INNSPUB

Journal of Biodiversity and Environmental Sciences | JBES
ISSN: 2220-6663 (Print); 2222-3045 (Online)
Website: https://www.innspub.net
E-mail contact: info@innspub.net
Vol. 28, Issue: 4, p. 73-88, 2026

RESEARCH PAPER
OPEN ACCESS

Intercropping camphor basil shrubs with selected food crops for ecosystem services in the upper midland agroecological zone of Western Kenya

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Key words: Agroecology, Biodiversity, Ecosystem-services, Intercropping, Shrubs

Received: 22 March, 2026 **Accepted:** 05 April, 2026 **Published:** 10 April, 2026

DOI: https://dx.doi.org/10.12692/jbes/28.4.73-88

ABSTRACT

Agroecology practices through a nexus of intercropping, biodiversity conservation and ecosystem services (ES) is gaining traction globally. However, they remain insufficiently documented in Kenya, which hampers their adoption by smallholder farmers and policymakers. This research examined two shrub-based intercropping systems to assess their potential for enhancing food security within a landscape adjacent to the protected Kakamega forest ecosystem. The study followed standard agronomic protocols for sowing during the 2023 cropping season under rain-fed conditions, using a Randomized Block Design. Soil health parameters, including Nematode counts, were measured before planting and after harvesting the intercrops. The advantages of intercropping in terms of biophysical yield were evaluated using Land Equivalent Ratios (LER) and percentage Land Saved (% LS). Crop resilience was assessed through Partial LERs, while overall intercropping performance was analyzed using the Pareto principle. The three-tier intercropping systems demonstrated a 70% reduction in land use while achieving higher yields (ranging from 558.3 kg/ha to 6432 kg/ha) compared to the two-tier cereal maize/bean systems, which yielded 4022.5 kg/ha with a 57.4% LS. Among the combinations of three crops i.e. Camphor basil, Cowpeas, NERICA rice, Maize, or Soybeans—those involving Camphor basil and Cowpeas showed the highest resilience, with PLER values of 1.597 and 1.23 respectively. Notably, soil health status with destructive nematode counts exhibited a significant decline ($p<0.05$) for *Pratylenchus* sp. and *Meloidogyne* sp. Overall, a shrub-based three-tier intercropping system offers greater ecosystem services compared to traditional cereal/legume systems, hence suitable for adoption by farmers at a broader scale.

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INTRODUCTION

Ecosystem services, food security, biodiversity loss, and soil health are linked to agricultural intensification within an agroecology framework, which includes intercropping practices. Only 20% of Kenya's land is arable (Soil Atlas, 2025), making intercropping vital for transforming Agrifood systems, particularly for smallholder farms near protected forests that rely on various forest shrubs for alternative livelihoods (Otieno and Analo, 2012). The study is premised on the assumption that key drivers of deforestation and soil degradation; include lack of viable intercropping options in forest adjacent landscapes. However, few studies document ecosystem services conferred by intercrops (Huss *et al.*, 2022), which are key to economic sustainability for smallholder farmers in forest adjacent areas. Intercropping-growing two or more crop species simultaneously-achieves spatial complementarity (Van der Meer, 1989) in Agri-food systems; but intercropping shrubs and food crops is rarely reported outside parkland agroforestry systems (Bekele, 2018).

Many studies emphasize two-tier intercropping, with limited data on three-tier systems that include shrubs for enhancing Agri-food systems and biodiversity. This paper examines a nature-positive farming approach through intercropping shrubs and food crops to support smallholder farmers near the Kakamega Forest National Reserve in western Kenya. We hypothesized that productive efficiency of intercropping systems would be higher in three-tier than two-tier mixtures or monocultures. The key research question is whether these intercropping systems can enhance yields, soil health and biodiversity without soil pesticides and compromise food security.

In western Kenya, maize and beans are primary food security crops grown in conventional two-crop per season intercropping known as Mbili-Mbili (Mucheru-Muna *et al.*, 2010). These crops are cultivated on small, densely populated farms with declining land and soil fertility, threatening sustainable agriculture and biodiversity. Generally, biodiversity is distinguished in agricultural land use as either planned or associated; whereby planned diversity includes the temporal and spatial organisation of crops, while associated diversity is constituted by the incidence of wild species (Wibbelmann *et al.*, 2013) and human interaction with forest shrubs.

Through various component interactions, intercropping enhances plant diversity in fields, fostering complementary and facilitative relationships (Duchene *et al.*, 2017). These inter-relationships include ecosystem services (ES), for providing a regulatory function in biological pest control and provisioning for food security (MEA, 2005). Several ecosystem services derived from different stages of shrub development (biodiversity, soil health) have been reported (Eldridge and Santiago-Soliveres, 2014), but rarely in intercropping systems. Given that food security entails both physical and/or economic access to safe food as an ecosystem service, transitioning to diverse intercropping systems with non-food shrubs may offer greater positive impacts on socioeconomic and ecosystem services, compared to continuous maize/bean intercrops in western Kenya.

The choice of crops for intercropping with complementary growth patterns is critical: Optimizing intercropping agronomically and ecologically (Brooker *et al.*, 2015), involves understanding component interactions affecting productivity, land use, biodiversity, and ultimately food security and sustainability. Selecting complementary crops is therefore necessary, since biologically efficient intercropping may not always be economically viable (Ghulam *et al.*, 2003). However, information on three-tier intercropping with shrubs for monetary and biophysical benefits is limited, with few studies addressing food security and biodiversity simultaneously in such systems. Intercropping promotes resilience through higher plant resource efficiency (space and nutrients) and natural suppression of soil pathogens (Huss *et al.*, 2022).

