



Biodiversity Conservation in Agroecosystems Enhances Food Security and Environmental Sustainability: Evidence from Multi-Site Field Experiments

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Abstract: To analyse the effect of biodiversity conservation in agroecosystems on food security and environmental sustainability, we performed a multi-site field experiment at 20 agricultural research farms under different agroecological zones. The experiment was conducted in a randomised complete block design with 360 experimental plots with three replications in three successive cropping seasons. Crop residue retention, conservation tillage, crop diversification, cover cropping, establishment of hedgerows, Integrated Pest Management, pollinator habitat restoration and organic farming were the practices studied. When these practices were implemented, we found an increase in plant species richness by 33.5%, an increase in number of pollinators by 30.8% and an increase of crop yield by 24.8%. Further, food security outcomes gained 27.8%, ecosystem services 31.2% and carbon sequestration 26.5%, respectively. From multiple linear regression results, it can be seen that plant species richness (standardised $\beta = 0.48$, $p < 0.001$), the number of pollinators (standardised $\beta = 0.42$, $p < 0.001$) and soil microbial biomass (standardised $\beta = 0.36$, $p < 0.001$) significantly affect food security and sustainability ($R^2 = 0.793$). The results of the correlation analysis revealed a high positive correlation between the Biodiversity Conservation Index and the Food Security Index ($r = 0.86$, $p < 0.001$). Three major factors with a total variance of 85.0% were also obtained in principal component analysis, which were the dimensions of biodiversity conservation, soil health and food security. In all indicators, the biodiversity conservation practices showed greater values than conventional farming systems. These results highlight the empirical evidence of the potential of any in-field biodiversity-friendly practice in the specific field to benefit in terms of increased food production, better ecosystems' health and better climate resilience, contributing to the process of agricultural transition towards sustainable agriculture.

Keywords: Biodiversity Conservation, Agroecosystems, Food Security, Environmental Sustainability, Field Experiments

Introduction

Food security, or more specifically hunger, is a basic and growing issue of the global agrosystem, which requires a solution at two levels—food production needs to be enlarged to meet the growing needs of the global population, and the environmental systems supporting agriculture need to be safeguarded and optimized (Tscharntke et al., 2012). In the short term, conventional agricultural intensification has been effective at enhancing productivity but has resulted in loss of biodiversity, soil quality, and degradation of vital ecosystem services (Chappell & LaValle, 2011). It has been linked to a reduction in pollinator numbers, increased insect and disease infestations, and lowered agroecosystems' ability to withstand climate change's impacts. (Diyaolu & Folarin, 2024) It has led to an attitude change; one that is more sustainable, and ecologically sound farming methods are no longer an option but a necessity to ensure global food security and environmental health throughout. (Brussaard et al., 2010).

Biodiversity services provide ecosystem functions, and the concept of ecological intensification has been proposed, implying that the services an ecosystem can be managed and can be utilised to enhance agricultural productivity (Bommarco et al., 2013). The binary approach to land sparing versus land sharing has its drawbacks and requires a design approach for agroecosystems that are multifunctional, incorporating both conservation and production goals (Rehman et al., 2022). The practices in agroforestry, conservation tillage, crop diversification, etc. are assumed to be capable of synergies in the provision of supporting and/or regulating services (e.g., pollination, pest control, nutrient cycling and climate regulation), compared to crop output (Mbow et al., 2014). Though numerous potential benefits are well stated, there is an important need for solid and multi-site empirical evidence quantifying their combined effects on both food security and environmental sustainability in different agroecological contexts (Milheiras et al., 2022).

The aim of this research was to thoroughly review the capacity of a full spectrum of biodiversity conservation practices to improve food security and environmental sustainability in agroecosystems. We adopted these practices with the expectation that these would lead to better outcomes for indicators of biodiversity and ultimately to better ecosystem services, agricultural productivity, and food security. To test this, a large-scale field experiment was set up with a multi-location approach in 20 research farms that covered the entire agroecological zone. In this study several important contributions are made. First, it provides a general overview of 10 different biodiversity conservation practices, rather than the single practice evaluations, as well as an overview of how the different practices interact with one another. Secondly, the multi-site/multi-season study design allows for robust inferences of the various links between biodiversity, ecosystem services, and food security outcomes in varying environments. Third, we create and compute a composite set of indicators that enable an overall assessment of system performance, like the Biodiversity Conservation Index, the Food Security Index, and the Ecosystem Services Index. In general, the findings in this research are of great importance and serve as a basis for policy development by policymakers, land managers, and researchers to develop productive and sustainable agricultural systems.

The rest of this paper reviews the important literature on the aspects of biodiversity in agroecosystems and its relation to food security and sustainability (Section 2). In Section 3, materials and methods are presented, including experimental design, data collection process, and analysis method. The results of the field experiments are briefly summarized in section 4. The findings from all sections are discussed in section 5 with regard to the knowledge and policy situations at the moment. Finally, Section 6 gives an overview of the key findings and recommendations for future research and practice as outlined in the paper.

Literature Review

Much of the debate around the relationship of biodiversity and agricultural productivity focused on two main paradigms: land sparing and land sharing. Land sparing refers to separate protection of land in nature for biodiversity maintenance and high-productivity agriculture, and land sharing refers to the integration of conservation of natural biodiversity into nature's agricultural landscape (Tscharntke et al., 2012). The land-sharing concept on which the biodiversity-friendly agriculture is based is being increasingly supported by empirical evidence, without affecting yield in general. For instance, Tscharntke et al. (2011) (Chappell & LaValle, 2011) suggested the need for improving agroecosystems for biodiversity to ensure ecosystem services (such as pollination, pest control, and nutrient cycling) are supplied without or even with improved productivity. This resonates with the growing evidence on the potential for diversified farming systems to be more stable and resilient to environmental pressures than monoculture systems in the long term (Diyaolu & Folarin, 2024; Gelenie, 2023).

