EISSN: 2707-0425

East African Journal of Science, Technology and Innovation, Vol. 2 (Special issue): May 2021

Optimization of ecosystems services for sustainable coffee production under changing climate

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Abstract

Legume cover crops have previously been evaluated for green manure, weed control and soil moisture conservation, this study includes further evaluation of biomass of the legume fodder. 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 completely Randomized Block Design 3 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. Results indicated that coffee intercropped with desmodium had 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 need for weeding as well as conserve soil moisture. There was significant savings on the cost of manual weeding with additional earnings or savings of 750 $ US from sales or utilization of the desmodium fodder per hectare. The study concludes that cover crops can enhance farmers' resilience to changing climate utilizing the same size of land while enhancing output and increasing revenue. Policy makers need to realign extension services to introduce legume cover crops in coffee production to reduce the labour costs and the high doses of synthetic fertilizers which emit greenhouse gases.

Keywords: *Biomass; desmodium; legumes; sustainability; weed control*

Cite as: *Ndiritu et al., (2021).* Optimization of ecosystems services for sustainable coffee production under changing climate. *East African Journal of Science, Technology and Innovation 2 (Special Issue).*

Received: 24/04/21
Accepted: 13/05/21
Published: 25/05/21

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 is ill equipped to accommodate the predicted yield losses (IPCC 2007). Agriculture their main stay has been categorized as the most vulnerable sector to climate change leading to sporadic incidences of food insecurity (Parker *et al.*, 2019). 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 (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. It is important to minimize greenhouse gas emissions with intentional reduction of environmental impact while still ensuring adequate income and sustained nutrition which is important for strengthening resilience. (Juma *et al.*, 2013).

Monocultural coffee production that was promoted during the green revolution (Pingali, 2012) that saw the research for sun tolerant varieties, technological packages with scientific packages relying heavily on synthetic inputs aimed at increasing yields 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 being derived from the progressive soil quality loss resulting from monocropping, has been associated with the 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 increase of other genera, indicated the influence of monocropping to simplification of bacterial communities with associated loss of 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). The assessment of the potential environmental impacts in diversified coffee cropping improved on carbon dynamics and resulted in higher outputs in terms of land use (Acosta-Alba *et al.*, 2020). Selection of 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, 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 (Zeng, 2015), build-up of crop related soil borne pathogens and other harmful plant substances due to disturbed microorganism ecosystems (Gil *et al.,* 2009). Fungal pathogens accumulation in the soil micro-biota, are thought to be responsible cause of the continuous cropping obstacle disease (Xiong *et al.,* 2015; Manici *et al.,* 2013). 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), while mono cropped sun grown coffee producing own allelochemicals is suspected to influence long term soil acidification (Ehrenfeld *et al.,* 2005).

Studies have been done evaluating the performance of different legume cover crops on coffee for weed control and nutrient benefits (Gachene and Wortmann 2004, Jassogne *et al.,* 2012) as a way of increasing sustainability in coffee production aimed at reducing the excessive use of synthetic nitrogen fertilizers and herbicides in weed control. Szumigalski and Van Acker, (2005) further looking at possibilities of eliminating chemical weed control using cover crops as sustainability measures of soil improvement. Previous studies were not focused on agricultural intensification practices in coffee production, the inclusion of ecosystem services provision in the coffee production systems and the evaluation on the biomass production potential of desmodium legume as livestock fodder while serving as a cover crop in coffee. The objective of the study was to evaluate the advantage of using desmodium legume cover crop in coffee production to reduce the competition from weeds and save farmers costs, reduce rates of soil evaporation and reduce soil erosion with the additional benefits of nitrogen fixation while producing biomass to serve as legume fodder for livestock.

Using cover crops for diversification as an adaptation to changing climate

Rural complex agroecosystems for small holder farmers comprise a mix of crop and animal production and interactions between the systems create synergies that sustain the relationships for a sustainable agro-ecosystem such as provision of manure for crops and fodder from crops (Swift *et al.,* 1996). Impacts and effects related to climate change influence broader farmer decisions based on opportunities and constraints related to the specific operational environment (Bergtold *et al.,* 2007). Sullivan (2003), 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 (Teasadale, 2013) includes cover crops provisioning of beneficial ecosystem services.