Some microbes like nematodes, significantly reduce crop yields and quality worldwide (Azlay *et al.*, 2022; Hallmann *et al.*, 2007) particularly affecting African Leafy Vegetables in Africa (Onkendi *et al.*, 2014). Deguine *et al.*, 2023, further report that utilizing soil biological diversity for plant nutrition may reduce the amount of mineral fertilizer use and improve resistance against plant diseases. With intercropping, socio-economic drivers also inform the agronomic decisions and evaluation (Agrell *et al.*, 2004) for resilience and pest control. However, unmitigated agricultural activities impact negatively on ecosystems and biodiversity (Mathikere and Kundlas, 2014); and this includes over-cultivation and intercropping linked to soil microbial diversity (Duchene *et al.*, 2017; Tripathi *et al.*, 2022), that affect nutrient transfer, plant health, and soil fertility. Harmful practices such as burning crop residues degrade soil health and microbes (Lin and Begho, 2022); and using toxic chemicals to control nematodes raises environmental and health concerns, leading to restrictions. Effective strategies for soil ecosystem services management in intercropping can therefore enhance agricultural biodiversity (Lehmann *et al.*, 2020), similar to the 'Agroecology Nexus Approach' for achieving sustainable food security (Mockshell and Villarino, 2019).

MATERIALS AND METHODS

Study area

The research was done at Muhudu in Vihiga County (Fig. 1), located in the upper midland (UM3) agroecological zone (Jaetzold *et al.*, 2010) of western Kenya between longitudes 34°30' and 35°0'E and latitudes 0° and 0°15'N. The county encompasses the southern portion of the Kakamega Forest called Kibiri, the only remaining Guineo-Congolian rainforest in Kenya, which supports a rich biodiversity and provides several ecosystem services (Mutoko *et al.*, 2015). The study area is further characterized by increased pressure on land and forest resources from a high population density of 1050 persons per Km^2, with mean annual rainfall of 1800mm-2000mm and diurnal average temperatures of 24 ^{o}C.

The experiment was carried out at a farmers' field, adjacent to Kibiri section of Kakamega forest, on relatively fertile soils and well drained. The selection of the intercropping components was based on their potential from secondary data profiles, such that intercropping represented an agroecology prospect for favourable yields, food security status and functional biodiversity, with maturity periods that fit an annual cropping season similar to farmers' practices. The Camphor basil shrub (*Ocimum kilimandscharicum*) was selected as a test shrub for intercropping, due to its resilience and domestication potential (ICIPE 2018), alongside cowpeas (*Vigna unguiculata*), NERICA rice (*Oryza sativa*), and soybeans (*Glycine max*) as alternative intercrops to the traditional maize (*Zea mays*) and beans (*Phaseolus vulgaris*), and agroecologically suitable for the study area.

Nursery establishment for the Camphor basil shrubs took place in a prior short rain (SR) season in 2022 at Shamiloli on the forest edges. Transplanting the seedlings of uniform heights and turgidity took place subsequently in the long rains (LR) season of 2023 on the same day with the food crop components. This was done in 20m^2 plots that mimic smallholder farms with local climatic and weather conditions, as pure stands or intercrops- shown in Table 1 treatments. The experiment was laid out in a randomized block design (RBD) with twelve treatments and three replications.

Planting of the maize, cowpeas, and soyabeans (monoculture and intercropping) followed the standard agronomic protocols for each respective crop according to the practice of Mucheru-Muna *et al.* (2010), but without any soil amendments. The only external input used was Agri-foliar organic liquid fertilizer applied to the vegetative shrub components once every two weeks to boost leaf vigour after transplanting. The intercropping series deployed were additive for monocrops (Maitra *et al.*, 2021) and replacement (Andersen *et al.*, 2008; Burgess *et al.*, 2022) or Mbili-Mbili (Kihara and Kinyua, 2022) for intercrops to mimic farmers' practices.