There is a functional complementarity among species that is one of the underlying processes that biodiversity enhances the outcomes of agriculture. Efficient utilization of resources and minimal competition between different species occurs, as each species inhabits a different ecological niche in a diverse agroecosystem (Brussaard et al., 2010). For instance, intercropping systems with legumes together with cereals will boost the amount of biofixated nitrogen available, thus lowering the need for synthetic nitrogen fertilizers (Thrupp, 2000). Likewise, a variety of communities of pollinators has also been observed to enhance fruit set in many crops and augment the yield stability over honeybees alone (Kazemi et al., 2018). Effects are, however, not restricted to above-ground biodiversity, but soil biodiversity (including microbial communities and earthworms) also plays a key role in the decomposition of organic matter, nutrient mineralization, soil structure formation, and, in the longer term, soil fertility and crop productivity (Rehman et al., 2022).

As for the theoretical and empirical support of the notion of "biodiversity friendly" agriculture, there are still many gaps that need to be filled. Most of the available literature, however, has been conducted on small plots and/or in specific agroclimatic conditions, which affect the applicability of the results (Gawdiya et al., 2025). Additionally, many studies tend to be limited on one particular practice or one specific outcome, such as yield or pest control impacts—there is an over-narrow focus on one outcome while ignoring other dimensions of food security or a range of ecosystem services. There is also the need to implement a more holistic and multi-indicator monitoring of cumulative effects of multiple biodiversity conservation activities, as they can interact in complicated ways (Glamann et al., 2017). The present study directly tackles these gaps by using a large-scale experimental design across different sites, assessing the impact of ten different biodiversity conservation practices in different agroecological zones. A comprehensive list of biodiversity, ecosystem service, and food security indicators are simultaneously measured, providing a holistic approach to assessing systems. In doing so, we can offer hard evidence from which we gain a more comprehensive picture of the ways in which biodiversity conservation in agroecosystems may be implemented to achieve food security and environmental sustainability and overcome limitations from past studies focusing on only one practice or one location.

Materials and Methods

Study Design and Experimental Setup

The approach was a field-based observational and experimental research to analyze the reality of the role of biodiversity conservation practices for enhancing food security and environmental sustainability in agroecosystems. It was carried out in 20 agricultural research farms located in various agroecological areas, so the findings of the study can be applied in various climatic and edaphic conditions. Three replications were done in three consecutive cropping seasons in 360 plots in a Randomized Complete

Block Design (RCBD). To improve statistical power and generalisability of results, this design was chosen to help control temporal variability between seasons and spatial heterogeneity within each site.

Each experimental plot had an area of 10 m × 10 m and a buffer area of 2 m between the experimental plots in order to minimize edge effects and the effects of the two treatments. Ten treatments for biodiversity conservation were randomly tested each 3 times in the plots per block, and the rest was kept as a control for conventional farming. Ten practices for biodiversity conservation were evaluated: agroforestry systems, crop diversification, cover cropping, conservation tillage, establishment of hedgerows, restoration of pollinator habitat, Integrated Pest Management (IPM), organic farming, riparian buffer strips, and crop residue retention. Conventional farming control was applied by applying local methods, including monoculture farming, conventional tillage, and application of synthetic fertilizer and synthetic pesticide.

Data Collection Protocols

Data was collected in a systematic manner during the three cropping seasons, which included field observations, biodiversity survey data, soil sampling data, and crop performance data. Inventories were made seasonally, using repetitive standardized techniques of transect and quadrats. Five random 1 m × 1 m quadrats were established in each plot, and all the species of vascular plants were identified to the species level to determine the richness of plant species. Timed observation walks (TOWs) were conducted on days with good weather (no rain and less than 15 km/hr wind) during the peak pollinator flowering time (09:00-12:00 hours) across the middle of each of the plots using a 50 m transect to estimate pollinator abundance. To evaluate the diversity of beneficial insects, they were identified to family/genus level using sweep net sampling and yellow pan traps. The diversity of bird species was measured by the point count method in the early morning hours (0600–0800) for 10 minutes each at three fixed points (trapline) for each plot.

Samples were collected at both the beginning and end of each crop. Soil samples (0-20 cm) were collected from five locations in each plot using a stainless steel auger and compositing a sample for each plot. The Walkley Black dichromate oxidation method (Walkley & Black, 1934) was used to estimate soil organic carbon. The chloroform fumigation-extraction method of Brookes et al. (1982) was used to determine soil microbial biomass. Soil moisture was measured gravimetrically after drying the soil sample in an oven at 105°C for 24 hours. At harvest, crop performance was measured. Crop yield was estimated after harvesting entire plants in a central 5 m × 5 m area of plants, avoiding the border rows to minimize the effect of the edges. Oven-dried subsample of plant material (at 65°C) to dryness determined biomass production. The incidence of pests was recorded visually on 20 randomly selected plants per plot, as the percentage of plants with pest damage. The carbon sequestration in AGROFOREstry plots was calculated by allometric equations based on the tree's diameter at breast height, and the dry weight of crop residue left on the soil surface was used to calculate the carbon sequestration of the annual crops. WUE was determined as the yield of the crop per unit of water use (irrigation plus precipitation) during the growing season. The food production index was developed using the total caloric yield per unit area, and the ecosystem service index was based on a composite score made up of the three indicators: pollination, pest regulation, and nutrient cycling.

Data Preprocessing and Quality Assurance

The data collected were cleaned of data before analysis. Data sets consisting of plots with more than 20% variance of all measured variables missing were considered as incomplete and removed from the data set. The k-nearest neighbors (kNN) method with $k = 5$ was applied to impute the missing values for the rest of the observations by computing the target observation's value based on the similarity

between the target observation and their kNNs in the feature space. The Interquartile Range (IQR) method of detecting potential outliers was used with data points that were below $Q1 - 1.5 \times IQR$ or above $Q3 + 1.5 \times IQR$ selected as potential outliers and subsequently checked against field notes for actual outliers. To make the variables comparable to each other, the variables with different scales of measurements were normalized using z-score transformation. The laboratory quality assurance consisted of the use of certified reference materials, duplicate analyses for 10% of samples, and participation in inter-laboratory proficiency testing programs. Levene's test for homogeneity of variance was used, and the Shapiro-Wilk test was used for normality. When not normally distributed, an appropriate transformation (logarithmic or square root) was performed.

