INNSPUB

Journal of Biodiversity and Environmental Sciences (JBES)
ISSN: 2220-6663 (Print) 2222-3045 (Online)
Vol. 19, No. 4, p. 16-35, 2021
http://www.innspub.net

RESEARCH PAPER OPEN ACCESS

Evaluating cover crop ecosystem services for buffering coffee against changing climate

Ndiritu James Mwangi*[1], Kinama Josiah Mavindani[2], Muthama John Nzioka[3]

[1]*Wangari Maathai Institute for Peace and Environmental Studies, University of Nairobi, Kenya*

[2]*Department of Plant Science and Crop Protection, University of Nairobi, Kenya*

[3]*Wangari Maathai Institute for Peace and Environmental Studies, University of Nairobi, Kenya*

Article published on October 26, 2021

Key words: Climate change, Desmodium, Ecosystem services, Herbicides, Legume cover crops

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 agro ecological 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 agro ecological modifications enhancing ecosystem services benefits should be demonstrated to farmers to enhance their understanding on the need to embrace agro ecology in their coffee production systems.

***Corresponding Author:** Ndiritu James Mwangi ✉ mwasnd@gmail.com

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.*, 2016; Sobota *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 Tain, 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-Boucard *et al.*, 2014). 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 *et al.,* 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 *et al.*, 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 *et al.*, 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 (CBD, 2021) requires reorientation. 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 (MA, 2005a). 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). Agro ecosystems 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*., 2021). 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*., 2021).

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 Oelosfe, 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 Oelosfe, 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 Oelosfe, 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 (Meuwissen *et al*., 2019). 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 agro ecological applications (Meuwissen *et al*., 2019). 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 (Ray *et al*., 2015; Potts *et al*., 2016).

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.

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. 1).

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.

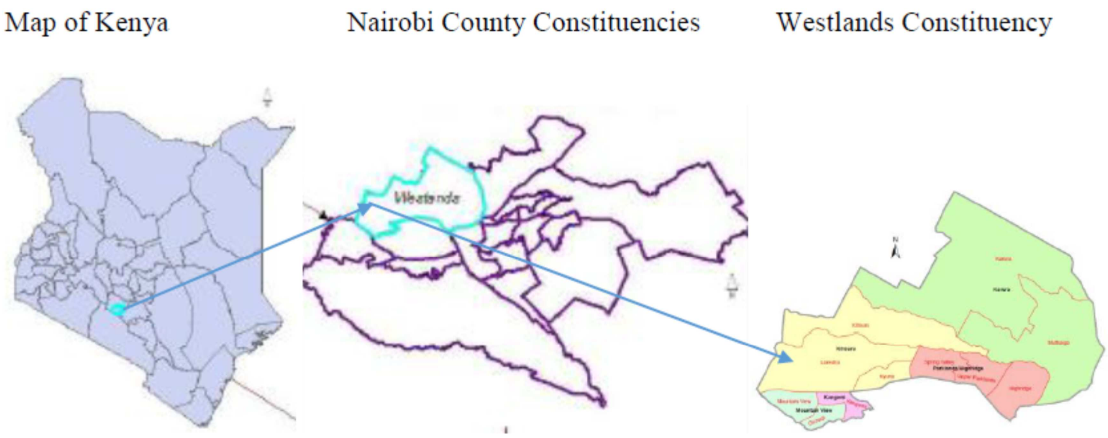

Fig. 1. Map of the study area (Source- Author).

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 1006mm 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 (1.0kg 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 6m x 12m 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.*, 1990) taken from each treatment plot, using a soil auger. The different soil samples from each treatment weighing approximately 1kg were taken to the University laboratory for soil moisture analysis monthly. Every 3 months, soil samples taken from a depth of 30cm 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

Table 1. Weather data for the period (Oct 2019 – Dec 2020) at the University of Nairobi Kabete field weather station.

Month	Temp. min	Temp Max	Rain fall 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.

The weather data was collected at the end of every month 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 1 and Fig. 2.)

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.

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 perkg were tested for normality using Shapiro-Wilk test on the R statistical software.