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 by Gachene and Wortmann (2004) while serving the role of weed control. 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.,* 2012).

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). 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 further declining crop yields with smallholder coffee farmers producing as low as 200kg per hectare resulting in food insecurity and increasing poverty levels (CBK, 2003 b). 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 (International Center for Tropical Agriculture, 2003; 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*., 2013).

Studies by Mureithi, *et al.,* (2003) looking at the fixation of nitrogen to the coffee plant in addition to weed control compared many types of legume cover crops, while Gachene and Wortmann, 2004) compared different legume cover crops for weed suppression and the additional biomass used for mulching and soil fertility improvement. The present study while amplifying the benefits of using legume fodder cover crops for weed suppression, soil moisture conservation, soil fertility improvement singles out desmodium legume fodder having a creeping habit thus not interfering with coffee operations and being a perennial having the capacity of producing livestock fodder for longer duration.

Cover crops and weed control

While weeds are already recognized as plants growing where not wanted affecting coffee due to competition for light, moisture and nutrients with resulting lowering of yields and quality and interfering with field operations, they could also serve as alternate host for coffee pests (CRF 2003). Baumann *et al.* (2000) reported that intercropping increases light interception by the main crops making the weakly competitive components of weeds shorten their lifespan reducing the critical period for weed control and reduce growth and abundance of late-emerging weeds. The adoption of vibrant cover crops that increases the competitiveness of the intercropping systems to weed control gives them an advantage for integration into low emission farming systems with low inputs or where options for chemical weed control are minimized or completely eliminated (Szumigalski and Van Acker, 2005). 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 biochemicals (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 diminishes the ability of weeds to grow (Mwendwa, 2017). 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).

Impacts of manual weed control through tillage

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) 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 *et al.,* 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.,* 2005). 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, 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.,* 2005). 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, 2007) 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.,* 2007) found that the soil erosion was reduced and the crop productivity would sustainably be maintained with less soil and nutrient loss.

Adoption of Cover crops

Cover crops such as desmodium *spp.* (Gachene and 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 under sun grown coffee (Rosenstock 2019). 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 (International Center for Tropical Agriculture, 2003). 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). Gabrielle et al (2017), 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.,* 2012). Studies on biological nitrogen fixation have proven that forage legumes can transfer almost 90% of their nitrogen (Gulwa *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).

Integrated Intensive crop & livestock systems

Challenges related to feed availability from fodder is projected to exponentially complicate their 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 during the seasonal rainfall fluctuations.

Theoretical framework

The rate of adoption of cover crops can be argued using two theories namely; theory of reasoned action and theory of planned behavior. The theory of reasoned action by Ajzen and Fishbein (1980), argues that the perception of the individual is dependent on the social pressure to perform or failure to perform the expected task or behavior. This is seen as being a subjective norm dealing with perceived prescription (Ajzen and Fishbein, 1980). A favorable evaluation of a behavior increases the number of people wishing the adoption of the behavior being seen as quite rational, while evaluating it with the systematic use of available information to be seen behaving sensibly while considering the implications of their actions (Ajzen and Fishbein, 1980). The theory thus argues that a person's intentions is the best predictor of the behavior as affected in turn by his/ her attitude with the perceived social pressure (Ajzen and Fishbein, 1980). Willock et al. (1999) indicates that the theory of reasoned action thus provides the theoretical framework which helps in examining the influence of goals and attitudes on voluntary behaviors. Fishbein (1980) however indicates that the theory of reasoned behavior restricts itself to voluntary behavior, opportunities or resources not freely available thus being unable to predict accurately other domains. The improved version of the theory of reasoned action is the theory of planned behavior (Beedell and Rehman, 2000), aiming to evaluate other encouraging factors that may affect human behavior. The planned behavior theory indicates that behavior results from personal intentions and goals, attitudes, social norms and perceived behavioral control according to Bergevote *et al*. (2004). Attitudes being defined as being formed by the individual perception of the truth about the subject or object (Beedell and Rehman, 2000). Since many values and beliefs may be the construct of an object (Willock *et al.,* 1999), this perception may therefore be based on knowledge and information emotionally attached to the subject or object. A personal judgment based on the evaluation of an object or subject, represented as aspects of knowledge are based on emotional information, cognitive information and information about past behavior (Allen *et al.,* 2003). The two theories can thus be used to evaluate the individual perceptions and attitudes in relation to the adoption of the use of cover crops in relation to the intentions and goals of the individual.