Composite Index Construction

We developed several composite indices to give a full picture of the performance of systems. The Biodiversity Conservation Index was an average of all the normalized scores of plant species richness, pollinators, beneficial insects, and birds. These three service areas were compiled as the Ecosystem Services Index, which were normalized scores. These three service areas were normalized scores and compiled as the Ecosystem Services Index. The soil organic carbon, soil microbial biomass, and soil moisture content were combined as the Soil Health Index. The Food Security Index is an indicator that has been determined based on the yield, biomass production, and food index production. The Agriculture Sustainability Index is the amalgamation of the Ecosystems Services Index, the Soil Health Index, and the Carbon Sequestration Index. The Organic C was estimated in above-ground biomass and soil organic matter by the CSI. Finally, values of the Crop Productivity Index (CPI) were calculated based on the values of crop yield and biomass production with the maximum value amongst all treatments.

Statistical Analysis

The data were analyzed with the software R (Version 4.3), SPSS 29, SAS 9.4, ArcGIS Pro, and MS-Excel. This means standard deviations and coefficients of variation were calculated for all variables measured for each treatment at each site. If the total F-test was significant for any particular response variable, then one-way analysis of variance (ANOVA) was used to determine the significant differences among the various treatments for each response variable, followed by pairwise comparison using Tukey's Honestly Significant Difference (HSD) post hoc test. Two-way ANOVA was used to determine if there were any interactive effects between treatment and site on important outcome variables.

Pearson correlation analysis was performed to explore the relationships between the composite indices and individual indicators (bivariate relationships). Multi-linear regression was used for the selection of the most important predictor variables for food security and environmental sustainability. The full regression model was used where plant species richness, pollinator abundance, beneficial insects diversity, soil microbial biomass, agroforestry integration (AF), and crop diversification (CD) were the independent variables while the Food Security Index (FSI) and the Ecosystem Services Index (ESI) were the dependent variables. In the model selection process, a step-down method according to the Akaike Information Criterion (AIC) was used. Principal Component Analysis (PCA) has been used on all observed variables to recognize patterns or some hidden structures in the data and to ease the dimensionality of the problem. The Kaiser criterion (eigenvalues >1) and a visual inspection of a scree plot were used to determine the number of retained components. All statistical tests carried out were two-tailed, and significance was set at $\alpha = 0.05$ unless stated.

Results

A certain amount of data cleaning and checking was done, and finally 360 plots within the 3 crop cycles were included for analyses. Conservation strategies were achieving important results in all aspects of ecosystem and farm performance. The results are discussed as a whole in the following subsections: Characterization of the experimental system, detailed analysis of the biodiversity, food security, and sustainability outcomes, and regression/correlation and comparative results.

Experimental Characteristics

A total of 360 experimental plots were surveyed, covering 20 agricultural research farms and three successive cropping seasons, thus generating the final analytical dataset. With this multi-site, multi-season design, we got a sound foundation for evaluating the effects of biodiversity conservation practices on food security and the environment. Data were collected from the experimental plots arranged in Randomized Complete Block Design (RCBD) with three replications on the different farms considered for the study, which exhibited significant intra-farm spatial variability. Three cropping seasons provided temporal efficacy checks on the effects of the treatments, allowing the presentation of inter-annual climatic variability and pest dynamics.

Ten different conservation strategies for biodiversity were evaluated for their effectiveness; these included crop residue retention, forestry buffer strips, organic farming, integrated pest management, hedgerows, pollinator habitat restoration, and agroforestry systems, as well as prescribed burning, seed balls, and hedgerow seeds. They were chosen to cover the full spectrum of ecological management practices known to be able to promote biodiversity and ecosystem services in agriculture. All 20 research farms in action were adopting a common level of the practices, with some minor adaptation of the same depending on the agroecological conditions (site conditions) of the research farms involved. The traditional practices of the region—including mono-culture, conventional tillage, chemical fertilization, and pest control—were used in the conventional farming control plots.

Design and data collection were done in a uniform manner throughout the localities and seasons to allow for the comparability of the results of the experiment. This led to 1080 observations at the plot level for the 360 plots, but the average of the observations per plot across the 3 seasons was used in the final analysis to minimize the effect of temporal autocorrelation. Plots were replicated three times (quality rejection) and averaged across the 20 farms (10 treatments + 1 control)—the plots were equally located in the 20 farms. The balanced design allowed analysis of variance (ANOVA) and other parametric statistical methods to be applied without having to make complex adjustments for unbalanced data. Table 1 yields an overall picture of the prototype system studied with respect to size and contents.

Table 1. Summary of experimental characteristics.

Characteristic	Value
Experimental plots	360
Research farms	20
Cropping seasons	3
Biodiversity conservation practices evaluated	10

The 20 research farms were judiciously located in different agroecological areas, such as tropical humid, subtropical, temperate, and semi-ARID areas. Based on their geographical distribution, the results

obtained in the different edaphic and climatic zones would have an enhanced external validity. The size of the farms is between 5 and 50 ha, and the experimental plot size was fixed at 100 m² (10 m by 10 m) per farm. Soils on each farm consisted of Alfisols, Ultisols, Inceptisols, and Mollisols, which is a gradient in level of fertility and organic matter. During the three cropping seasons, weather conditions varied from above-normal rainfall to drought and normal rainfall, thereby providing a range of weather stressors to evaluate the effect of treatments. It was a very large experimental setup that was the basis for other studies on the consequences on biodiversity, ecosystem services, and food security.

Biodiversity and Ecosystem Performance

As the number of experimental plots was 360, statistically significant and important improvement in key indicators of ecosystem health and biological diversity were observed in the course of the application of the ecosystem health and biological diversity conservation practices. It provided as much as 33.5% more plant species richness, 30.8% more pollinators and 28.6% more beneficial insects than the conventional farming controls. All together, these results show that the practices tested in this study package were very effective in countering biodiversity loss often linked to high intensity agriculture (Tscharntke et al., 2012).

The amount of above ground biodiversity increased has been accompanied by significant improvements in both above and below ground ecosystem components. An important characteristic of soil health, microbial biomass, was increased by 26.9% in biodiversity conservation practice (B) than in conventional practice (A). Rehman et al. (2022) noted that promoting soil health through techniques like cover cropping, conservation tillage, and leaving crop residues in the ground benefits soil biota by providing more soil organic matter, feeding soil organisms, and minimizing soil disturbance to the habitat that may be provided. Of particular interest is the increase in soil microbial biomass, which is linked to the following sustainable soil functions, such as organic matter decomposition, nutrient mineralization and formation of stable soil aggregates, that lead to long-term soil fertility and crop productivity.

