

EXAMINING THE EFFECTIVENESS OF CROP ROTATION AND SOIL FERTILITY MANAGEMENT TECHNIQUES IN SMALLHOLDER FARMING SYSTEMS

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Abstract

Soil fertility decline remains a major constraint to agricultural productivity and sustainability in smallholder farming systems across sub-Saharan Africa. This study evaluated the effects of crop rotation combined with integrated soil fertility management on soil health, nutrient dynamics, and crop productivity in the Mount Bamboutos ecosystem of Cameroon. A mixed-methods experimental approach was employed, integrating multi-season field experiments with participatory qualitative assessments. Quantitative results showed significant increases in soil organic carbon, total nitrogen, and available phosphorus under cereal-legume rotation systems compared to baseline management practices. Crop yields and nutrient-use efficiency improved consistently across experimental plots, demonstrating enhanced productivity and yield stability under integrated nutrient inputs. Graphical analyses further revealed strong relationships between soil fertility indicators and crop performance, highlighting the role of organic matter accumulation and nutrient cycling in system resilience. Seasonal trends confirmed cumulative soil fertility gains and reduced spatial variability under agroecological management. Qualitative findings corroborated these results, with farmers reporting improved soil structure, moisture retention, and reduced vulnerability to climatic stress. Overall, the study confirms that agroecological crop rotation combined with integrated nutrient management significantly improves soil fertility, productivity, and resilience, offering a sustainable and scalable solution for smallholder agriculture in nutrient-depleted and climate-sensitive environments.

Article History

Received:
August 26, 2025

Revised:
September 29, 2025

Accepted:
October 24, 2025

Available Online:
December 31, 2025

Keywords: Agroecological Intensification, Crop Rotation, Integrated Soil Fertility Management, Soil Organic Carbon, Smallholder Farming Systems, Sustainable Agriculture

INTRODUCTION

The predicament of the smallholder farmers in places such as the Mount Bamboutos ecosystem in Cameroon is so huge because the soils have reduced fertility hence reducing the agricultural production and degradation of the habitat destruction (Nkembu et al., 2023). To mitigate the condition in such unstable systems, the sustainable soil management practices of crop rotation are demanded to help in ameliorating the soil health to ensure the long-term sustainability of agriculture (Bienvenu et al., 2023, p. 186; Naazie et al., 2023, p. 10). This type of practice that includes the use of fertilizer and manure is necessary to ensure that millions of smallholder farmers become less reliant on inorganic inputs and develop agriculture in a sustainable and sufficient manner (Malik et al., 2024; Nishi and Subramanian, 2023, p. 122). To fully use the available natural resources and raise the amount of agricultural production, crop rotation as a traditional but amazingly effective approach that is premised on the alternation of different combinations of crops in the next rotation is used (Bienvenu et al., 2023, p. 181). It is the method that in addition to disrupting the life cycles of pests and diseases, will play a significant role in making sure that the soil is fertile because it promotes the loss of nutrients (Mwatawala & Burian, 2024, p. 89). Along with these benefits, crop rotation plays a significant role in enhancing the percentage of soil organic matters and soil structure, which is critical in water absorption/retention and is needed specifically in semi-arid areas (Bienvenu et al., 2023, p. 186). In addition, the logical role of the legumes in the crop rotation cycle facilitates the development of a more nutritious nutrient balance in the soil and reduces the quantity of synthetic nitrogen fertilisers since the process triggers the fixation procedure of nitrogen (Akanmu et al., 2023, p. 8). It is also possible to develop the synergy between organic and inorganic