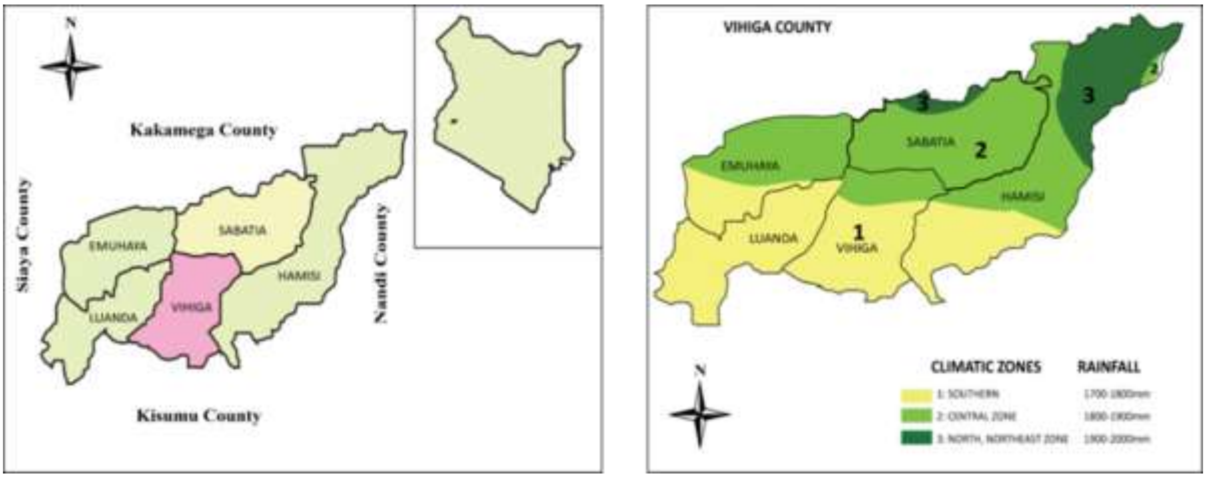

Fig. 1. Map of study area

Table 1. Intercropping plot design

Plot no.	Treatment (Cropping design)	Intercropping series
1	Camphor + NERICA Rice	Replacement series where crops are grown by sacrificing a proportion of the population of one component (Burgess *et al*., 2022; Maitra *et al*., 2021).
2	Camphor+Maize	
3	Soyabean + NERICA Rice	
4	Soyabean + Maize	
5	Camphor+ Maize+ Cowpeas	Mbili-Mbili[1] (Mucheru-Muna *et al*., 2010)
6	Soyabean + Maize+ Cowpeas	
7	Camphor Sole Crop	Additive series where the main crop is sown with 100% of its recommended population in pure stand (Maitra *et al*., 2021)
8	Soya Bean Sole Crop	
9	Cowpeas Sole Crop	
10	NERICA Rice Sole Crop	
11	Maize Sole Crop	
12	Maize + Beans+ Cowpeas	Mbili-Mbili[1] control (Farmers' practice)

Mbili-Mbili1: Paired row planting arrangement where two rows of the main crop is paired and planted by reducing the interspace so that another row of a different crop is introduced with provision for other subsequent paired rows (Kihara and Kinyua, 2022; Mucheru-Muna *et al*., 2010; Woomer *et al*., 2004).

Soil sampling and testing

Soil testing occurred twice: once before planting the fallow with crops and again after harvesting all intercrops at the experimental site. Samples were collected using a zig-zag pattern down to a depth of 0-15 cm, yielding half-kilogram units suitable for analysis as outlined by Okalebo *et al.* (2002). These samples were labeled appropriately before being sent to the KALRO-Kibos agronomy lab in Kisumu for processing.

Preparation and analysis

Soil samples underwent crushing, air-drying, and sieving following standard protocols (Okalebo *et al*., 2002) for laboratory analysis of several parameters including soil microbe analysis-specifically nematodes-were counted per kg of soil using the Modified Baermann Funnel technique, with identification to genus level according to Coyne *et al.* (2014).

Yield and yield components

The grain and leaf yields as air-dry weight from respective crops were recorded in kg/sample plot from every plot and extrapolated into per hectare (Ha) basis. Each treatment (plot) of 20m^2 (5m×4m) was extrapolated for all yield and yield component analysis. The averages of five individual plants per plot were used for the yield measurements using a digital weighing scale, as yields in Kg/ha and monetary values in KSh/ha. Component interactions of facilitation in the intercropping systems were assessed by results from relative yield advantages with indices of LER, PLER and soil micro-nutrient status. The aggregate biological and economic yield advantage of the component crops in the intercropping system was quantified as follows:

The Land Equivalent Ratio (LER) for yield advantages was calculated using the equation from Willey (1979):

$$LER = \Sigma(\frac{Y_p}{Y_{mi}})$$

where Yp is the yield of each crop variety in the intercrop, and Ym is the yield of each crop in the sole crop. The LER was used as a relative measure of resilience from 'Partial LER' of individual crops (PLER). The partial LER can indicate which component crop is dominating or is suppressed in resource exploitation (Dhima *et al.* 2007). It is hereby assumed that the higher the PLER value, the more resilient the crop component is in the intercropping mixture;

The monetary advantage index, (MAI) was calculated according to Gosh (2004) and Willey (1985),

$$MAI = Vx\Sigma_{n=12}(\frac{LER - 1}{LER})$$

Where V= value of combined intercrops. The higher the index value, the more profitable the intercropping system (Dhima *et al.*, 2007), and to determine which crop was the driver of system productivity from land saved.

The main advantage of mixed cropping (Willey, 1985) was described in terms of the cultivated land area saved by using an intercropping system, and illustrated in this study as the percentage land saved (% LS) according to Baraki *et al.* (2023):

$$LS = \Sigma_{n=12}(\frac{LER - 1}{LER}) \times 100$$

So that where land saved (%)>0 or land saved (%) <0 there is advantage or disadvantage respectively in terms of land used.

Component interactions of facilitation and competition in the intercropping systems were assessed by observational and experimental results from relative yield advantages with LER and soil health.

Biodiversity was quantified according to the Shannon-Wiener simplified method of crop species count in each treatment, with higher values indicating greater species diversity in the crop mixtures.

Overall system productivity was determined by the Pareto-Optimality ranking technique (Kennedy *et al.*, 2008; Shija *et al.*, 2022), by seeking to optimize the use of the intercropping indices in the two-tier and three-tier nature as a set of multiple variables, to identify the best fit scenario. The Pareto chart was generated by computer using aggregate data from LER, MAI and LS as optimal yield components with absolute units from each respective intercropping treatment.