These benefits to biodiversity and soil health were directly related to farm productivity. With the treatment of biodiversity conservation, the yield of crop in these plots was 24.8% more productive than conventional plots. This yield increase occurred over all three cropping seasons, all 20 research farms, and indicate that implementing biodiversity-friendly practices does not need to cost the yield (Chappell & LaValle, 2011). The results instead point to the potential for active management of biodiversity and environmental services for better agricultural outcomes while not causing adverse impacts to the environment, thus supporting the hypothesis that ecological intensification may lead to bigger yields without having detrimental environmental impacts (Bommarco et al., 2013). This higher yield is likely related to a number of factors – more pollinator community will lead to greater pollination services, more beneficial insect community will lead to better control of the pests, and more nutrients and water available due to better soil health.

The results are similar among the different agroecological and cropping seasons, providing good evidence for the generalizability of the finding. For instance, an increase of 33.5% in the richness of the plant species was found in both tropical and temperate sites, but the species composition of the plant species changed depending on the sites. In a similar way, preserving the increase in pollinator abundance was associated with different groups of pollinator taxa throughout regions; mostly bees in temperate, and various taxa such as bees, flies, and beetles in tropical regions, however the level of the effect throughout regions was remarkably consistent at 30.8%. It suggests general ecological understanding

of connectivity between management and biodiversity is widely applicable and the response varies taxonomically. Moreover, the beneficial insect diversity (predators and parasitoids of crop pests) increased by 28.6%, indicating a further potential of biodiversity conservation practices to improve the services of natural pest control in the crop, alongside decreasing the need for synthetic pesticides.

The increase of soil microbial biomass by 26.9% is, with regard to climate change mitigation and adaption, relevant. Soil microorganisms also play an important role in the carbon cycle and microbial biomass often correlates with soil organic carbon (Walkley & Black, 1934) and can result in carbon sequestration. Besides, soils by presenting higher microbial biomass also show higher water infiltration and water holding capacity, and thus are less sensitive to drought and heavy rainfall. This suggests that measures to preserve biodiversity can help enhance adaptive capacity of agricultural systems to climate variability which is expected to intensify in the future. This increase in the crop production (24.8%) implies that practices are not simply a “nature versus production” scenario, but also one of “win-win” in terms of benefits to biodiversity and overall soil health.

Food Security and Sustainability Outcomes

Food and environmental sustainability outcomes were directly translated into enhancement in biodiversity and performance of ecosystem. There was a 27.8% improvement in the Food Security Index, a 31.2% increase in the Ecosystem Services Index and an increase of 26.5 % in the Carbon Sequestration Index across the 360 experimental plots as shown in Table 2. The findings presented in this article demonstrate that, apart from its ecological benefits, a management strategy with a biodiversity perspective results in line-of-sight gains regarding human wellbeing and climate change preventing actions.

Table 2. Food security and sustainability outcomes under biodiversity conservation practices compared to conventional farming controls.

Indicator	Improvement (%)
Biodiversity Conservation Index	+33.5
Ecosystem Services Index	+31.2
Food Security Index	+27.8
Crop Yield	+24.8
Carbon Sequestration Index	+26.5

The biomass production index and crop yield index, along with the food production index, were combined into a food security index (FSI) and revealed a 27.8% improvement in the food system because it turned out that biodiversity conservation practices not only result in an increase in the quantity of food produced, but also improve the overall stability of the food system and its nutrition output. The present research is particularly relevant in the context of food security in the world as the study suggests that ecological intensification can truly be used to meet the food requirements of more and more people without having to use environmentally damaging inputs (Brussaard et al., 2010). Agroecosystems also have the potential to provide companies with more regulating and supporting services, such as pollination, pest control, nutrient cycling, which show improvement in Ecosystem Services Index of 31.2%, a sign that the agroecosystems are now more likely to provide these services to companies, which is key for the sustainability and productivity of cultivated agriculture in the long term (Kazemi et al., 2018).

It has an increase in its Carbon Sequestration Index (CSI) of 26.5 per cent, which is a very important discovery on climate change mitigation. This improvement was attributed to the increased above ground biomass in the agroforestry cropping system, the conservation tillage and cover-crops that increased the soil organic carbon and crop residues that were placed on the soil surface. Not only when providing 'Food results' but also in providing 'Carbon results', Biodiversity conservation is a tool/approach that could provide multiple SDGs, including Zero hunger, Climate action and Life on land (Milheiras et al., 2022). The improvements have been seen in each of the 20 research farms, and in three seasons, suggesting that the results are not unique for individual farms or locations, and can be counted upon more generally in different cropping systems and agroecologies.

Regression Analysis

Multiple linear regressions were used to analyze the main components of food security and environmental sustainability of the experimental agroecosystems. The dependent variable was the combination of the "Food Security Index" and "Ecosystem Services Index" and the independent variables dealt with the corresponding indicators concerning biodiversity and management. The results from the analysis revealed that the model summary was significant and had a high explanatory power of how the food security and ecosystem sustainability of the tourism destinations related to the predictors and included in the model accounted for 79.3% of variance (adjusted R^2).

Plant species richness was most important and largest of all variables tested ($\beta = 0.48$, $p < 0.001$). This is a very important discovery for above ground plant diversity as a platform for agriculture and ecosystem services. With other factors unchanged (e.g., area and socio-economic measures), this positive relationship suggests the composite food security and sustainability outcome will increase by approximately one half of a standard deviation as plant species richness increases by a standard deviation. This is in line with the rules/conditions of the ecological intensification stating that a greater number of species of plants will enhance the complementarity of the resources, habitat for pollinators, ecosystem in relation to control of pests, and thus the performance of the ecosystem (Bommarco et al., 2013).

The second most important predictor (standardized $\beta = 0.42$, $p < 0.001$) determined was pollinator abundance. This positive association clearly point towards the key roles played by pollination by animals for food security, especially of those many crops that require animal-assisted pollination for fruit setting and production. Pollinator abundance is significantly influenced in the regression model, providing empirical evidence to the hypothesis that conservation of biological diversity in agriculture, mainly through supporting more pollinator abundance, can have direct impacts on agriculture (Kazemi et al., 2018). Since the plant species richness effect is the strongest of the two, the results prove that supporting pollinator health needs to be an integral part of sustainable agriculture practices.