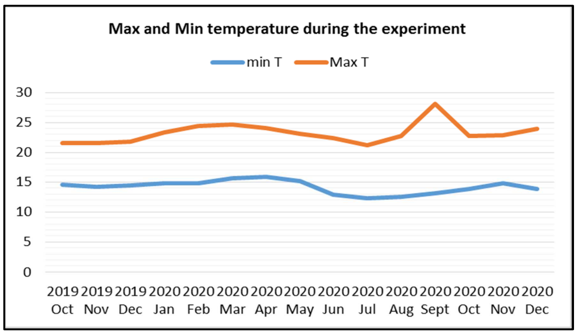

Fig. 2. Graphical presentation of the monthly average minimum and maximum temperature during the period of experiment (Oct 2019 – Dec 2020).
Source: University of Nairobi, Kabete weather station.

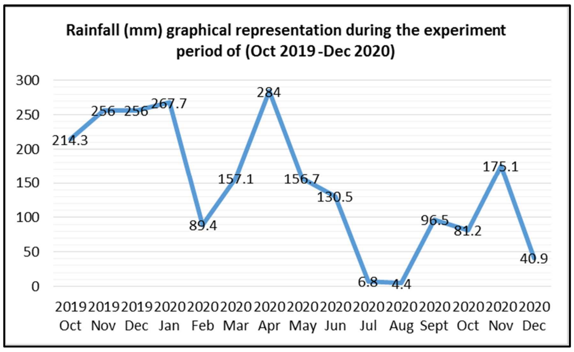

Fig. 3. Graphical presentation of rainfall inmm during the period of experiment.

Source: University of Nairobi, Kabete weather station.

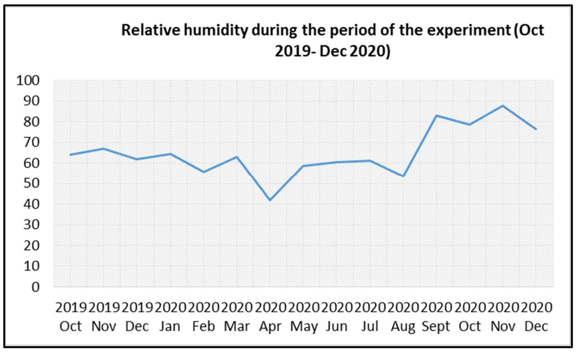

Fig. 4. Graphical presentation of the monthly average relative humidity in% during the period of experiment.

Source: University of Nairobi, Kabete weather station.

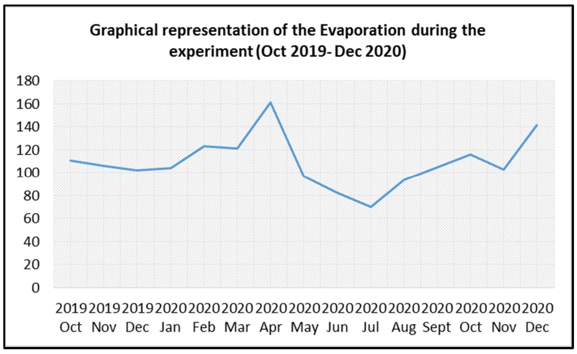

Fig. 5. Graphical presentation of evaporation inmm during the period (Oct 2019 – Dec 2020) during the experiment.

Source: University of Nairobi, Kabete weather station.

The data was then fitted into a mixed effect linear regression model using the lme 4 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 package tools.

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 20cm height were uprooted and grouped. A wooden frame of 1m x 1m 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 20cm in the 1m x 1m 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 2) 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 2. Soil moisture% trends based on the treatments during the period of 6 months (November 2019 - April 2020).

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 2.)

Table 3. Coffee yields in kilograms (kgs) for the different treatments per bush/ tree and the total per treatment plot.

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

Coffee harvest yield results

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 4 and Fig. 6).

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 4 and Fig. 6). 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 5).

Table 4. Linear regression model for the different 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-R^2 (fixed effects) = 0.30

Pseudo-R^2 (total) = 0.45

Where: AIC- Akaike information criterion

BIC- Bayesian information criterion

Table 5. Inter cluster correlation between the groups in the random variables.