Statistical analysis

All relevant data was analysed using GIS mapping where applicable and the SAS JMP statistical software package, and subjected to ANOVA to determine significant differences among variables or factors and their interactions using parameter estimates. The ANOVA tables are presented in the annex (as supplementary material). The Means separation of Land Equivalent Ratios (LER), Partial Land Equivalent Ratios (PLER), and % Land Saved (LS) data collected, and homogeneity of variances was done with Bartlett's LSD at 5% significant levels. For all analyzed parameters, P<0.05 was interpreted as statistically significant. The multivariate analysis capability of the JMP statistical tools supported the design of each treatment as an intercropping system, where data as response variables are context specific to aid in cross validation, with predictive modeling ability using 'Intercept Values'. The response variables in the JMP toolkit were yields, and yield components including soil micro-nutrients for soil health, LER PLER, and LS. The aggregate statistical results for each treatment as absolute values subsequently informed the Pareto Chart for evaluating overall system productivity of intercropping in the context of agroecology.

RESULTS AND DISCUSSION

Intercropping yields and yield components

For an interactive evaluation of the biophysical effects and relative value of intercropping on the yields of crop components per block, the results for context specific treatments on yields are presented in Tables 2, 3, 4, and the Pareto Chart in Fig. 2.

The test samples for yield advantages were Camphor basil shrub and cowpea leaves, harvested grains of maize, NERICA rice and soyabeans, and soil samples for nutrients and nematodes for soil health evaluation in the intercropping treatments that mimic a nature positive system. The intercropping yields (Table 2) and parameter estimates for validation (Table 3), indicate that all the treatments had a significant effect on yields compared to the sole crops, whereby the three-tier intercropping patterns of Camphor + Maize + Cowpeas (T_5), Soyabeans + Maize + Cowpeas (T_6), and Maize + Beans + Cowpeas (T_{12}) yielded higher with 6326.7kg/ha, 6432kg/ha, than the two-tier systems of intercropping Camphor + Maize (T_2) and Soyabeans + NERICA rice (T_3) and Camphor + NERICA rice (T_1), with total yields of 4022kg/ha, 2668.7kg/ha and 2403.3Kg/ha respectively. All the highest yielding intercropping treatments T_1, T_2, and T_5 contained a Camphor basil component, suggesting that the shrub is suitable for domestication as an intercrop (either two-tier or three-tier system) with promising returns. There was greater variation in yields between the three-tier intercropping systems and their respective sole crops, compared to the variation observed in the two-tier systems and sole treatments. The variation in yields between component crops can be attributed respectively to inter-plant competition, facilitation and/or complimentarity.

Generally, these results align with Baumann *et al.* (2002), who report that crop yield variability arises from complex interactions among environmental, spatial, and abiotic factors in a field. In low-input intercropping systems, as shown in this study, increased plant functional diversity enhances yields through inter-plant facilitation, where crop components positively influence each other as earlier reported by Jose *et al.* (2015) or Saharan *et al.* (2018) for 'bio-fertilization' in finger millet/pigeon pea intercrops.

Table 2. Intercropping block yields Y-(Kg) and value (KSh) per ha

Treatments (T)	Block A	Block B	Block C	Y-kg/ha	Value(KSh)
T_1-Camphor + Nerica Rice	2595.5	2306	2308.5	2403.3^{c}	283450^{g}
T_2-Camphor + Maize	3709.5	4534.5	3823.5	4022.5^{b}	372513^{de}
T_3-Soya Beans + Nerica Rice	2640	2778	2588	2668.7^{c}	341183^{fge}
T_4-Soya Beans + Maize	4588	5043	3365	4332^{b}	410943^{cde}
T_5-Camphor+Maize+ Cowpeas	5222	5022	6518	5587.3^{a}	441407^{cd}
T_6-Soyabeans+Maize+ Cowpeas	5348	6778	7170	6432^{a}	550743^{b}
T_7-Camphor	401.5	344	472	405.8^{f}	14204^{h}
T_8-Soya Beans	740	742	742	741.3^{fe}	51893^{h}
T_9-Cowpeas	1460	1200	1670	1443.3^{de}	72167^{h}
T_{10}-Nerica Rice	2100	2050	2060	2070^{dc}	310500^{fg}
T_{11}-Maize	4770	4985	4785	4846.7^{b}	484667^{cb}
T_{12}-Maize + Beans + Cowpeas	5630	6445	6905	6326.7^{a}	700542^{a}

Key: Y- yields Block average. Means in a column of yields and Value with the same letter are not significantly different at ($p<0.05$); KSh 130= 1 USD

The overall yields within the three-tier and two-tier systems were not significantly different from each other in each category. The Maize sole crop (T_{11}) performed better in yields of 4846.7kg/ha than the Camphor+Maize (T_2) intercrops with 4022kg/ha but the difference was non-significant. This may be attributed to the competitive effect of the shrub component in suppressing the cereal for growth resources. Another notable observation is that apart from Maize, the Cowpeas crop component also appeared in every crop mixture with the highest significant effect on yield ie T_5, T_6 and T_{12}. This suggests that Cowpeas is the most resilient crop in the intercropping mixtures in this study or when grown in association with similar crop components. The two-tier intercropping treatments with a significant t-Ratio (> 0.05) were T_1, and T_3, indicating mean yields that were lesser than the control experiment (T_{12}). The three tier intercropping treatments with a significant t-Ratio (<0.05) were T_5 and T_6, indicating mean yields that were significantly higher than the sole crops of Camphor basil shrubs (T_7), Soyabeans (T_8) and Cowpeas (T_9) as shown in Table 4. The 'Intercept' yield using parameter estimates was significant, indicating that the mean intercropping yields greater than 0, represent the minimum break even yield of the intercropping system.