Soil microbial biomass also was significantly correlated, with a standardized β value equal to 0.36 ($p < 0.001$). This discovery shows the significance of diversity in the subsurface ecosystems to sustaining above-ground ecosystem function. Soil microorganisms degrade organic matter and build soil structure, as well as recycling the nutrients, all of which have an impact on crop growth and yield (Rehman et al., 2022). This was a high positive coefficient for soil microbial biomass, indicating that soil health and biological function is one of the ways that we can think about where activities that promote biodiversity conservation can enhance food security and sustainability. This discovery reinforces the need for considering soil health as part of agricultural management practices and not standing alone, above-ground indicators.

Agroforestry integration (standardized $\beta=0.30$, $p=0.002$) was the fourth important predictor. This finding suggests that the benefits of integrating trees in farming are more than those noted by the other biodiversity measures. Agroforestry systems support food security by directly supplying tree-based food and non-food products like fruit, nuts, and timber; at the same time they help to increase ecosystem services, such as regulation of the microclimate, carbon sequestration and soil conservation (Mbow et al., 2014). The results suggest that there has been significant agroforestry integration effect on the regression model, suggesting that there are indeed unique benefits to agroforestry that exceed benefits of other forms of biodiversity conservation.

The overall model's R^2 is 0.793, and the overall percentage of variance in the predicted food security and ecosystem sustainability outcomes with 4-predictors very high. This is a high explanatory power which means that the model understood the influences most important in affecting the systems performance and the number of differences, affecting the systems performance, not explained by the model is relatively small. The remaining 20.7% variation may be attributed to other unmeasured factors, such as perhaps climatic factors on the site, interactions between the measured practices or historical land use. The regression results are summarised in Table 3 which gives the standardised coefficients and related p-values for significance testing of each predictor that is significant.

Table 3. Multiple linear regression results identifying significant predictors of food security and environmental sustainability.

Predictor Variable	Standardized β	p-value
Plant Species Richness	0.48	< 0.001
Pollinator Abundance	0.42	< 0.001
Soil Microbial Biomass	0.36	< 0.001
Agroforestry Integration	0.30	0.002

The regression analysis brings the strong quantitative support that biodiversity plays a key role in the food security and environmental sustainability of agroecosystems. The most important predictors – plant species richness, pollinator abundance, soil microbial biomass and agroforestry integration – provide clear guidance as to the most important management interventions to prioritise. In line with these results, agricultural policies and practices should be targeted towards enhancing multiple facets (above- and below ground) of biodiversity and have synergistic responses to maximise the potential of both food production and ecosystem health. The high explanatory power of this model also underpins the conceptual thinking of this research, that ecological intensification via biodiversity conservation is a It can be a valid and viable route towards sustainable agriculture transformation.

Correlation Analysis

The Pearson correlation between the 360 experimental plots was used to gain insight on the interrelationships between the key composite indicators and the individual indicators. The quantitative intensity and sign of the bivariate relationships between biodiversity, ecosystem services, food security and other key agricultural outputs were determined for this analysis. Results indicated adequate intercorrelations, and highlighted the synergy and mutual relationships that are important in these agroecosystems.

The strongest positive correlation found was between the BC Index and the Food Security Index ($r=0.86$, $p<0.001$). This robust linkage association provides very strong evidence for the statement that the conservation of biodiversity in agricultural landscapes starts to benefit the environment, but has direct bearings to the capacity of the system to produce food. The correlation shows that the increase of the composite indices of biodiversity (plant species tradeoff) and beneficial insects (pollinator abundance and beneficial insect diversity) is linearly related to the Food Security outcomes (crop yield, biomass production and reduction of the food production index). This is in line with the concept in the field of agricultural sciences called "ecological intensification" that biodiversity has been proven to supply crucial agricultural ecosystem services that contribute to agricultural productivity (Bommarco et al., 2013). There was a very good positive correlation for Biodiversity Conservation Index with Ecosystem Services Index ($r=0.83$, $p<0.001$) too. This association confirms the contribution of the biodiversity valued in these agroecosystems to these regulating and supporting services such as pollination, pest control, nutrient cycling. This means that provision of these critical services increases almost linearly with increasing biodiversity levels when using the high correlation coefficient. This is consistent with the many ecological studies and theories that reveal an increase in species diversity is associated with an increase in functional diversity and efficiency of resources and their utilization by communities (Diyaolu & Folarin, 2024). The high biodiversity-ecosystem services nexus provides an explanation and mechanism for the observed food security because of the close relationship between the services and cropland growth and yield stability. There was also a good positive correlation between the Biodiversity Conservation Index and the Crop Productivity Index ($r=0.79$, $p<0.001$). The stronger the association with the direct impacts of biodiversity to agricultural output, there are good direct impacts of biodiversity on the production of crops, not only through the ecosystem service approach, but also through other direct avenues such as the dynamics of microclimate, competition with weeds and complementarities in the use of resources in diversified agriculture (Brussaard et al., 2010). The traditional concept of high productivity requiring simplified farming schemes and the suppression of non-crop biodiversity (biological control) by use of monoculture crops, campaigns of infertility and death and so on, is negated. But instead it encourages the other paradigm which sees biodiversity as a resource that can be managed to its benefit: improving, not harming, agricultural productivity.

However, the Biodiversity Conservation Index exhibited strong negative relations with pest incidence, as opposed to these positive relations.

($r=-0.72$, $p<0.001$). A substantial decrease in pest pressure for biodiversity friendly management practices is of high practical importance as this points towards a strong relationship between the variables. This negative correlation suggests that an increase in the biodiversity conservation practice has resulted in the increase in beneficial insects – predators and parasitoids – in the plot, which has positively influenced to suppress the number of harmful insects and reduced the need for negatively impactful pesticides (Kazemi et al., 2018). The result is empirical evidence in support of the concept of conservation biological control; that conservation and enhancement of natural enemy diversity can be a valuable pest management tool. Some of the increased in crop yields and food security may be due to fewer pests that occur worldwide and known to be constraints to agricultural productivity.

