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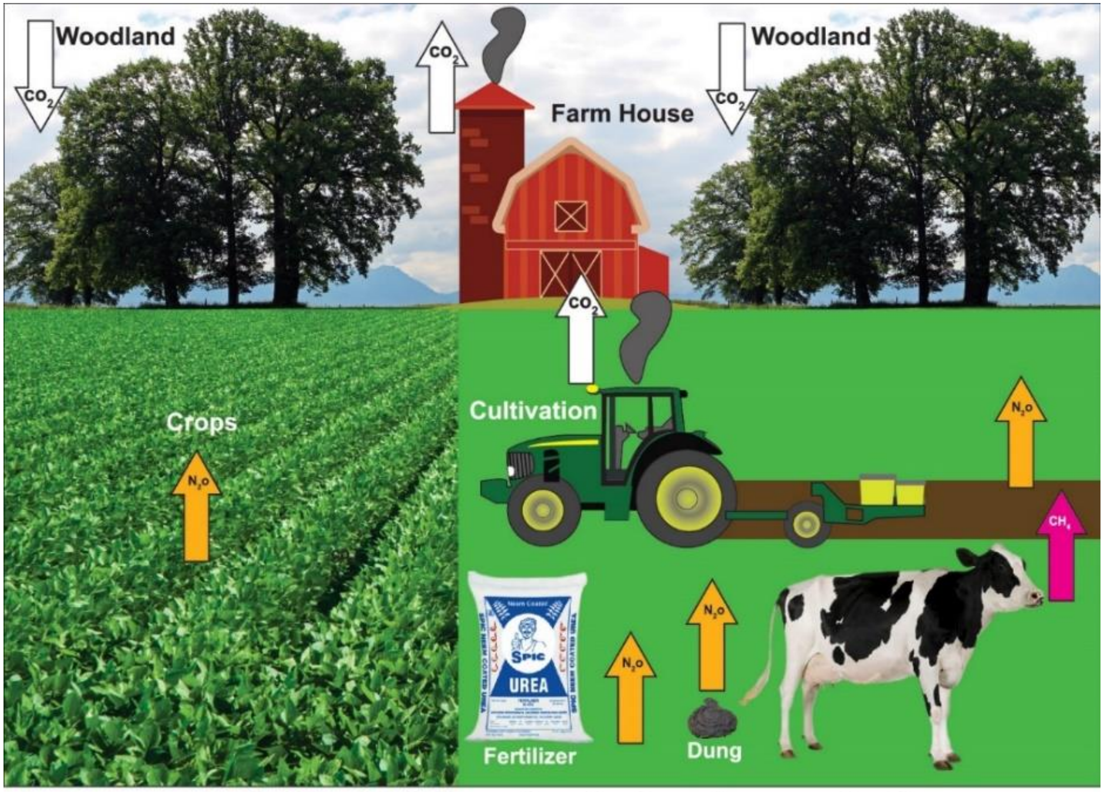
APPENDICES