Generally, LER values indicate the relative efficiency of land use with intercropping as compared to monocropping in respective crop mixtures. In all multi-cropping treatments, LER was greater than 1 as shown in Table 4 while the sole crops returned unit values. However, when subjected to parameter analysis for validation, the sole crops of Camphor T_7, NERICA rice T_{10} and Maize T_{11} returned partial LER values less than unit value, while the cowpeas and soyabean sole crops returned LER unit values. In addition, all the treatments had a significant effect on LER above the intercept value of 1.506 where the higher values of LER were realized from the three-tier intercrops Soyabean+Maize+Cowpeas; while lower values of LER was observed from the two-tier intercrops. These results further indicate that T_5 (Camphor+ Maize+ Cowpeas) was the most productive three-tier intercropping system, while T_1 (Camphor + NERICA Rice) was the most productive two-tier system.

Table 3. Parameter estimates (PE)-yields in Kg per Ha

Treatment	Mean Yields	Std Error	DFDen	t Ratio	Prob>|t|
Intercept	3357.075	123.467	1.8	3.28	0.0139*
T_1-Camphor + Nerica Rice	2403.3^{de}	549.853	1.838	0.77	0.5288
T_2-Camphor + Maize	4022.5^{c}	644.406	1.928	0.55	0.6372
T_3-Soyabean + Nerica Rice	2668.7^{d}	549.853	1.838	-0.34	0.7664
T_4-Soyabean + Maize	4332b^{c}	349.933	1.838	-0.48	0.6826
T_5-Camphor+Maize+Cowpeas	5587.3^{b}	64.576	2.858	6.83	0.0112*
T_6-Soyabean+Maize+Cowpeas	6432^{a}	349.93	1.838	4.51	0.0233*
T_7-Camphor Sole Crop	405.8^{fg}	356.576	1.858	0.59	0.618
T_8-Soya Bean Sole Crop	741.3^{efg}	364.576	1.858	-0.49	0.678
T_9-Cowpeas Sole crop	1443.3^{e}	264.406	1.928	3.49	0.0338*
T_{10}-Nerica Rice Sole Crop	2070d^{e}	354.576	1.858	0.55	0.6401
T_{11}-Maize Sole Crop	4846.7^{ab}	584.386	1.885	-0.29	0.8032
T_{12}-Maize+Beans+Cowpeas	6326.7^{a}	39.4671	3.081	4.9	0.0205*
Block A	3267^{bc}	539.4671	3.081	-1.9	0.1505
Block B	3519^{bc}	754.2456	3.35	0.23	0.8305
Block C	3534^{bc}	539.4671	3.081	-0.12	0.9142

KEY* Denotes significant values; Means in a column with the same letter are not significantly different at ($p<0.05$)

The LER returns for both the three-tier and two-tier treatments were all significant except the sole crops of Camphor (T_7), NERICA rice (T_{10}) and Maize (T_{11}). The sole crop of Cowpeas recorded a significantly higher partial LER of 1.055 from the parameter estimates (PLER), indicating higher resilience. The critical value of LER is 1.0 whereby a LER >1.0 indicates an advantage of intercropping over mono cropping, while values of LER<1.0 show that the intercropping is disadvantageous, and a unit value of LER indicates a break-even status (Dhima *et al.*, 2007; Lithourgidis *et al.,* 2011; Bedoussac *et. al.*, 2015). Thus, all the intercropping regimes except the pure stands of Camphor (T_7), NERICA rice (T10) and Maize (T11), returned a yield advantage when using LER (>1) as an indicator.

In respect to monetary advantage, the results from parameter estimates (Table 4) further show that all the shrub-food intercrops had significant MAI values and outperformed sole crops in LER but not MAI, since the objective was to achieve crop diversity on a given land area. However, when intercropping is evaluated for its ability to produce marketable raw products without concern for diversity and market prices, all the intercrops except T_{12} (Maize+Beans+Cowpeas) may result in a yield loss for monetary advantage compared with the most productive sole crop like T_{10} (NERICA rice sole) and T_{11} (Maize sole). Monetary advantage in intercropping systems is subject to farm-gate prices or value of end products. Similar observations were made by Li *et al.* (2023) in a meta-analysis of 226 field experiments on the productive performance of intercropping systems.

However, several authors have used the monetary advantage index (MAI) to describe the financial advantage of intercropping compared to monoculture, as critical for determining the economic viability of an intercropping system (Dhima *et al.*, 2007; Gitari *et al.,* 2020; Baraki *et al.*, 2023). The low farm-gate prices of camphor basil, cowpeas and soyabeans negatively affected the system productivity of intercropping in this study. The agroecological implication of this observation is that intercropping systems may need value addition (agro-processing) to crop components for better prices in order to achieve greater monetary advantage and enhance overall system productivity.

Results from MAI indicate that while biological land use efficiency (LER) shows great potential, it does not guarantee economic viability for intercropping at current farm-gate prices of respective value chains. This issue arises because agro-processing value is often excluded from LER calculations, leading to an underestimation of intercropping's real economic benefits. Gitari *et al.* (2020) also reported that despite LER being the most common index in agronomy studies, it does not account for the real economic value of the cultivated crops. Thus, low Monetary Advantage Index (MAI) as derived from LER for intercropping Soyabean and Camphor basil is linked to unexploited value chains; Soyabean yields cholesterol-free milk, highly valued in the market (Niyibituronsa *et al.*, 2018; Jung *et al.*, 2021), while Camphor basil produces essential oils and serves as a bio-pesticide (ICIPE, 2018), fetching good prices.