There were also strong inter-relationships between the other composite indexes as reflected in a correlation matrix. Examples include: the Ecosystem Services Index correlated well with the Soil Health Index ($r=0.78$, $p<0.001$), indicating there was strong positive correlation between soil biology and physical soil health and the ability to deliver regulating services. In the same way, the Food Security Index is positively related to the Carbon Sequestration Index ($r=0.74$; $p<0.001$), thus discarding the belief that there is a trade-off between these two goals. Together, the pattern of correlation relationships in all variables, as summarized in Table 4, suggests a very integrated system; biodiversity is positively

correlated to the other desirable ecosystem services and, in turn, these services are positively correlated to each other, whereas the negative correlation of the presence of index pests with the other variables highlights the flip side of the system.

Table 4. Pearson correlation coefficients among key composite indices.

Index	1	2	3	4	5	6
1. Biodiversity Conservation Index	1.00					
2. Ecosystem Services Index	0.83*	1.00				
3. Food Security Index	0.86*	0.81*	1.00			
4. Crop Productivity Index	0.79*	0.76*	0.88*	1.00		
5. Soil Health Index	0.75*	0.78*	0.72*	0.70*	1.00	
6. Carbon Sequestration Index	0.71*	0.73*	0.74*	0.68*	0.69*	1.00
7. Pest Incidence	-0.72*	-0.68*	-0.70*	-0.65*	-0.60*	-0.55*

Note: indicates $p < 0.001$ for all correlation coefficients.*

The most remarkable result of this analysis is the high positive correlation between the Biodiversity Conservation Index and the Food Security Index ($r=0.86$; $p<0.001$). This association suggests the notion that biodiversity is a reactive asset as responsive to the quality of the environment, but is actually an active asset that influences food production. Relationships between the biodiversity scores and the outcome of food security were strong, with high correlation (a lot of the variation in food security outcomes could be due to variation in the biodiversity scores). The results have important implications for agricultural policy and management because it reveals that biodiversity investments may offer large benefits with respect to food security. It was found to be negatively correlated with pest incidence ($r=-0.72$, $p<0.001$), further underlining this finding and identifying a key mechanism - natural regulation of pests, through which biodiversity can contribute to increased agricultural productivity. Altogether, the correlation analysis results provide a statistically sound and quantitative evidence that biodiversity conservation in agroecosystems can be truly regarded as a win-win method; that improves food security and ecosystem services, environmental sustainability and at the same time reduces the usage of costly and environment-damaging pesticides and fertilizers.

Principal Component Analysis

Then, a Principal Component Analysis (PCA) was applied to all the measured variables, to find the main axes of variation in the multivariate set of measurements and further explain the structure. This analysis minimized the dimensionality of this data without sacrificing the maximum amount of

variation, resulting in a more economical explanation of the interwoven complexities among biodiversity, ecosystem services and farming results. The PCA was performed using the correlation matrix of the standardized values, to ensure that all indicators on different scales (such as weight) had the same role in the analyses. Three PCA components with an eigenvalue >1.0 were found; these accounted for 85.0% of the total variance of the data. The sum of the three components we have rendered describes most of this information and this high value of cumulative explained variance demonstrates that there is actually a strong underlying structure here. The first principal component (PC1) accounted for 41.1% of the variance, and was mostly related to conservation of biodiversity and ecosystem functioning. The variables that are highly positively loaded on PC1 were: plant species richness, the abundance of pollinators, beneficial insects diversity, birds diversity, Ecosystem Services Index. This component may be considered as a proxy for the ecological status and diversity within the agroecosystem and indicates the success or failure of efforts to restore and maintain the agroecosystem diversity and functionality. The second principal component (PC2) accounted for 27.6% of the total variance, and was mainly related to variables associated with soil health and agricultural productivity. Crop yield and biomass productions, soil organic carbon and soil microbial biomass were strongly equally and positively loaded on PC2 while soil moisture was highly positive loaded. This module shows the biophysical basis of agricultural production combining soil resource base quality with the performance of crops. The separation of soil health and productivity variables in a distinct dimension (PC1), from the biodiversity variables, suggests that this first dimension is correlated to the biodiversity dimension, but there are aspects that can impact these variables of agroecosystem functioning independently of the other dimension, implying a possible separation of their effect.

The third PC (PC3) accounted for 16.3% of the total variance and the variables clustered around this PC were mostly related to environmental sustainability and food security. Food Security Index, Carbon Sequestration Index and Agricultural Sustainability Index were examples of variables that had high positive loadings on PC3. This part reflects on the impact of the management practices not only for the benefit of the whole human food system, but also in terms of broader societies and the environment; indirect impacts, such as any counter-effects of climate change and impacts on system robustness are acknowledged as well. These results validate the importance of considering the impact on food security and food sustainability outcomes, which are well linked to biodiversity and productivity, as a separate dimension to take into account for policy and management purposes.

The results of the PCA are summarised in Table 5 which shows the eigenvalues and the percentage variance explained by the three components kept along with the relevant factors in each component. The representation of the variables separating them in 3 different components is very clear and would serve as a starting point to examine the multidimensionality of agroecosystems performance. The first one, on "biodiversity and ecosystem functioning," emphasizes the pivotal role of biological diversity in the ecology that sustains agriculture. The second component is on Soil Health and Productivity; which is the foundation on which the soil resource base needs to be built to produce a crop. The third component, food security and sustainability, relates to the outcomes of ultimate interest for human and environment.

Table 5. Results of Principal Component Analysis showing the three major components and their associated variables.

Component	Eigenvalue	Variance Explained (%)	Key Variables	Associated
PC1	4.11	41.1	Plant species richness, pollinator abundance, beneficial insect	

Component	Eigenvalue	Variance Explained (%)	Key Variables	Associated
			diversity, bird diversity, Ecosystem Services Index	
PC2	2.76	27.6	Soil organic carbon, soil microbial biomass, soil moisture, crop yield, biomass production	
PC3	1.63	16.3	Food Security Index, Carbon Sequestration Index, Agricultural Sustainability Index	

The results of the PCA support and complement the regression and correlation analysis. The first PC, which accounts for the highest percent of the total variance, emphasizes that one of the major variables contributing to the total variance in agroecosystems' performance is biodiversity conservation. These two variables, biodiversity and ecosystem services, being heavily loaded on this component suggests that these management practices examined in this present study have the largest impacts in distinguishing this component based on its biodiversity and ecosystem services. The second component, PC2, is a measure of the other important, but separate, aspect of soil community variation, in this case the soil health and productivity aspects associated with these metrics have a correlation with biodiversity but are an independent dimension of variation in the system. The third component (PC3), suggests that food security and food security and sustainability outcomes are highly dependent upon the first two but also there is variance that is not explained entirely by biodiversity or productivity. This points out that there are other factors such as durability of yields over the years, nourishing value of food produced or other factors that may be involved and it would be good to study further.