fertilizers owing to the techniques of crop residues mulching, intercropping of cereals and legumes, and the application of farmyard manure, which have already been proven to be sustainable, economical, and environmental-friendly because there are other benefits associated with the use of organic and inorganic fertilizers, including the higher fertility of soils in smallholder farming (Parwada et al., 2023, p. 2). It is an amalgamation of the measures that facilitate agro-ecological intensification that is critical in climate change response and sustainability of agricultural production under low-resource environment (Naazie et al., 2023, p. 11). The issue of food and nutrition insecurity remains an issue in West and Central Africa, despite the richness of the natural resources and agricultural production as over 70 percent of the citizens have made farming their lives (Kaushal et al., 2025, p. 1). This reliance typically leads to the poor agricultural productivity and gradual decline in agricultural output along with the low and erratic rainfall, conventional farming methods, poor use of nutrients and poor use of inputs (Haufiku et al., 2025, p. 2; Parwada and Chinyama, 2021, p. 2). Farmers are embracing such agro ecological practices as crop rotation, intercropping and organic fertilization in order to fight these ills. The methods enhance the fertility of the soil and the ability to endure extreme weather conditions (Dagunga et al., 2023, p. 10). With the help of the least amount of available resources, reducing the need in the use of artificial fertilizers, such practices increase the activity of plants, and organic carbon in the soil increases (Elouattassi et al., 2023, p. 58; Naazie et al., 2023, p. 4). That is why in order to obtain the resilience of farming systems (particularly in the areas, where the lack of nutrients is observed and unreliable rain affects the fields), the agroecological soil management (which encompasses the specified methods) is required

(Boutagayout et al., 2025; Naazie et al., 2023, p. 2; Yeboah et al., 2021, p. 11). Correct soil fertility management policy, including the use of organic fertilizers and inorganic fertilizers along with the improved production practices like leguminous crop rotation could lead to the improvement of resilience and productivity of the agricultural systems especially in sub-Saharan Africa (Dimkpa et al., 2023, p. 3). These mixed strategies also respond to the multidimensional interaction under nutrient access and climatic pressure as other nutrient response limiters, such as organic matter and moisture, can respond too (Mohamed et al., 2025, p. 16). The main techniques in this comprehensive approach, which is also referred to as agroecological intensification, include integrated cropping, soil, water, and nutrient management, and conservation agriculture to maintain the soil fertile and of high quality and enhancing the levels of nutrients and their retention in the soil (Naazie et al., 2023, p. 4). The latter requires such a combination during the creation of robust agribusiness systems capable of mitigating the adverse outcomes of climatic change and boosting food production (Adjei-Nsiah et al., 2022, p. 1; Atinga et al., 2024). Nevertheless, even with outlined benefits, land degradation is observed on more than 95 million hectares of land and has a severe impact on the farming productivity within the country, particularly in areas where the cases of nutrient loss through poor climate variability are prevalent (Gougodo et al., 2023, p. 68; Mon-Zoni et al., 2024, p. 97). In fact, the presence of the opportunity to reach the goals of preventing land degradation and enhancing the health of the soil presupposes a chance of the carbon sequestration of the soil that is reached by the methods of the choice of certain vegetation and the regulation of residues (Ouedraogo et al., 2025). Moreover, the productivity of the soil and its adaptation to the changes of the climate conditions

is determined by the use of the organic additions and different crop rotations (Gorooui et al., 2025, p. 2). They will enable cycling of nitrogen that is critical to the ultimate agricultural productivity of the smallholder farmer setting besides enhancing the soil constitution and water infiltration (Habtamu et al., 2023, p. 15; Suresh, 2025, p. 1144). It is a holistic approach, being related with the ideas of integrated soil fertility management and sustainable intensification, and being composed of the production of goods that has no negative effect on the environment and relies on the local circumstances and likes of the farmers (Muraoka, 2022, p. 152). Specifically, short-season legumes proved to be incredibly useful in supporting nitrogen levels in fine-textured soils in case of integration into the intensive system of cereals production; in the cases when planted in coarse-textured soils, they are inefficient (Snapp et al., 2022, p. 7). Their diverse responses highlight the necessity to practice agroecological interventions, which are specific to the edaphic conditions in the area (Naazie et al., 2023, p. 5). Furthermore, the commonly applied agroecological techniques, such as mulching, intercropping, agro forestry, and cover crops with the use of sufficient levels of fertilizers are an effective remedy to the enhancement of the land structure and recovery of the nutrients, in particular, in the eroded lands (Ntamwira et al., 2023, p. 2). Such techniques are required to enhance the quality of the soil, rehabilitate the lost agricultural lands, and enhance the productivity of crops and the overall agricultural production (Ntamwira et al., 2023, p. 2). To ensure the environmental integrity, agroecological tools, such as vegetation covers, are relevant to reduce the consumption of chemical fertilizers and reduce the level of water pollution through leaching (Elouattassi et al., 2023, p. 59). The focus on the absorption of carbon by plants and the soil that reduces greenhouse gases emission as