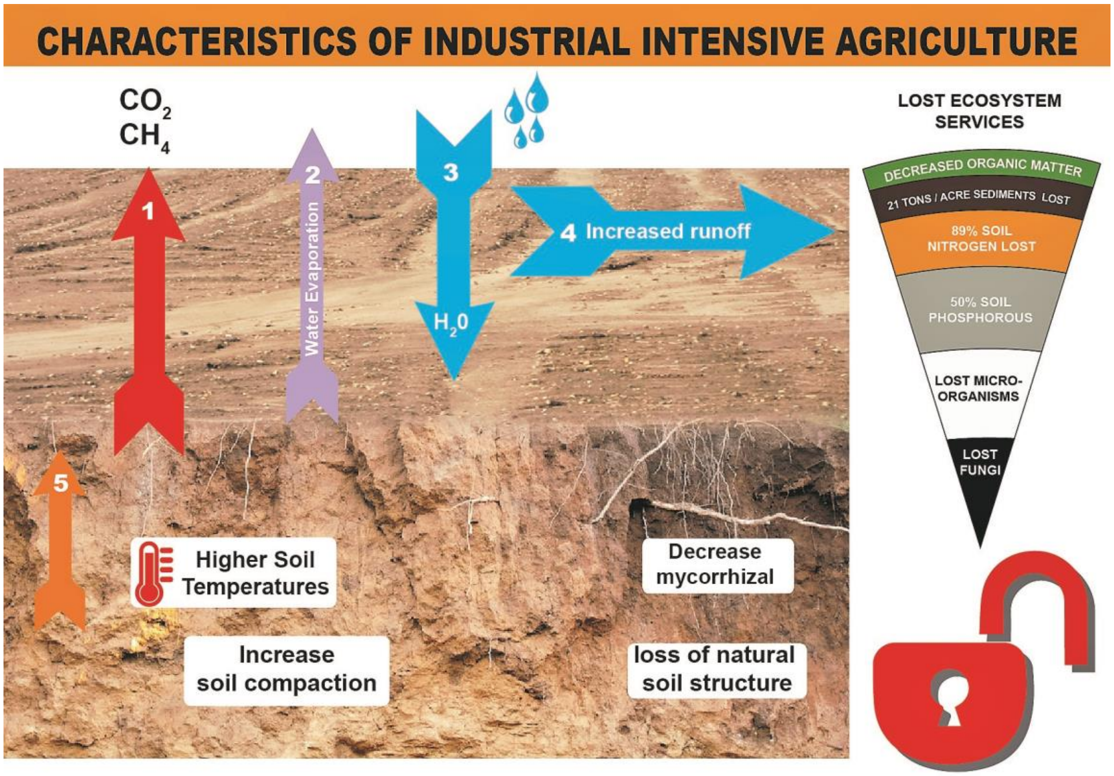
Appendix 1 Illustration with the depiction of carbon emissions from agriculture by the IPCC



IPCC depiction of emissions from agriculture

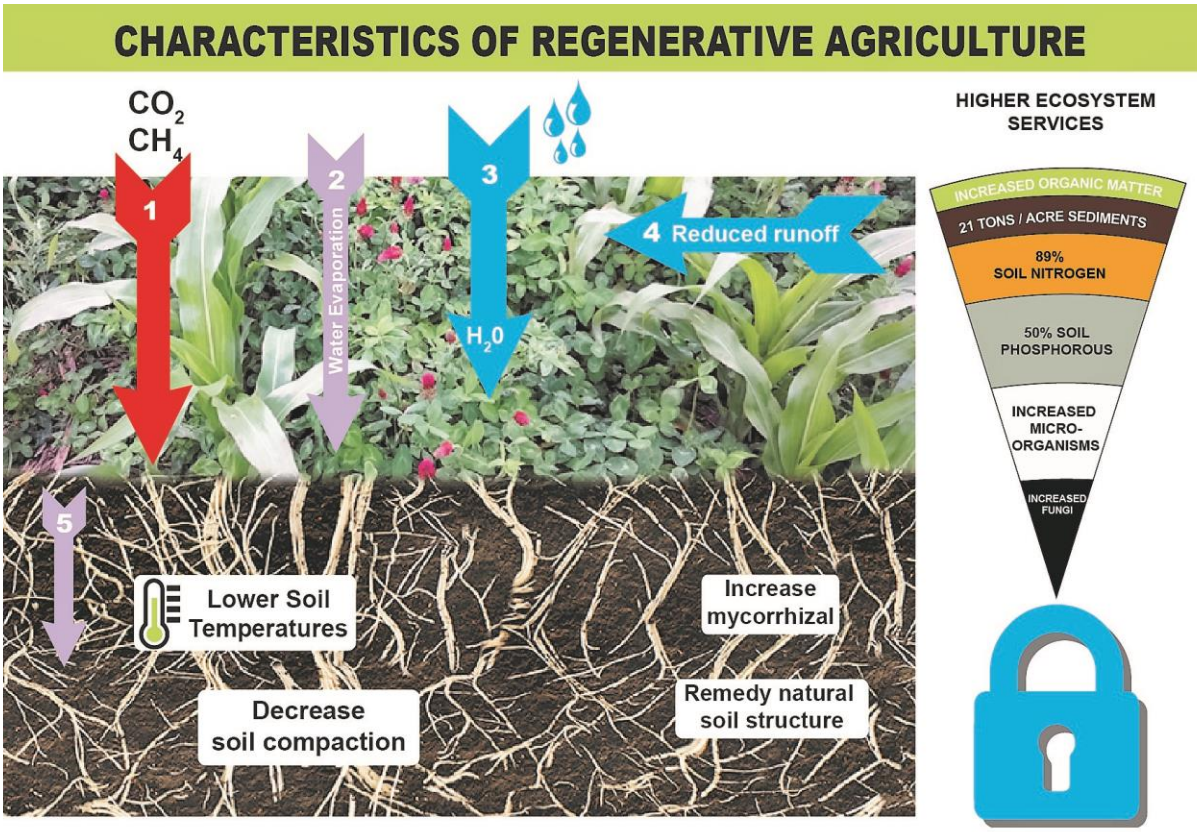
The IPCC attribution of emissions in the agricultural sector summarized