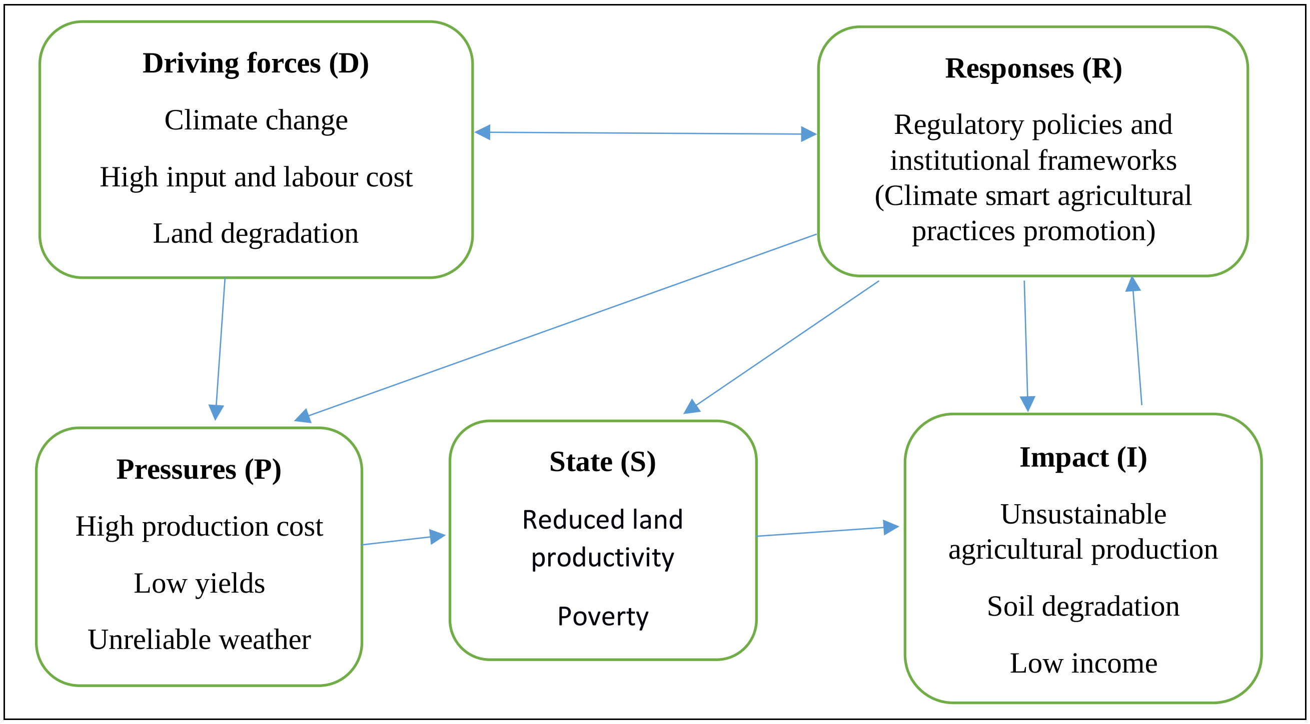

Figure 1. Conceptual framework; Adopted from the drivers, pressures, state, impact and response (DPSIR) Framework from the European Environment agency (1999)

Materials and methods

Study area description

The research study was located at University of Nairobi field 7 station at Kabete Campus coffee plantation with coordinates of 1°15l S and 36° 44l E selected for its proximity, 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 (>30m) (Mwendwa *et al.*, 2020). The soil is classification by Karuku *et al.*, (2012) (as humic Nitisol having absence of sealing or crusting at the surface although percentage of clay may increase with depth (Gachene, 2012). The location enjoys bimodal rainfall 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.*, 1982). Gradient of 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 mirror 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).