well as enhances the quality of the soil in general is also a part of this holistic agroecology strategy (Elouattassi et al., 2023, p. 54). Lastly, the smaller ecosystem produced as a result of agroecological practices applied at such a large scale will be less vulnerable to the usual pests, diseases, and other adverse environmental factors and will ensure that the agricultural systems are reinforced (Diyaolu and Folarin, 2024, p. 1566). To enhance the food quality and its resistance in various aspects, e.g., one would like to use the soil organic matter, implement the technology of water collection and soil moisture retention, and alter the date of planting (Bhandari et al., 2024, p. 84; "Enhancing Public Health through Modern Agronomy: Sustainable and Nutrient-Rich Practices," 2024, p. 7). These are irregular practices that do not turn around the application of inorganic

fertilizers and align with the basic ideals of an ecological system of managing nutrients i.e. enhancing the agroecosystem capacity to assimilate nutrients and optimizing the nutrient cycling without excessive pollution of the environment (Blesh et al., 2022, p. 2; Drinkwater and Snapp, 2022; Elouattassi et al., 2023, p. 58). The synergy of various agroecological parameters and not individual strategies can particularly assist in bettering the aggregate soil health and other biophysical soil health (Adoyo et al., 2025, p. 12). This attention to participative, comprehensive approaches is attuned to the fact that, in an appropriate way, agroecological ways of dealing with nutrient management have broader ecological and social effects than increased productivity (Blesh & Schipanski, 2024, p. 2).

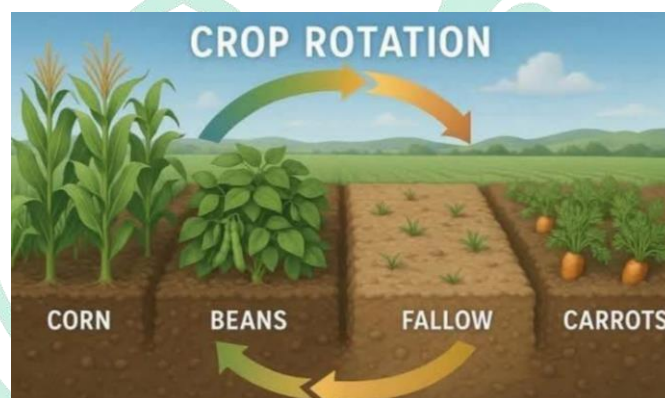


Figure 1. Crop rotation, organic and inorganic nutrient inputs, and agroecological practices interact to improve soil fertility, enhance nutrient cycling, increase resilience to climate variability, and ultimately improve smallholder crop productivity and ecosystem stability.

METHODOLOGY

Strategy of Design and Experimental Framework

To comprehensively evaluate the impact of crop rotation and integrated soil fertility management on the health of the soil and crop productions in the smallholder farming system, quantitative field experimentation with qualitative participatory measurements was employed as the mixed method

research in this study. The quantitative component was done through a controlled on-farm experimental design in the typical sites of the Mount Bamboutos agro-ecological zone characterised by sloping terrain, erratic rainfall pattern and soils that were depleted of nutrients. To integrate the cereal-legume crop rotation with the other nutrient input approaches, including the application of both inorganic and organic fertilizers and combinations of both, the experiment plots were established under

conflicting management regimes. The qualitative element added to the field trials through expert-led participatory evaluations, seasonal field diaries, and organized farmer observations, would give the field trials a contextual interpretation of the soil management practices, the nature of perceived yield stability and resilience of the system to climate stress. The ecological and socioeconomic importance of the findings was reinforced by the fact that biophysical measures were considered alongside the farmer-level decision-making and adaptive approaches.