Group	Number of groups	ICC
Bush_number	8	0.02
Harvest_Period	3	0.19

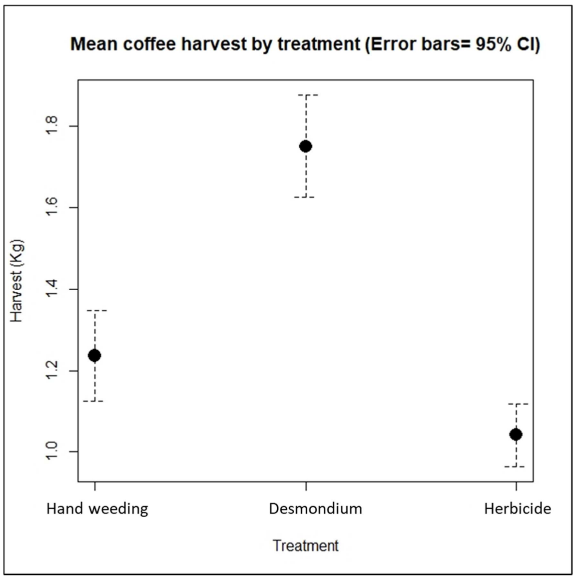

Fig. 6. Graph showing comparison of coffee yields in relation to weed control method
Legend; Error bars represent the standard deviation.

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.

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 Carmago (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 ± 16.87kg 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 (Carmago, 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 1490mm with unusually high rainfall received in January 2020 at 267mm 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 40.9mm had implications in harvesting since coffee cherry ripening is affected by inadequate rainfall (Da Matta *et al.*, 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 – 1800mm annually, with a dry period preferred in the middle for flowering and our site achieved 1490mm which shows its suitability in line with previous studies (Da Matta *et al.*, 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 4.4mm 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 Da Matta *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, 2019) 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 4.4mm) 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 (2011). 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 CRF (2003). The study by CRF (Coffee Research Foundation) 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 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 & 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 & Wall, 2009).

Studies by Blanco-Canqui *et al*., (2013) 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*., 2012). 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*., 2013).

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 for attaining high yields as emphasized by Tully and mc Askill (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 in agreement with studies by Bünemann *et al*., (2018). Gruver and Weil (2017) 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.* (2014) 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.*, 2005; Oliveira *et al.*, 2017; Krstić *et al.*, 2018). 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 (Nascente *et al.*, 2015; Hallama *et al.*, 2019).

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 *et al.* (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 800mm of rainfall annually benefit from increased water storage in the soil and better crop production than pure stand crops (Blanco-Canqui *et al.*, 2012). Since our study site had rainfall amounting to 1490mm, 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 (Balkcom and Reeves, 2005; Blanco-Canqui *et al.*, 2012).

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 800mm 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 *et 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 (VaÂzquez *et al.*, 2018). Studies by VaÂzquez *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 (VaÂzquez *et al.*, 2018).

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.*, 2019).

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 *et al.*, 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 agro ecological 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.

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 800mm 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 800mm 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 cover in coffee production need to be understood by farmers so that they can increase their profitability (Dunn *et al.*, 2016).

References

Abdalla M, Hastings A, Cheng K, Yue Q, Chadwick D, Espenberg M, Truu J, Rees RM, Smith P. 2019. A critical review of the impacts of cover crops on nitrogen leaching, net greenhouse gas balance and crop productivity. Global change biology **25(8),** 2530-2543.

Alguacilmm, Lumini E, Roldán A, Salinas-García J, Bonfante P, Bianciotto V. 2008. The impact of tillage practices on arbuscular mycorrhizal fungal diversity in subtropical crops. Ecological applications: Ecological Society of America **18,** 527-36.

Alyokhin A, Nault B, Brown B. 2020. Soil conservation practices for insect pest management in highly disturbed agro ecosystems – a review. Entomologia Experimentalis et Applicata **168,** 7-27.

Balkcom K, Reeves D. 2005. Sunn-Hemp Utilized as a Legume Cover Crop for Corn Production. Agronomy Journal **97,** 26-31.10.2134

Begum N, Qin C, Ahanger MA, Raza S, Khan MI, Ashraf M, Ahmed N, Zhang L. 2019. Role of Arbuscular Mycorrhizal Fungi in Plant Growth Regulation: Implications in Abiotic Stress Tolerance. Frontiers in Plant Science **10,** 1068.