Furthermore, intercropping aromatic shrubs can enhance economic and environmental benefits (Chuan-chao *et al.*, 2009). Determination of the precise production efficiency in intercropping systems by smallholder farmers therefore remains a big challenge, necessitating the use of several indices in combination to measure productivity, which includes the MAI and % LS as complementary to LER in the holistic context of agroecology. This approach may significantly improve ecosystem service analysis and support investment and income generation for farmers near forest reserves, thereby reducing forest encroachment, as seen in the Kakamega ecosystem.

Table 4. Model fit for intercropping efficiency under different systems

Treatments (T)	Ratio	$PLER_1$	$PLER_2$	$PLER_3$	LER	LS %	MAI
T_1-Camphor$_1$+NERICA Rice$_2$	1:1	1.5967^{a}	0.84^{ab}	-	2.43^{c}	57.74^{c}	177948^{de}
T_2-Camphor$_1$+Maize$_2$	1:1	1.1633^{bc}	0.74^{b}	-	1.89^{d}	45.65^{d}	79763^{g}
T_3-Soyabean$_1$+NERICA Rice$_2$	1:1	0.9967^{bc}	0.93^{ab}	-	1.93^{d}	48.13^{d}	239346^{c}
T_4-Soyabean$_1$+Maize$_2$	1:1	0.9933^{bc}	0.74^{b}	-	1.74^{d}	42.04^{d}	131853^{efg}
T_5-Camphor$_1$+Maize$_2$ + Cowpeas$_3$	2:1:1	1.34^{ab}	0.77^{ab}	1.23^{a}	3.35^{a}	70.05^{a}	184765^{de}
T_6-Soyabean$_1$+Maize$_2$+ Cowpeas$_3$	2:1:1	1.00^{bc}	0.84^{ab}	1.09^{a}	2.95^{b}	66.06^{ab}	304141^{b}
T_7-Camphor Sole Crop	1	1.00^{bc}	-	-	1.00^{e}	0.00^{e}	10145^{h}
T_8-Soya Bean Sole Crop	1	1.00^{bc}	-	-	1.00^{e}	0.00^{e}	148267^{ef}
T_9-Cowpeas Sole Crop	1	1.00^{bc}	-	-	1.00^{e}	0.00^{e}	115467^{fg}
T_{10}-NERICA Rice Sole Crop	1	1.00^{bc}	-	-	1.00^{e}	0.00^{e}	351900^{a}
T_{11}-Maize Sole Crop	1	1.00^{bc}	-	-	1.00^{e}	0.00^{e}	218100^{cd}
T_{12}-Maize$_1$ + Beans$_2$+ Cowpeas$_3$	1:2:1	0.84^{c}	1.00^{a}	0.62^{b}	2.46^{c}	59.23^{bc}	297435^{b}
R^2		0.538	0.475	0.86	0.96^2	0.9	0.9587
Mean		1.08	0.84	0.98	1.81	32.41	224683.5
C.V.(%)		21.42	16.36	16.5	11.36	14.5	17.09%
LSD (0.05)		0.3911		0.37	0.206	7.96	38411.05

Land use efficiency (LUE) and ecosystem services

Among the intercrops, T_5 (Camphor+Maize+Cowpeas) recorded the highest land use efficiency by saving 70% of cultivated land, followed by T_6 (Soyabeans+Maize+Cowpeas) at 66.06% and T_1 (Camphor+NERICA rice) at 57.4% (Table 4). In this study, both the two- and three-component intercrops consisted of half and a third of the sole crop sowing ratios of each species respectively (Table 4), similar to the practice of Andersen *et al.* (2008); and LER results confirm the three-tier intercropping system to be more efficient than the two-tier system on the same land management unit. For optimum utilisation of small farm sizes, a three tier intercropping system is therefore more viable than a two-tier system in the study area, or similar agroecological zones in the global south.

The precise quantification of intercropping benefits to ecosystem services (ES) and land-use efficiency (LUE) remains unclear across agroecological zones similar to the upper midland (UM) areas described by Jaetzold *et al.* (2010). However, higher yields at landscape level through shrub-food crop intercropping imply reduced land needs for food security, potentially minimizing forest encroachment and deforestation as reported by Jayathilake *et al.* (2021). In order to enhance ecosystem services (ES), it is feasible to maximize complementary interactions and minimize any competitive interactions for growth resource in three-tier intercropping with beneficial shrubs. This study provides more evidence on promising nature-positive shrubs intercropped with food crops for facilitative component interactions, and delivery of multiple ecosystem services (MEA, 2005) in the provisioning category or food security, efficient land-use and management for smallholder farming, and regulatory ES without the use of soil chemical amendments.

In this regard, a three-tier intercropping system as in T_5 (Camphor + Maize + Cowpeas) and T_6 (Soya Beans + Maize + Cowpeas) is more resilient with more ecosystem functions than a two-tier system like T_3 (Soyabeans + Nerica Rice) or T_2 (Camphor + Maize) suitable for smallholder farms, depending on the choice of crop components for land use efficiency through % Land Saved (LS). This is in comparison to Andersen *et al.* (2008) who reported that the performance of each crop species was very different when it grew with a second species rather than in monoculture. However, the addition of a third crop species had minor effects on performance of the individual crops as illustrated by the partial Land Equivalent Ratios (PLERs) in Table 4. The component crop that is dominating has higher PLER than their companion.