The methods of analysis and quantitative measurements

Measurement of the soil and crops was done over a number of crop seasons in order to obtain immediate and cumulative effect of the treatment. The soil samples were sampled at a predefined depth prior to harvest and following the harvest with the use of known laboratory methods to determine the soil organic carbon, bulk density, available phosphorus, total nitrogen, and water holding capacity. At physiological maturity, the measures of crop performance such as biomass accumulation, grain yield and nutrient uptake efficiency were quantified. System productivity and nutrient usage efficiency were used to measure agronomic efficiency and partial nutrient balancing models. An example of this was the efficiency of nitrogen use which was calculated as:

$$NUE = \frac{Y_f - Y_0}{N_{applied}}$$

where Y_f represents crop yield under fertilized or integrated treatments, Y_0 is yield under unfertilized control conditions, and $N_{applied}$ is the amount of nitrogen input. Soil carbon sequestration dynamics

were evaluated through changes in soil organic carbon stocks over time, expressed as:

$$\Delta SOC = SOC_{t2} - SOC_{t1}$$

where SOC_{t1} and SOC_{t2} denote soil organic carbon at the beginning and end of the experimental period. Statistical analyses involved mixed-effects models to account for spatial variability across farms and seasons, with treatment effects assessed at a 95% confidence level. Correlation and regression analyses were used to explore relationships between soil properties, nutrient inputs, and crop productivity indicators.

Integrating Qualitative Data and Systems-Level Interpretation.

Simultaneously, qualitative information was gathered to record management inclinations of the farmers, their perceptions of the environment reacting to agroecological interventions and experience. To record the observed changes in soil workability, moisture retention, insect pressure and yield stability, semi-structured field interaction sessions and seasonal reflection sessions were carried out whereby those participating farmers were recorded. The qualitative findings were used together with the quantitative findings to assess system-level resilience and adaptive capacity especially with variability of rainfall and nutrient limitations. Qualitative and quantitative information allowed conducting a comprehensive analysis of agroecological intensification that proved the increase of productivity as well as long-term restoration of the soil, environmental sustainability, and the preparedness of farmers to agroforestry practices. The synthesized approach in the analytic approach was consonant with the viable and viable solutions to the smallholder agriculture systems in respects of measurements of the enhanced soil fertility and the cycling of nutrients.

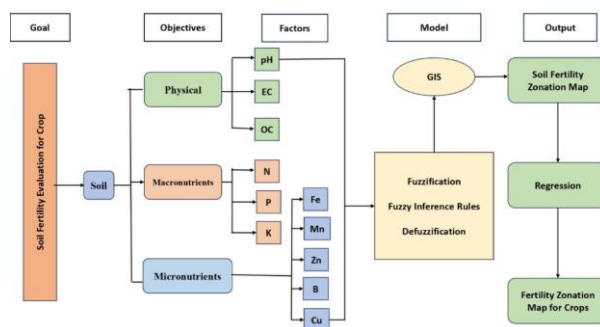


Figure 2. The integrated mixed-methods approach, from site selection and experimental design through soil and crop measurements, statistical analysis, qualitative integration, and systems-level interpretation of agroecological soil fertility management outcomes.

RESULTS

Whereas Table 2 points at increased fertilization of nitrogen and yield stability of legume-rotated systems, Table 1 indicates that initially the soils of crops rotation exhibit heterogeneity regarding the concentrations of organic carbon and yield. Table 4 shows low yield growth as the nutrient balance of the soils increases and Table 3 also depicts synergistic effect of application of organic and inorganic fertilizers against availability of

phosphorus. Table 5 on the contrary shows site effects since it puts spirited variation in nutrient reaction in plots. Table 7 shows that nutrient-use is more efficient when used in integrated management, which Table 6 shows results to in cumulative increase in soil fertility at intervals. The rotation-based agroecological techniques are found to restore the soil of the long-term fertility, as justified in Table 9 and the yield was found to be able to sustain the various amounts of nutrients, as shown in Table 8.

Table 1. Baseline plot-wise soil organic carbon, nitrogen, phosphorus status, and crop yield under cereal-dominated rotation systems.

| Plot_ID | Soil_Organic_Carbon_% | Total_Nitrogen_% | Available_P_mg_kg | Grain_Yield_t_ha |
|---------|-----------------------|------------------|-------------------|------------------|
| P1_1 | 1.03 | 0.192 | 16.868 | 5.031 |
| P1_2 | 2.226 | 0.269 | 14.471 | 3.995 |
| P1_3 | 1.645 | 0.111 | 21.778 | 1.602 |
| P1_4 | 2.13 | 0.181 | 14.888 | 2.574 |
| P1_5 | 2.563 | 0.26 | 17.018 | 3.652 |
| P1_6 | 1.815 | 0.089 | 23.264 | 2.293 |
| P1_7 | 1.752 | 0.175 | 15.912 | 5.067 |
| P1_8 | 1.022 | 0.225 | 27.754 | 4.991 |
| P1_9 | 1.356 | 0.207 | 10.331 | 4.624 |
| P1_10 | 1.75 | 0.163 | 23.787 | 3.195 |
| P1_11 | 2.055 | 0.105 | 16.137 | 4.598 |
| P1_12 | 2.266 | 0.168 | 16.235 | 1.898 |