Beniston J, Shipitalo M, Lal R, Dayton E, Hopkins D, Jones F, Joynes A, Dungait J. 2015. Carbon and macronutrient losses during accelerated erosion under different tillage and residue management. European Journal of Soil Science **66,** 218-225.

Blanco-Canqui H, Claassen M, Presley D. 2012. Summer cover crops fix nitrogen, increase crop yield, and improve soil–crop relationships. Agronomy journal **104,** 137-147.

Blanco-Canqui H, Ruis SJ. 2020. Cover crop impacts on soil physical properties: A review. Soil Science Society of American Journal **84,** 1527-1576.

Blanco-Canqui H, Shapiro CA, Wortmann CS, Drijber RA, Mamo M, Shaver TM, Ferguson RB. 2013. Soil organic carbon: The value to soil properties. Journal of Soil and Water Conservation **68,** 129A-134A.

Blanco-Canqui H, Shaver TM, Lindquist JL, Shapiro CA, Elmore RW, Francis CA, Hergert GW. 2015. Cover crops and ecosystem services: Insights from studies in temperate soils. Agronomy Journal **107,** 2449-2474.

Bünemann E, Bongiorno G, Bai Z, Creamer R, Deyn GB, Goede RGM, Fleskens L, Geissen V, Kuyper T,Mäder P, Pulleman M, Sukkel W, Groenigen J, Brussaard L. 2018. Soil quality - A critical review. Soil Biology and Biochemistry 120. 105. 10.1016.

Bybee-Finley K, Ryan M. 2018. Advancing Intercropping Research and Practices in Industrialized Agricultural Landscapes. Agriculture **8(6),** 80.

Cabell JF, Oelofse M. 2012. An indicator framework for assessing agroecosystem resilience. Ecology and Society **17(1),** 18.

Carmago M. 2010. The impact of climatic variability and climate change on Arabica coffee crop in Brazil. Bragantia **69(1),** 239-247.

Craparo CW, VanAsten PJA, Läderach P, Jassogne LTP, Grab SW. 2015. Coffea arabica yields decline in Tanzania due to climate change: Global implications, Agricultural and Forest Meteorology **207,** 1-10.

CRF. 2003. (Coffee Research Foundation). Weed Control in Coffee. Technical Circular No. 502

DaMatta FM, Ramalho J, Cochicho D. 2006. Impacts of drought and temperature stress on coffee physiology and production: a review. Brazilian Journal of Plant Physiology **18(1),** 55-81.

DaMatta FM, Rodrigo TA, Amanda AC, Samuel CVM, José CR. 2018. Physiological and Agronomic Performance of the Coffee Crop in the Context of Climate Change and Global Warming: A Review Journal of Agricultural and Food Chemistry **66(21),** 5264-5274.

De Novais CB, Sbrana C, da Conceição JE. 2020. Mycorrhizal networks facilitate the colonization of legume roots by a symbiotic nitrogen-fixing bacterium. Mycorrhiza **30,** 389-396.

Delgado JA, Mosquera VHB, Alwang JR, Villacis-Aveiga A, Ayala YE, Cartagena N, Donnamc, López LOE. 2021. Potential use of cover crops for soil and water conservation, nutrient management, and climate change adaptation across the tropics. Advances in Agronomy, Academic Press **165,** 175-247.

FAO. 2016. Mainstreaming ecosystem services and biodiversity into agricultural production and management in East Africa. Rome, Italy.

Farina WM, Balbuena MS, Herbert LT, Mengoni GC, Vázquez DE. 2019. Effects of the Herbicide Glyphosate on Honey Bee Sensory and Cognitive Abilities: Individual Impairments with Implications for the Hive. Insects **10(10),** 354.

Fikadu Z. 2020. Pesticides use, practice and its effect on honeybee in Ethiopia: a review. International Journal of Tropical Insect Science **40,** 473-481

Folke C, Biggs R, Norström AV, Reyers B, Rockström J. 2016. Social-ecological resilience and biosphere-based sustainability science. Ecology and Society **21(3),** 41.