Appendix 2 Illustration of the depiction of the IPCC summary findings on the impacts of industrial agriculture on ecosystem services loss



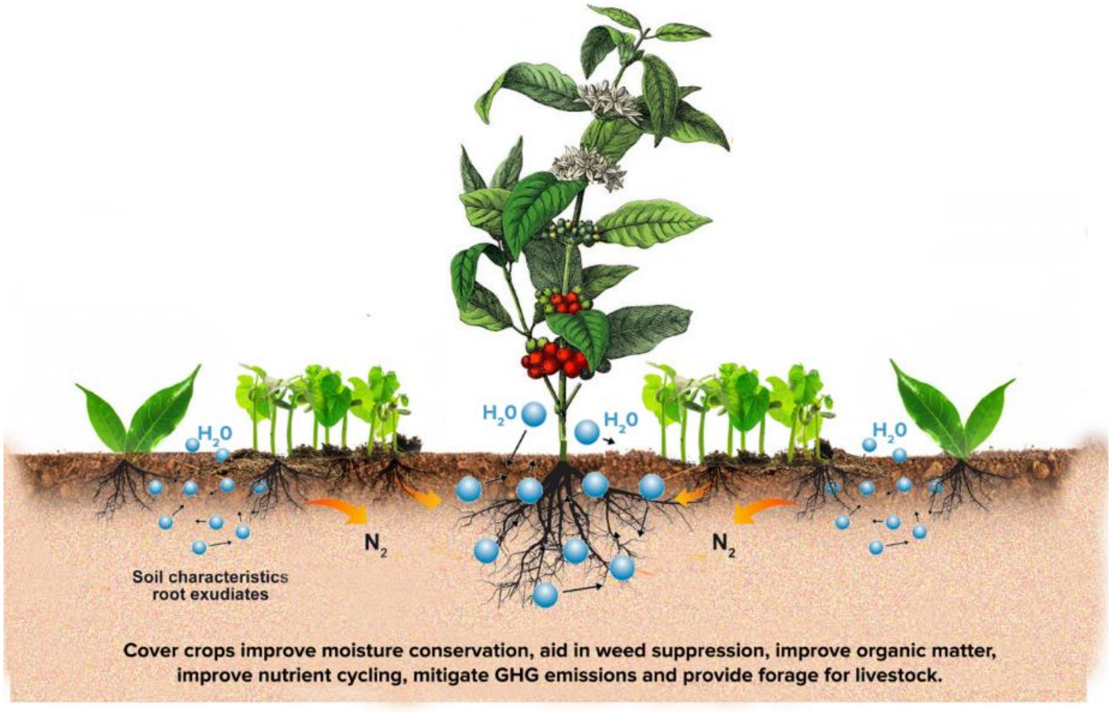
The opened padlock on the pie indicates the lost benefits of increased erosion with loss of soil organic matter, lost sediments, lost nitrogen and phosphorus, decreased microorganism and beneficial fungi (present in the organic matter).