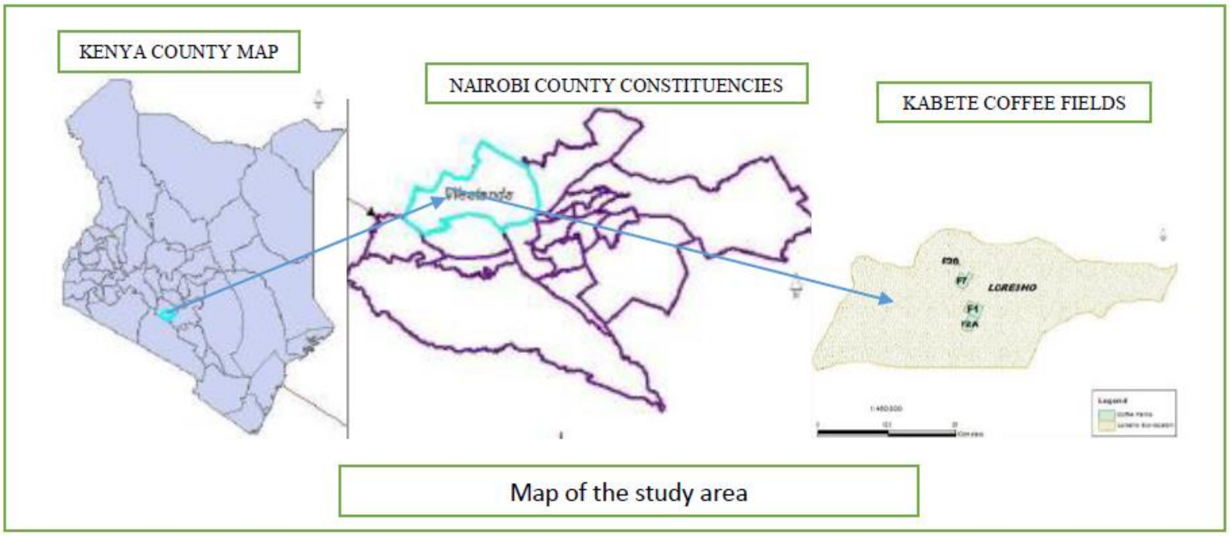

Figure 2. Map of the study area
Adopted from Chepkonga, 2015

Study design
Four treatments arranged in a complete randomized block design 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 the area measuring (6m x 12m x 4) 288 m^2. The area was cleared of weeds manually and desmodium spp planted in the 3 of the blocks (A1, B3 and C3). After the rains in October 2019, glyphosate herbicide was applied on the blocks A3, B2 and C1, while hand weeding was done on the blocks A3, B3 and C2. Every month, soil samples using a soil auger were collected in all the four blocks and taken to the University laboratory for soil moisture 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 and weighed at the intervals of every 4 months from the date of planting.

Data collection
Data was obtained through a field case study where 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 were coffee + desmodium legume cover crop, coffee + hand weeding, Coffee + herbicide and sole desmodium separately.

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. The 1st /baseline sample was taken in October 2019 and every other month for 6 months respectively for moisture analysis. The soil samples were collected and delivered to the University of Nairobi soil science laboratory at Kabete within 2 hours of collection.

Data analysis

Descriptive statistics for the soil nutrients and soil moisture concentration was summarized using Ms excel software 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 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.

Results

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 for each individual plot 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 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.

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. The results obtained using Desmodium legume cover crop after establishment indicated complete weed suppression since the creeping habit of desmodium was able to completely cover 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 (FAO, 2003, Thierfelder & 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, 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.

The study found out that after establishment of desmodium, there was a better moisture retention which could also be related to better rainfall percolation which would also be indicative of better control of runoff. 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.