Gachene CKK, Wortmann CS. 2004. Green Manure/Cover Crop Technology in Eastern and Central Uganda: Development and Dissemination. In: Eilitta M, Mureithi JG, Derpsh R. (eds). Green Manure/Cover Crop Systems of Smallholder Farmers. Experiences from Tropical and Subtropical Regions. Kluwer Academic Publishers, Netherlands pp. 219-236.

Gao Y, Dang X, Yu Y, Li Y, Liu Y, Wang J. 2016. Effects of tillage methods on soil carbon and wind erosion. Land Degradation & Development **27,** 583-591.

Giovannini L, Palla M, Agnolucci M, Avio L, Sbrana C, Turrini A, Giovannetti M. 2020. Arbuscular Mycorrhizal Fungi and Associated Microbiota as Plant Biostimulants: Research Strategies for the Selection of the Best Performing Inocula. Agronomy **10(1),** 106.

Gruver JB, Weil R. 2007. Farmer perceptions of soil quality and their relationship to management-sensitive soil parameters. Renewable Agriculture and Food Systems **22,** 271-281.

Hallama M, Pekrun C, Lambers H, Kandeler E. 2019. Hidden miners – the roles of cover crops and soil microorganisms in phosphorus cycling through agro ecosystems. Plant Soil **434,** 7-45.

Hatfield JL, Walthall CL. 2015. Soil biological fertility: Foundation for the next revolution in agriculture? Communications in Soil Science and Plant Analysis **46,** 753-762.

Heap I. 2014. Global perspective of herbicide-resistant weeds. Pest Management Science **70,** 1306-1315.

Houba VJG, Temminghoff EJM, Gaikhorst GAV. 2000. Soil analysis procedures using 0.01 M calcium chloride as extraction reagent. Communications in Soil Science and Plant Analysis **31(2000),** 31.

Imbach P, Fung M, Emily HL, Navarro-Racines C, Roubik D, Ricketts T, Harvey C, Donatti C, Laderach P, Locatelli B, Roehrdanz P. 2017. Coupling of pollination services and coffee suitability under climate change. Proceedings of the National Academy of Sciences **114,** 201617940.

Jannoyer M, Bellec LF, Lavigne C, Achard R, Malézieux E. 2011. Choosing cover crops to enhance ecological services in orchards: A multiple criteria and systemic approach applied to tropical areas. Procedia Environmental Sciences **9,** 104-112.

Kabubo-Mariara J, Mulwa R. 2019. Adaptation to climate change and climate variability and its implications for household food security in Kenya. Food Security **11,** 1289-1304.

Kaspar T, Singer J. 2011. The use of cover crops to manage soil. In: J.L. Hatfield and T.J. Sauer, editors, Soil Management: Building a Stable Base for Agriculture. American Society of Agronomy and Soil Science Society of America, Madison, WI pp. 321-337.

Kath J, Vivekananda MB, Shahbaz M, Craparo A, Porcel M. 2021. Temperature and rainfall impacts on robusta coffee bean characteristics, Climate Risk Management, V **32,** 100281,

Kaye PJ, Quemada M. 2017. Using cover crops to mitigate and adapt to climate change. A review. Agronomy for Sustainable Development, Springer Verlag/EDP Sciences/INRA **37(1),** pp. 4. DOI: 10.1007/s13593-016-0410-x.

Kihara J, Bolo P, Kinyua M, Nyawira SS, Sommer R. 2020. Soil health and ecosystem services: Lessons from sub-Sahara Africa (SSA), Geoderma **370,** 114342.

Kinama JM, Stigter CJ, Ong CK, Ng'ang'a JK, Gichuki FN. 2005. Evaporation from soils below sparse crops in contour hedgerow agroforestry in semi-arid Kenya. Agricultural and Forest Meteorology **130,** 149-162.

Klein A, Steffan-Dewenter I, Tscharntke T. 2003. Bee Pollination and Fruit Set of Coffea arabica and C. canephora (Rubiaceae). American Journal of Botany **90(1),** 153-157.

Kremen C, Miles A. 2012. Ecosystem services in biologically diversified versus conventional farming systems: benefits, externalities, and trade-offs Ecology and Society **17(4),** 40.