To enhance biodiversity and crop productivity through resilience in nature-based intercropping systems, modeling species combinations can improve ecosystem service functioning and promote sustainable agriculture. The three-tier intercropping system supports greater biodiversity than two-tier systems and monocrops. This approach mimics nature, allowing for optimal yields from intercropping domesticated shrubs with multiple priority food crops in the same season. Intercropping camphor basil shrubs offers alternative livelihoods and helps conserve forest biodiversity, reducing the pressure of shrub extraction from forests. Camphor basil also performs well with NERICA rice in two-tier systems, while cowpeas are the most resilient in three-tier systems, contributing to higher food security. This is in agreement with Cole and Bustan (2009), who indicate that generating cash income from cultivated shrubs is crucial for farm families facing marginal socio-economic conditions, similar to landscapes neighbouring Kakamega forest of western Kenya.

Pareto optimality analysis

The 'Pareto Principle' is a decision support tool for optimal scenarios primarily in the commerce disciplines, and can be used the same way in agroecology to identify the few practices that deliver most benefits to achieve sustainable agriculture. These practices include intercropping and the benefits observed from this study are enhanced yields, improved soil health and biodiversity. Given the need for sustainable agriculture models that are both productive and environmentally-friendly (Garbisu *et al.*, 2025), a mechanism for determining the best fit scenario in intercropping systems is hereby proposed with the Pareto optimality analysis, similar to Kennedy *et al.* (2008) and Shija (2022).

According to the Pareto optimality principle, in three- and two-tier intercropping systems, a small number of crops (20%) lead to most (80%) of the overall effect (Ecosystem services). A computer-generated Pareto diagram organizes factors contributing to positive outcomes in descending order by their impact. This analysis, illustrated in Fig. 2, highlights which intercrops require the most focus, ranking the three-tier and two-tier systems accordingly.

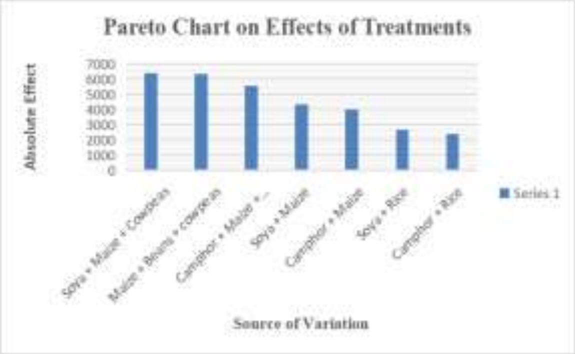

Fig. 2. Intercropping productivity based on the Pareto chart

This scenario is informed by the fact that although the LER (or relative yield) provides an ideal base on which to compare intercrops, it gives no indication of absolute yields (Willey, 1985). Single-source measures of productivity and efficiency including yields per unit area, economic value from farm gate prices (MAI) and LER for biological yield advantages, may grossly underestimate efficiency of intercropping systems as reported by Alene *et al.* (2006), and thus cannot be solely relied upon to precisely assess productivity of an intercropping system.

The most absolute effect of intercropping apart from the control T_{12} (Maize+Beans+Cowpeas) was realised from Soyabean+Maize+Cowpeas, followed by Camphor+Maize+Cowpeas and Soyabean+Maize crop mixtures, while the least absolute effect was observed from Camphor+Nerica rice intercrops (Fig. 2). In absolute terms, it is apparent that system productivity favours a three-crop mixture than a two-crop mixture. This can be attributable to increased biodiversity and niche differentiation for more complementary effects in the mixtures with more crop components (Chumba *et al.*, 2013).

It is noteworthy that despite having equal crop diversity in two-tier mixtures, the Soyabean+Maize intercrops recorded a higher absolute effect than other two-tier intercrops with a shrub component, Camphor+Maize and Camphor+NERICA rice. This is in agreement with Yang *et al.* (2015), that one of the drivers of intercropping yield advantage is temporal differentiation of crop growth, but with multiple unaccountable factors that contribute to overall system productivity apart from LER indices. These factors may include the N-fixing ability of the legume crops in below-ground component interactions, enhanced photosynthetic activity of the taller over-storey plants like maize in the crop mixtures, or inter species competitive effects of the shrub and rice components against each other. The latter two factors may account for Camphor+Maize intercrop having more absolute effects, hence more efficient than the Camphor+NERICA rice mixture.

When only two companion crops are involved in an intercropping system, LER values can be conveniently presented for analysis (Willey, 1985). The results (Fig. 2) suggest that it is feasible to design a stable Agri-food system among intercropping options with the Pareto principle, as an optimal set of factors, and trade-offs in intercropping with more than two crop components in the mixture. Thus, Pareto Chart results from Fig. 2 generally imply that the three-tier systems are more efficient than two-tier intercropping systems. In the three-tier systems, the Soya beans+Maize+cowpeas are the most efficient, while in the two-tier systems, Soya beans+ maize are the most efficient intercrops.

Among the crop components, soya beans is a common denominator in the best performing crop mixtures with absolute effects in both three-tier and two-tier (Fig. 2), suggesting higher productivity and more beneficial component interactions to the intercropping system than other legume crop components. However, cowpeas are also a common denominator in all the three-tier intercrops, suggesting that it is more resilient than soyabeans in the intercropping system. As legumes, this may also suggest that cowpea exerts stiff intraspecific competition over soyabeans both in the shrub and non shrub components. For these reasons, a two tier intercropping pattern of soyabeans and maize is observed to be a better alternative to the traditional maize and beans intercrops, for sustainable agriculture on smallholder farms. For optimum food security from shrub based intercrops, Camphor basil+Maize is more efficient than intercropping NERICA rice with the Camphor basil shrubs, while incorporating Cowpeas with Maize and Camphor basil results in the most efficient three tier intercropping system with shrubs (Fig. 2). Shija *et al.* (2022), also used the 'Pareto Principle' as a ranking technique in smallholder dairy-cattle farming to identify positive deviants that attain outstanding performance and inform targeted improvements of comparable farms under similar environmental conditions in Tanzania. In addition, Laloy and Bielders (2009) used the 'Pareto Principle' for modelling intercrop management impact on runoff and erosion in a continuous maize cropping system.