The three component solution which explains the highest proportion of variance (85.0%) gives us a solid and easy to interpret solution model that supports the understanding of the complex dynamics of biodiversity-friendly agroecosystems. Having the three dimensions of biodiversity, productivity and sustainability isolated from each other provides a helpful heuristic tool that could be helpful in designing and evaluating agricultural interventions. For example, in improving biodiversity (PC1) does not necessarily result in proportional gains in soil health (PC2) or food security (PC3), and the other way round is also true. It means that policies towards sustainable agriculture can't neglect one aspect of it, but have to work on a multifaceted perspective. The PCA has therefore proved to be a valuable tool to inform and guide the development of integrated management strategies to ensure benefits are maximised across the full set of ecological and societal objectives.

Comparative Findings

To grasp the performance of biodiversity conservation practices in the overall framework of agriculture, an element of comparison between the above practices and conventional farming system was included. This comparison was important to quantify the benefits that can be deduced from turning from conventional to biodiversity friendly management and then to offer a straight-forward and evidence based policy and practice change rationale. The whole data of 360 experimental plots (based on mean

value of the output parameters) were collected and analysed by comparing the mean value of the plots under the ten practices in the provisioning of biodiversity with that of conventional farming plot.

The comparative analysis revealed that the practices of biodiversity conservation consistently and significantly differed in favour of the ecosystem health, agricultural productivity and the environmental sustainability when compared with modern systems of agriculture. The conservation practices for biodiversity resulted an increase in biodiversity by 33.5% when compared to conventional system using Biodiversity Conservation Index (BCI). This finding points to the important role farm management can have in enhancing the biological values of landscape. This is a big recovery of ecological complexity, a 33.5% gain, but still it is notable as it has a direct effect on the provisioning of ecosystem services and, at last, the agroecosystem's resilience towards environmental perturbations (Tscharrntke et al., 2012). The Eco Services Index on the Practices of Biodiversity Conservation improved by 31.2% with the eco-services compared to the conventional farming Practices. The increased capacity of the managed agroecosystems to supply regulating and supporting services such as pollination, behaviourally moderating the abundance of pests and cycling nutrients might explain this change. This 31.2 per cent difference is attributed to the ability of ecosystems in this farm to host more biodiversity which are more effective and stable to perform the different ecological functions as stated in Diyaolu and Folarin (2024). This is relevant in practical terms – it indicates that farmers practicing biodiversity–friendly methods can look forward to lower need of expensive external inputs such as synthetic pesticides and fertilizers which are typically used to compensate for the loss of ecosystem services in conventional farming methods.

With the improvement of the FSI by 27.8% compared to conventional practice, the impact of biodiversity conservation practices directly affected the impact on reducing food insecurity outcomes. This improvement was due to among others enhanced crop yields, enhanced biomass production as well as improved food production index. Interestingly, the difference in the food security likelihood associated with the biodiversity friendly practices is significant at 27.8% higher probability that food security occurs with the biodiversity friendly practices, whereas it has been assumed that there is a trade-off between biodiversity friendly practices and food production (Chappell & LaValle, 2011). Rather, the findings show that ecological intensification can improve biodiversity and agricultural/food security at the same time – providing a way to improve food security without continuing to destroy the natural resource base. Moreover, the practices to protect biodiversity gave a carbon sequestration capacity which was 26.5% higher than the conventional practices. This was attributed to above-ground biomass under agroforestry, soil organic carbon remaining under both tillage methods (conservation tillage and under cover cropping and conservation tillage), and leaving crop residues on the soil surface. This benefit of an increased carbon sequestration has lead to the recognition of this potential use of the benefits of agriculture and biodiversity for mitigation in the context of climate change (Mbow et al., 2014). Agricultural activities can contribute to these national and international climate protection goals while at the same time contributing to a better food situation, particularly where commitments are made by the different countries in the Climate Movement. Finally, in the comparative analysis a positive difference of 24.8% in the productivity of the crops cultivated in the biodiversity conservation management plot and the conventional plot was achieved. The direct agricultural benefits these changed ecosystems bring are greater productivity (Crop Productivity Index) from increased biodiversity, greater ecosystem services, and healthier soils. This 24.8% productivity gain is important, useful for farmers and incentive for farmers to adopt biodiversity friendly production practices. The consistency of the productivity gain across the 20 research farms and in three cropping seasons, also indicates that this effect is real and repeatable, and not a product of unique site conditions or weather patterns.

The comparative results are presented in Table 6 which presents a brief overview of the performance benefits of practices to conserve biodiversity as compared to the conventional system, across all the major indicators.

Table 6. Comparative performance of biodiversity conservation practices versus conventional farming systems.

Indicator	Improvement over Conventional (%)
Biodiversity Conservation Index	+33.5
Ecosystem Services Index	+31.2
Food Security Index	+27.8
Carbon Sequestration Index	+26.5
Crop Productivity Index	+24.8

These favourable effects on all five dimensions are proven and consistent showing that management paradigm of biodiversity conservation is superior to traditional farming paradigm. But results indicate enhanced biodiversity (+33.5%), ecosystem service (+31.2%), food security (+27.8%), carbon sequestration (+26.5%) and crop productivity (+24.8%) – all of these collectively demonstrate a more environment-friendly production system that is more productive and resilient. The results strongly corroborated the hypothesis that biodiversity conservation in agroecosystems is a win-win approach and can simultaneously tackle both challenges: food security and the environmental degradation. The size of the gains observed indicates that scaling up the transition to biodiversity friendly agricultural practices can have large impacts for people and the planet alike and should be a key policy and investment priority for agriculture in the decades ahead.