Appendix 3 illustration with the summary of the benefits associated with climate-smart agriculture on ecosystem services benefits from legume fodder cover crops



The closed padlock on the pie indicates the benefits of increased soil organic matter, reduced loss of the sediments, reduced loss of nitrogen and phosphorus, increased microorganism and beneficial fungi (present in the organic matter).

Appendix 4 illustration of the benefits associated with legume cover crops in coffee production



Graphical presentation of the benefits associated with legume cover crops when intercropped with coffee

Appendix 5 Questionnaire for the coffee farmers with livestock in Githunguri

Part 1: Bio data

Date:				Locality:	
Name: (optional				Age: ≥30 ≥30 ≤ 40 ≥ 45 ≥50 ≥ 55 ≥60 ≥65	
Gender	M / F			Years in coffee	
Education	Primary	Secondary	Tertiary	Coffee Acreage	≤ 0.5 acres, < 0.5 – 1 acre ≥, > 1 acre.
Village				Coffee variety	
Farm size				No of bushes	
Time of harvest				Annual yields	

(Note: Tick where appropriate).

Part 2: Coffee production and livestock

Main challenges experienced in coffee production. On a scale of 1- 3 choose magnitude, with 3 having the most weight

(Terms definition – Primary – Beyond farmer's capacity; Secondary – Reduces profitability; Tertiary – Manageable within farmer's capacity)

Insert number	**Primary problem**	**Secondary problem**	**Tertiary problem**
Unreliable weather			
Labour cost			
Pests			
Diseases			
Timing of payment			

Farm related activities

Other crops	Crop		Acreage	
Livestock	Number		Milk yields	
Livestock fodder	type		Yields	
Source of animal feeds	Own farm		Purchase	

Part 3: Knowledge, Attitude and practices (indicate in the table below the appropriate answer)

Basing on a scale of 1- 4 (4 = strongly agree; 3 = Agree; 2 = Disagree; while 1= strongly disagree), indicate the extent of your agreement with the statements below.

	Statement	SA	A	D	SD
1	My coffee production requires regular clear weeding which is expensive				
2	I only use manual weed control mostly in my coffee production				
3	My family labour is enough in weeding my coffee production				
4	Weeding my coffee twice per year is adequate				
5	I don't intercrop my coffee with other crops or legume fodder because it's not allowed by coffee Bylaws				
6	I have a part of my coffee farm intercropped with desmodium legume fodder for my livestock				
7	In my farm I grow adequate legume fodder for my livestock for the whole year				
8	I grow desmodium which is a good source of protein as fodder for livestock reducing my need to buy fodder.				
9	I am buying more livestock fodder due to shortages resulting from poor rainfall				
10	When I use legume fodder crops, I increase my milk production.				
11	The recent changes in the seasonal rainfall patterns have reduced my ability to get adequate fodder for my livestock.				