Krstić Đ, Vujić S, Jaćimović G, D'Ottavio P, Radanović Z, Erić P, Ćupina B. 2018. The Effect of Cover Crops on Soil Water Balance in Rain-Fed Conditions. Atmosphere **9(12),** 492.

Lawley YE, Weil RR, Teasdale JR. 2011. Forage radish cover crop suppresses winter annual weeds in fall and before corn planting. Agronomy journal **103,** 137-144.

Lu C, Tian H. 2017. Global nitrogen and phosphorus fertilizer use for agriculture production in the past half century: shifted hot spots and nutrient imbalance. Earth System Science Data **9,** 181-192.

Malone RD. Jaynes T, Kaspar K, Thorp EK, L Ma D, James J, Singer XM, Searchinger T. 2014. Cover crops in the upper midwestern United States: Simulated effect on nitrate leaching with artificial drainage. Journal of soil and water Conservation **69,** 292-305.

Martins S, Sanglard M, Morais L, Menezes-Silva P, Mauri RA, Rodrigo V, Camilo CA, DaMatta F. 2019. How do coffee trees deal with severe natural droughts? An analysis of hydraulic, diffusive and biochemical components at the leaf level. Trees **33,** DOI: 10.1007/s00468-019-01889-4.

McKenna TP, Koziol L, Bever JD, Crews TE, Sikes BA. 2020. Abiotic and biotic context dependency of perennial crop yield. PLOS ONE **15(6),** e0234546.

Meuwissen MPM, Feindt PH, Spiegel A, Termeer CJA, Mathijs E, deMey Y, Finger R, Balmann A, Wauters E, Urquhart J, Vigani M, Zawalińska K, Herrera H, Nicholas-Davies, Midega CAO, Wasonga CJ, Hooper AM, Pickett JA, Khan ZR. 2017. Drought-tolerant Desmodium species effectively suppress parasitic striga weed and improve cereal grain yields in western Kenya, Crop Protection **98,** 94-101,

Motta-Erick VS, Raymann K, Moran NA. 2018. Glyphosate perturbs the gut microbiota of honey bees. Proceedings of the National Academy of Sciences **115(41),** 10305-10310; DOI: 10.1073/pnas.

Motta-Erick VS, Moran NA. 2020. Impact of Glyphosate on the Honey Bee Gut Microbiota: Effects of Intensity, Duration, and Timing of Exposure. M Systems **5(4),** e00268-20;

Mus F, Crook MB, Garcia K, Garcia-Costas A, Geddes BA, Kouri ED, Paramasivan P, Ryu MH, Oldroyd G, Poole PS, Udvardi MK, Voigt CA, Ané JM, Peters JW. 2016. Symbiotic Nitrogen Fixation and the Challenges to Its Extension to Nonlegumes. Applied and Environmental Microbiology **82(13),** 3698-3710.

Nascente AS, Stone LF, Crusciol CA. 2015. Soil chemical properties affected by cover crops under no-tillage system. Revista Ceres **62(4),** 401-409.

Novais SMA, Nunes CA, Santos NB, D`Amico AR, Fernandes GW. 2016. Effects of a Possible Pollinator Crisis on Food Crop Production in Brazil. PLOS ONE **11(11),** e0167292.

Odhiambo J, Norton U, Ashilenje D, Omondi E, Norton J. 2015. Weed Dynamics during Transition to Conservation Agriculture in Western Kenya Maize Production. PLoS ONE.
DOI: 10. 10.1371/journal.pone.0133976.

Oerke EC. 2006. Crop losses to pests. The Journal of Agricultural Science **144,** 31-43.

Oliveira RAD, Comin JJ, Tiecher T, Piccin R, Somavilla LM, Loss A, Lourenzi CR, Kürtz C, Brunetto G. 2017. Release of Phosphorus Forms from Cover Crop Residues in Agroecological No-Till Onion Production. Revista Brasileira de Ciência do Solo DOI: 10.1590/18069657rbcs20160272

Ovalle-Rivera O, Läderach P, Bunn C, Obersteiner M, Schroth G. 2015. Projected Shifts in *Coffea arabica* Suitability among Major Global Producing Regions Due to Climate Change. PLoS ONE **10(4),** e0124155.