Despite the advantages of intercropping in three-tier systems over two-tier systems as highlighted by the Pareto principle, this study noted limitations. These include yield reductions of the main crop, impacting food security and Agri-food systems as similarly reported by Gliessman (2015): Studies show that monocultures yield higher as in Maize sole crop (T11) due to less competition for nutrients and light. If the main crop has a higher market value, yield losses can significantly affect the overall land equivalent ratio (LER). Additionally, intercropped canopy cover or overstorey crops may alter the microclimate, affecting yields and productivity in ways that are not measured. Intercropping a maize landrace (*Zea mays* L.) with bambara groundnut (*Vigna subterranea* (L.) Verdc.) is beneficial because the latter's smaller canopy offers little competition to the cereal crop (Saxena *et al.*, 2018).

Intercropping and soil health

The soil health status of agrobiodiversity with microbes was analysed and presented in Fig. 3 for nematodes, before planting and after harvesting all the intercrop treatment samples in the test plots. Soil microbial communities serve as indicators of ecosystem stress or recovery. The experimental plots are assumed to be similar in previous pest-management practices in fallow fields, and were thus grouped into single sampling units to represent the landscape scenario before and after intercropping to mimic smallholder farmers' practice.

Fig. 3. Nematode count at Muhudu test site

The observed sharp decline (Fig. 3) in destructive nematodes (*Pratylenchus* sp. and *Meloidogyne* sp.) indicates that intercropping Camphor shrubs with crops like maize, NERICA rice, cowpeas, and soybeans significantly enhances soil health through agrobiodiversity in the short term period. Shrub-based biological controls in intercropping effectively manage root-knot nematodes as reported by Azlay *et al.* (2022) and Mukerji and Saxena (2008), and may apply to farming landscapes, as well as vertical and rooftop gardens prone to nematode infestation.

This intercropping approach in regenerative agriculture can stabilize nematode-infested soils in smallholder farms without harmful nematicides. It aligns with the idea that soil health strengthens resilience for sustainable agriculture by reducing synthetic chemical use (Davis *et al.*, 2023). The agroecological adaptation of plants to biotic and abiotic factors including soil microbes in intercropping mixtures has previously been reported by several authors (Lithourgidis *et al.*, 2011; Saharan *et al.*, 2018; Nyawade *et al.*, 2019).

Since this study was conducted at a single location and during one cropping season, it may restrict generalization of the results because long-term effects on soil health requires more seasons to manifest, due to fluctuations with weather patterns or climate change impacts. However, the need for nature-positive strategies to enhance soil health and crop yields in the face of climate changes cannot be dependent on long term trials. While low-risk agrochemicals (Desaeger *et al.*, 2020) exist, no selective nematicide has been found that effectively targets the pathogenic nematodes without harming other beneficial soil microbes.

This highlights the urgency of managing nematodes without toxic chemicals, as crucial to protect beneficial microbes, and for resilient, environmentally responsible agricultural practices (Preety *et al.*, 2026). With increasing food safety concerns about the effects of external input application to the environment and human health, integration of Camphor basil shrubs in smallholder farming to provide ecosystem services is therefore of great interest to policy makers, researchers and other stakeholders of agroecology.

CONCLUSION

The short-term performance of the shrub intercropping trials exhibited varying results of critical importance for evidence-based policy making in agroecology, targeting soil health and food safety. The intercropping systems enhance ecosystem services by providing food, soil pest control, and economic benefits for smallholders, despite challenges like price volatility. All systems showed a biological yield advantage, indicating the complementary benefits of shrubs on crop diversity. The systems promote reduced agrochemical reliance, support nature-positive interventions for improving soil health by lowering soil nematode counts without usage of chemicals.

Both three-tier and two-tier intercropping yielded more than respective sole crops, with the three-tier system being more effective for yield diversification and higher biodiversity. Intercropping Soyabeans, Maize, and Cowpeas is best for food security, while Camphor basil shrubs grown in association with Maize and Cowpeas is ideal for biodiversity and economic gain.

A three-tier intercropping of Camphor, Maize, and Cowpeas is recommended for optimal land use, economic benefits, and enhanced biodiversity. Integrating Cowpeas improves resilience in three-tier systems, while Soyabeans and Maize excel in a two-tier setup due to higher yields and improved soil health.

RECOMMENDATIONS

1. This study highlights the need for further research on Long-term effects of shrub-intercropping with food crops for agroecosystem redesign using ecological principles.
2. Selected shrub species like Camphor basil (*Ocimum kilimandscharicum*) are ideal for domestication from forests, aiming to enhance ecosystem services such as biological pest control, income generation, food security, forest conservation and empowerment of rural women and youth.
3. A three-tier intercropping method allows more diversity and fallowing on limited land, optimizing soil nutrient use and enabling smallholder farmers to sustain productivity while conserving agroecological resources
4. Promoting the intercropping of more beneficial shrub species with food crops within an Agroecology policy framework can improve sustainable Agri-food systems at scale.

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