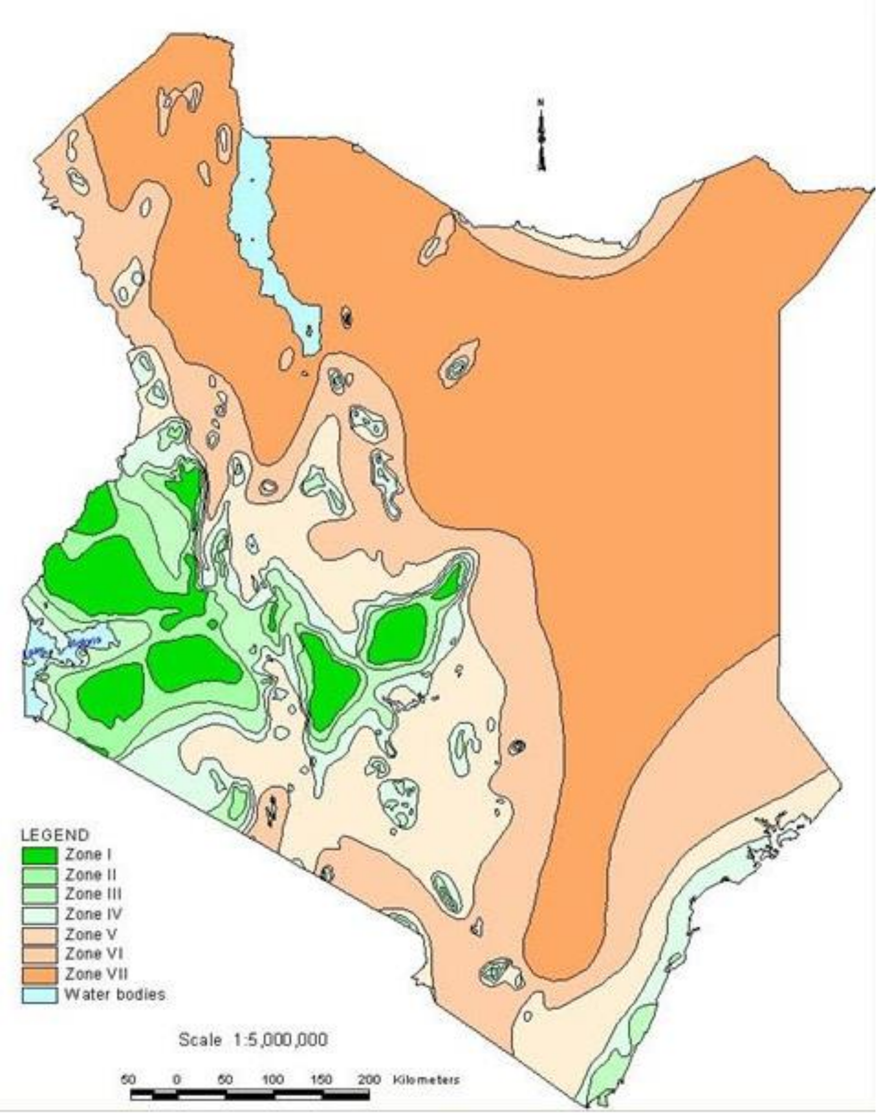
1 (strongly disagree) and 4 (strongly agree).

	Statement	SA	A	D	SD
	I am not motivated to use legume cover crops for my coffee weed control				
	Using legume cover crop in my coffee farm for moisture conservation is not very encouraging since the returns are low.				
	Using desmodium legume fodder cover crop for my livestock fodder intercropped in coffee has not given me better returns				
	I am not very enthusiastic to use desmodium to reduce my use of fertilizers in my coffee farming				
	I have low Motivation for looking for desmodium planting material to use as legume fodder cover crop in my coffee farm.				
	I have not realized any significant savings from using legume fodder cover crop in my coffee production				
	I have not seen any reduction on my animal fodder purchase even when I have desmodium legume cover crop in my coffee farm.				
	I have realized enough production from my livestock even when not using desmodium legume fodder.				
	I don’t see the big benefit of controlling soil erosion using desmodium legume cover crop in my coffee farm.				
	I have no interest in intercropping desmodium legume cover crop in my coffee farm since it’s a lot of work.				

1 (strongly disagree) and 4 (strongly agree).

	Statement	SA	A	D	SD
1	I use labour intensive methods for weed control in coffee production.				
	I have been trained on intercropping coffee with legume fodder to sustain production in the times of changing weather patterns.				
	I grow enough fodder for my livestock to last for the whole year				
	I always buy fodder and other animal feeds to sustain livestock productivity				
	I have devised new ways of growing fodder for livestock with the decreasing land sizes				
	I am devising new methods of improving moisture conservation in coffee production due to increased temperatures and reduced rainfall				
	I have reduced my focus on coffee production due to high production costs				
	My coffee production has been declining since the costs of inputs like fertilizers are high				