Table 1. Soil moisture trends across the treatments for the 6 months sampling

Treatment	**Baseline**	**1st samp**	**2nd samp**	**3rd samp**	**4th samp**	**5th samp**
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

samp = sampling

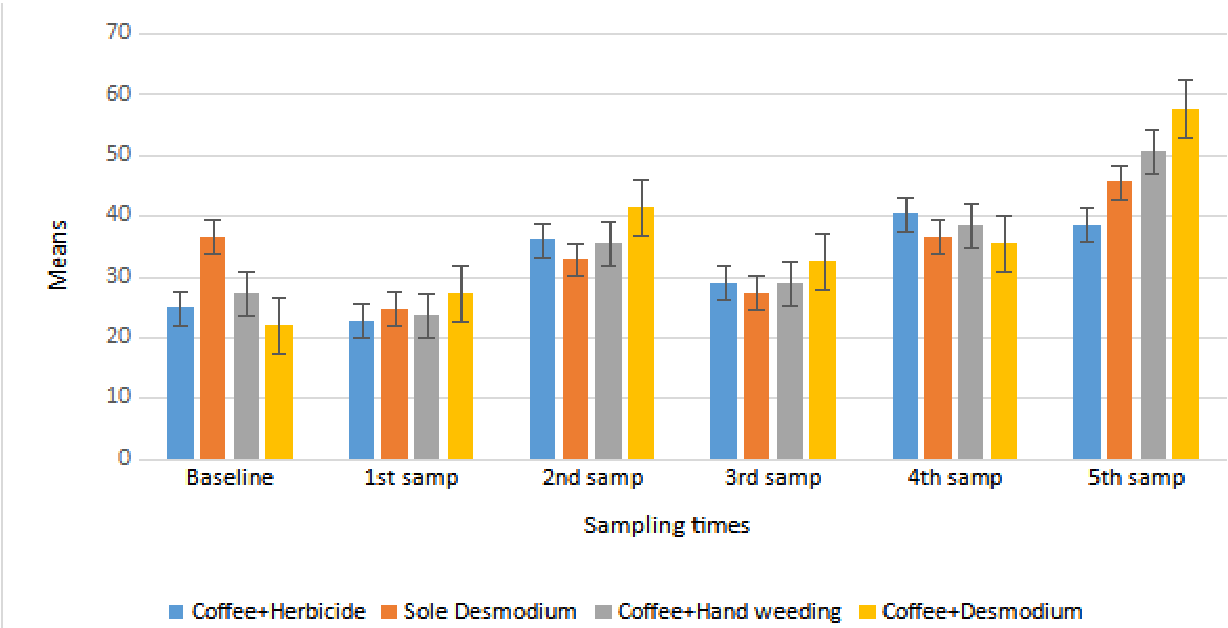

Figure 3. The graphical presentation of the soil moisture from the Kabete coffee field

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 Bergetold *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. 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=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=0.009).

Table 2. *Nutrient trends across the treatments for the sampling period*

Treatment	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.