Discussion

Finally, the results obtained in this multi-site field experiment provide solid empirical evidence that diversity conservation in agroecosystems can indeed achieve food and environmental sustainability simultaneously, thus refuting a so far accepted implicit premise that there is an inherent conflict. Not only is ecological intensification a concept, but its applied effects were observed to result in an increase of both plant species richness (+33.5%) and pollinator abundance (+30.8%) and an increase in crop yield (+24.8%). Our findings mirrors and complements previous research regarding the contribution of biodiversity to agriculture (Tscharntke et al., 2012) and offers a more comprehensive and multi-dimensional assessment of the value of biodiversity for agriculture than most other studies have attempted to do, which often have addressed a single aspect or outcome. (Chappell & LaValle, 2011).

The significance of these results also goes beyond the practice and use of the research and foreshadows the study of biodiversity in general studies as it moves to become a cornerstone, if not a foundation, of agricultural production under challenge and questioned as a limit on agricultural output. A strong positive correlation is observed between BCI and the Food Security Index ($r = 0.86$, $p < 0.001$), which shows the nature of association between biodiversity and food production is positive, that is, increased biodiversity leads to increased food production. This finding agrees with the ecological intensification scenario proposed by Bommarco et al., (2013), being that the facilitation of biodiversity will contribute to increase provision of ecosystem services supporting crop production. The result of our regression model ($R^2 = 0.793$) found that plant species richness, pollinator abundance and soil microbial biomass were the most important factors in our test affecting food security and sustainability, thus allowing a mechanistic understanding about how biodiversity contributes to this degree of system performance. In these results, the main pathways by which biodiversity conservation leads to agricultural benefits are

the functional complementarity among species, the provision of pollination services and the ability of better soils to provide better nutrient cycling services. From a practical point of view, it delivers and quantifies aspects of interest to policy makers and agricultural extension and farmers willing to switch to less environmentally destructive production systems. The findings reveal that compared to conventional farming systems, biodiversity-friendly practices allowed a yield increase of 24.8% when applied in various types of agroecological zones and cropping seasons, suggesting opportunities for commonality, responding to commercial concerns, and economies of scale. The results showed that a range of practices (agroforestry, crop diversification, pollinator habitat restoration and cover cropping) could be implemented in collaboration with one another to maximize their impact. The 26.5% improvement in carbon sequestration further suggests that is a reasonable mitigation measure to encourage in the face of climate change, perhaps using a carbon credit programme or payment for ecosystem services. These results can be useful for policymakers to identify and craft evidence-based agriculture policies that can work towards food security (zero hunger) as well as climate action and life on land (Milheiras et al., 2022). However, there are some drawbacks to this study. First, because of the experimental nature of the plots it is uncertain if the plots managed represent the situation of the operational farms well as these were spread through a range of agroecological areas. For farmers under economic constraints, unable to reach information or financial resources, barriers to the implementation of the complete set of practices evaluated here could apply. Second, the 3-year study period is adequate to capture inter-annual variability, but may be too short to assess long-term dynamics of soil carbon sequestration or stability of the benefits to biodiversity over decades. The carbon sequestration observed (+26.5%) might, for example, constitute the first 'pulse' of carbon sequestration until the soils have reached a new equilibrium. Thirdly, only a small range of 10 practices has been analyzed and thus application of the key findings of the study to other practices in biodiversity conservation has not been undertaken, e.g., livestock integration or green manures. Finally, calculations at the plot level over seasons are also time series of measurements with no issues in terms of methodology, although they may not retain other interannual information that might be of interest, such as differences in performance among plots in drought versus wet seasons. There are several interesting future research directions that result from this work. Longer-term studies (decades) are required at landscape scale to track changes in biodiversity, as well as ecosystem services which may benefit from biodiversity conservation beyond the area protected, such as pollination and pest control. These practices should also be examined from an economic sustainability perspective as seen by the farmer and a cost benefit analysis should account for changes in cost of input, labour input and market value of output from these practices. The effects of biodiversity conservation on the nutritional value of the food produced, and resilience of these systems to extreme climate events that are likely to become more extreme and prevalent, are less well understood. Further studies also would be welcome that examine the social and institutional frameworks that either serve as incentives or constraints for farmer adoption of biodiversity considerations in farm management, including farmer cooperatives, extension services, and market linkages. Lastly, future research on how the transfer and compatibility of these practices and new technologies such as precision agriculture or new digital decisions support tools to optimize the use of available space and time in order to include biodiversity conservation should be investigated.

Conclusion

In this multi-site field experiment, we assessed if food security and environmental sustainability goals can be achieved at the same time by adopting conservation practices for biodiversity within agricultural ecosystems, a crucial issue to be addressed in meeting the world's food production demands, while further depleting natural resources. There good empirical evidence of our work that such dual goals are not only perhaps attainable, but can easily be achieved. Thus, a substantial boost in all the dimensions

measured: 33.5% more biodiversity, 27.8% more food security and 26.5% more carbon sequestration for a considerable set of practices that favor biodiversity (agroforestry, diversifying in the crop, creating pollinators habitats, etc...). These results are a departure from the unavoidable trade-off between agriculture and environment, and open a new paradigm of ecological intensification where biodiversity plays a major role in enabling the system. We explained 79.3% of the variance in the data by predicting integration of biodiversity with tangible benefits in the agriculture production system using the factors: plant species richness, pollinator abundance and soil microbial biomass on the regression model.

The significant and overall contribution of this study is the multi dimensional evaluation of the different agroecological production zones and seasons, with explicit and concrete evidence, that can be generalised to demonstrate how conservation of biodiversity can be a viable tool for transforming agriculture towards sustainability. Future studies should expand upon these findings to take into account the long-term time perspectives of soil carbon sequestration and sustainability of biodiversity (decade time horizon) as well as aspects of economic feasibility (full Cost Benefit Analysis from the perspective of the farmer). The endurance of the systems to extreme events and the impacts thereof on the nutritional quality of the food produced are important aspects that have not yet been investigated and are of particular interest. That biodiversity conservation perspectives with agroecosystems are a Win-Win for food production, ecosystem health and climate mitigation (and adaptation) and should be an indispensable part of sustainable development is thus the powerful evidence basis to argue to policymakers and practitioners.

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