Pereira L. 2017. Climate Change Impacts on Agriculture across Africa. Oxford Research Encyclopedia of Environmental Science.

Poeplau C, Don A. 2015. Carbon sequestration in agricultural soils via cultivation of cover crops–A meta-analysis. Agriculture, Ecosystems & Environment **200,** 33-41.

Potts SG, Imperatriz-Fonseca V, Ngo HT. 2016. Safeguarding pollinators and their values to human well-being. Nature **540,** 220-229.

Rahn E, Laderach P, Baca M, Cressy C, Schroth G, Malin D, van-Rikxoort H, Shriver J. 2014. Climate change adaptation, mitigation and livelihood benefits in coffee production: where are the synergies? Mitigation and Adaptation Strategies for Global Change. Springer Netherlands Vol **19(8),** p. 1119-113719.

Ray DK, Gerber JS, MacDonald GK, West PC. 2015. Climate variation explains a third of global crop yield variability. Nature Communications **6.**
DOI: 10.1038/ncomms6989.

Robyn A, Chase C, Swisher M, Mengistu T, Jeune W. 2018. Potential Cover Crop Options for Nematode and Weed Suppression in Haiti. Proceedings of the Florida State Horticultural Society **131,** 132-137.

Smith DR, Harmel RD, Williams M, Haney RL, King KW. 2016. Managing Acute Phosphorus Loss with Fertilizer Source and Placement: Proof of Concept. Agricultural & Environmental Letters.
DOI: 10.2134/ael2015.12.0015.

Sobota DJ, Compton JE, mcCrackinm L, Singh S. 2015. Cost of reactive nitrogen release from human activities to the environment in the United States. Environmental Research Letters 10.1088.

Tahatmm, Alananbeh KM, Yahia AO, Leskovar DI. 2020. Soil Health and Sustainable Agriculture Sustainability 2020 **12,** 4859.

Thierfelder C, Wall PC. 2009. Effects of conservation agriculture techniques on infiltration and soil water content in Zambia and Zimbabwe. Soil & Tillage Research **105,** 217-227.

Treadwell D, Klassen W, Alligood M. 2008. Annual cover crops in Florida vegetable systems Part I. Objectives: Why grow cover crops. HS387. Institute of Food and Agricultural Sciences, University of Florida.

Tully KL, mc Askill C. 2020. Promoting soil health in organically managed systems: A review. Organic Agriculture **10,** 339-358.

Va Âzquez DE, Ilina N, Pagano EA, Zavala JA, Farina WM. 2018. Glyphosate affects the larval development of honey bees depending on the susceptibility of colonies. PLoS ONE **13(10),** e0205074.

Vázquez-Boucard C, Anguiano-Vega G, Mercier L, Rojas EC. 2014. Pesticide residues, heavy metals, and DNA damage in sentinel oysters Crassostrea gigas from Sinaloa and Sonora, Mexico. Journal of Toxicology and Environmental Health, Part A **77,** 169-176.

Venancio LP, Filgueiras R, Mantovani EC. 2020. Impact of drought associated with high temperatures on *Coffea canephora* plantations: a case study in Espírito Santo State, Brazil. Scientific Reports **10,** 19719 (2020).
https://doi.org/10.1038 /s41598-020-76713-y

Vukicevich E, Lowery T, Bowen P, Úrbez-Torres JR, Hart M. 2016. Cover crops to increase soil microbial diversity and mitigate decline in perennial agriculture. A review. Agronomy for Sustainable Development **36(3),** 48.

Wagner S, Jassogne L, Price E, Jones M, Preziosi R. 2021. Impact of Climate Change on the Production of Coffea arabica at Mt. Kilimanjaro, Tanzania. Agriculture **11(1),** 53.

Wilkes TI, Warner DJ, Davieskg, Edmonds-Brown V. 2020. Tillage, Glyphosate and Beneficial Arbuscular Mycorrhizal Fungi: Optimising Crop Management for Plant–Fungal Symbiosis. Agriculture **10(11),** 520.

Zaller J, Heigl F, Ruess L, Grabmaier A. 2014. Glyphosate herbicide affects belowground interactions between earthworms and symbiotic mycorrhizal fungi in a model ecosystem. Scientific Reports **4,** 5634.