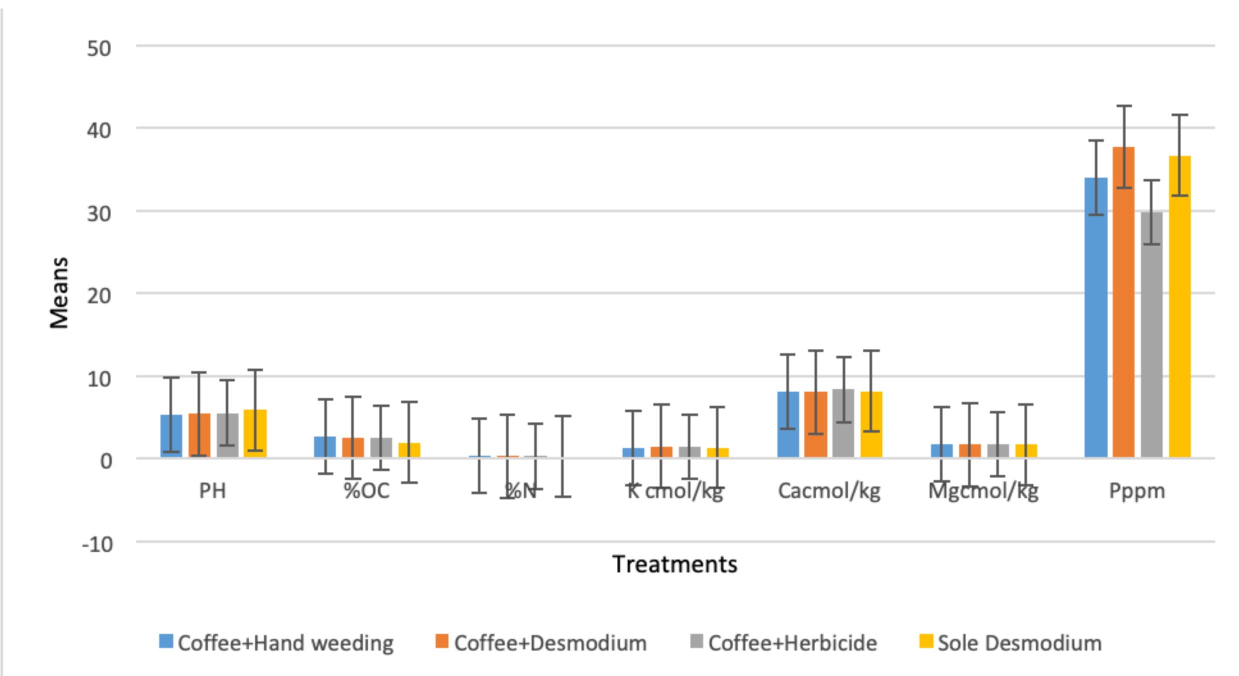

Figure 4. Trends in the nutrients across the treatments for the season

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.

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Desmodium Biomass

The results from the harvesting of desmodium done 3 times per year yielded a fresh biomass of 17,000 kgs per hectare. This closely related to the potential indicated by ILRI (2013) of harvesting 19 tons / hectare of desmodium fresh forage 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 3. Returns on labour for the different treatments per hectare

Treatment	Cost of labour per ha (US $)	Frequency of labour (US $)	Total costs per year (US $)	Extra labour	Returns on (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.

Assumptions: 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 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; Santo *et al.*, 2016).

Discussion

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 coffee + desmodium intercrop could be due the cut and carry system when the soil mineralization of the biomass is not captured although there has been confirmation of direct nitrogen transfer to adjacent non legume crop through mycelial Arbuscular fungal network as reported by Marta 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 (Mitter *et al.,* 2020; Mendes *et al.,* 2013). 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 (Hartman *et al.,* 2018; Hu *et al.,* 2018).

Conclusion and recommendations

Agricultural Intensification which is aimed at optimizing natural resources in the era of climate change when adopted will increase coffee farmer's resilience to climate change while sustainably producing goods with the benefits of ecosystem services. There are increasing reports of growing weed resistance to herbicide usage which requires a change in the perspectives of weed control. Economic considerations for legume cover crop adoption in coffee plantations for the extra income that farmers can earn or saving them from buying fodder is economically important optimizing same space and producing more. Weeding costs are declining coffee farmers' incomes as increased rainfall demands regular weeding thus increasing costs of production.

Intensification of agricultural systems to increase multiple products while utilizing the same area and inputs will increase farmers' sustainability by increasing optimization of the available land space. Mixed crop and Livestock production practiced by most smallholder farmers in most coffee producing areas will benefit from the extra source of fodder or the revenue from the sale of the biomass which could greatly supplement the farmers' incomes. The ability of desmodium to smother weeds, providing the ground cover to reduce soil evaporation and soil erosion will lead to increased land use efficiency by having the benefit transferred to livestock feed. Farmers' ability to reduce the impacts associated with bare soils such as during the heavy downpours will greatly help in reduction of soil erosion and land degradation.

Embracing desmodium legume cover crop which has a crude protein of 18% will also serve as a cheaper protein source for livestock saving farmers the need for commercial substitution, while freeing up the grains used in animal feeds as protein source for human food thereby improving the food security status. Cover crops have also been recommended as a climate smart production system that uses same or less land to produce more while reducing greenhouse gas emissions related to inefficient input usage while ensuring adequate income and sustained nutrition. The moisture conservation benefit while still harvesting fodder for livestock is a great advantage for farmers carrying out sustainable intensification.

Based on our findings, policy makers need to urgently intensify the dissemination of the benefits associated with Agricultural intensification while benefiting from the ecosystem services associated with using legume cover crops to enable farmers increase their resilience to climate change impacts in the face of increasing weather uncertainty and sustainably reduce the emission of greenhouse gases associated with Agriculture.

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