Appendix 6. Map of Kenya with Agro climatic Zones



Kenya’s Agro climatic zones description

Zone	Description and weather characteristics	Locations
Zone I	Classification Humid - Moisture index >80 Altitude range is above 1500 m asl Mean Temperature below 18° C. Rainfall above 2000 mm annually. Agriculture suitability - perennial crops Coffee, pyrethrum, tea, Avocado Annual crops- beans, horticulture , maize Livestock – Dairy and sheep	High elevations Locations surrounding Mt Kenya and Mt Elgon
Zone II	Classification sub humid - Moisture index 65 - 80 Altitude range is above 1000 - 1600 m asl Mean Temperature average 18° C. Rainfall above 1000 – 1600 mm annually. Agriculture suitability - perennial crops Coffee, pyrethrum, tea, Avocado Annual crops- beans, horticulture , maize Livestock – Dairy and sheep	Located in areas around the Aberdare ranges, Kericho, Kirinyaga, Kitale, Mau escarpment ranges, Webuye
Zone III	Classification semi humid and medium potential - Moisture index >80 Altitude range is above 900 – 1800 m asl Rainfall above 800 - 14000 mm annually Agriculture suitability - perennial crops Coffee,	Bomet, Nandi, Nakuru, parts of central Kenya, parts of Nyanza region, parts of western region and small strip of the coast region.

	mangoes, pyrethrum, tea, Avocado Annual crops- barley, beans, cassava, coconut, horticulture , maize and wheat Livestock – mixed livestock breeds and sheep	
Zone IV	Classification semi humid to semi-arid areas Moisture index- 40-50 Altitude range is above 900 – 1400 m asl Rainfall above 600 - 11000 mm annually Temperature ranges - 22° C- 40° C Agriculture suitability - perennial crops mangoes, Avocado Annual crops- beans, cassava, maize Livestock – mixed livestock breeds and goats	Some parts of central Kenya and Eastern Kenya, Laikipia, Machakos, parts of Kajiado and south coast
Zone V	Classification semi-arid areas Moisture index- 25- 40 Altitude range is lower elevation Rainfall above 300 - 600 mm annually Temperature ranges - 22° C- 40° C Low Agriculture suitability - only irrigation Livestock – pastoralist and wildlife conservation in the range lands	Most parts of the north eastern region, lower Makueni, North Baringo, and Turkana areas

Zone VI	Classification- arid areas Moisture index- 15-25 Altitude range is lower elevation Rainfall above 300 - 550 mm annually Temperature ranges - 22° C- 40° C range land with low animal population- Low livestock variety	Chalbi desert, Marsabit, Mandela, Turkana and Wajir
Zone VII	Classification- semi-desert Moisture index- < 15 Altitude range is lower elevation Rainfall above 150 - 350 mm annually Temperature ranges - 22° C- 40° C Range land with some wildlife	Chalbi desert, Marsabit, Mandela, Turkana and Wajir

Source; Sambroek et al., (1982) and EPZ (2005)

Appendix 7. Moisture data collected.

Treatment Plot	Description	Moisture sample 1	Moisture sample 2	Moisture sample 3	Moisture sample 4	Average Moisture content
1A	C+ F	28	37	29	36	31%
1B	C+ F	26	39	29	35	31%
1C	C+ F	27	39	33	36	33%
1D	C+ F	28	46	36	35	36%
2A	C+HW	22	35	29	31	28%
2B	C+HW	25	36	30	32	30%
2C	C+HW	24	35	28	30	29%
3A	C +HB	21	36	28	29	28%
3B	C +HB	23	34	28	28	28%
3C	C +HB	25	38	31	32	31%
4A	D S	26	36	29	24	30%
4B	D S	26	32	28	22	28.50%
4C	D S	22	31	25	23	26%

Note:

C+ F - Coffee Intercropped with fodder

C+HW - Coffee with Hand weeding

C+ HB - Coffee with Herbicide application

D S - Desmodium Sole crop

Appendix 8; Illustration showing the ecosystem services associated with desmodium used as a cover crop in coffee production

Associated ecosystem benefits of intercropping desmodium legume fodder cover crop in coffee production systems.