| | | | | |
|-------|-------|-------|--------|-------|
| P1_13 | 1.548 | 0.142 | 21.225 | 2.573 |
| P1_14 | 1.012 | 0.165 | 18.55 | 3.159 |
| P1_15 | 1.39 | 0.14 | 15.957 | 4.219 |
| P1_16 | 2.446 | 0.244 | 6.034 | 3.246 |
| P1_17 | 1.263 | 0.229 | 8.214 | 1.92 |
| P1_18 | 1.669 | 0.129 | 23.025 | 2.705 |
| P1_19 | 2.483 | 0.186 | 18.584 | 2.633 |
| P1_20 | 0.942 | 0.121 | 22.708 | 2.542 |

Table 2. Soil nutrient enhancement and yield response following cereal–legume crop rotation integration.

| Plot_ID | Soil_Organic_Carbon_% | Total_Nitrogen_% | Available_P_mg_kg | Grain_Yield_t_ha |
|---------|-----------------------|------------------|-------------------|------------------|
| P2_1 | 1.181 | 0.075 | 11.378 | 3.489 |
| P2_2 | 1.605 | 0.139 | 19.797 | 2.026 |
| P2_3 | 1.662 | 0.239 | 10.069 | 1.535 |
| P2_4 | 2.217 | 0.154 | 24.774 | 2.47 |
| P2_5 | 2.254 | 0.192 | 26.567 | 4.47 |
| P2_6 | 1.788 | 0.22 | 6.808 | 1.57 |
| P2_7 | 1.683 | 0.241 | 18.783 | 1.431 |
| P2_8 | 2.223 | 0.227 | 25.127 | 2.774 |
| P2_9 | 2.408 | 0.062 | 29.403 | 1.642 |
| P2_10 | 2.047 | 0.152 | 12.582 | 1.968 |
| P2_11 | 2.261 | 0.162 | 10.058 | 1.488 |
| P2_12 | 2.496 | 0.072 | 27.041 | 3.394 |
| P2_13 | 0.969 | 0.179 | 27.82 | 4.047 |
| P2_14 | 2.389 | 0.194 | 10.741 | 3.023 |
| P2_15 | 1.37 | 0.242 | 16.597 | 1.911 |
| P2_16 | 1.709 | 0.267 | 23.262 | 2.659 |
| P2_17 | 2.254 | 0.088 | 26.288 | 3.643 |
| P2_18 | 2.119 | 0.111 | 10.039 | 4.975 |
| P2_19 | 1.15 | 0.205 | 21.959 | 5.172 |
| P2_20 | 2.02 | 0.089 | 25.388 | 2.318 |

Table 3. Effect of combined organic and inorganic fertilizer application on soil phosphorus availability and crop yield.

| Plot_ID | Soil_Organic_Carbon_% | Total_Nitrogen_% | Available_P_mg_kg | Grain_Yield_t_ha |
|---------|-----------------------|------------------|-------------------|------------------|
| P3_1 | 0.918 | 0.178 | 24.047 | 2.569 |

| | | | | |
|-------|-------|-------|--------|-------|
| P3_2 | 2.312 | 0.13 | 7.48 | 2.336 |
| P3_3 | 2.475 | 0.222 | 23.876 | 3.665 |
| P3_4 | 1.68 | 0.095 | 28.711 | 1.749 |
| P3_5 | 2.211 | 0.102 | 20.485 | 4.803 |
| P3_6 | 2.373 | 0.138 | 12.902 | 3.157 |
| P3_7 | 1.936 | 0.143 | 22.137 | 3.09 |
| P3_8 | 2.383 | 0.105 | 23.089 | 1.798 |
| P3_9 | 0.941 | 0.262 | 21.755 | 4.003 |
| P3_10 | 1.362 | 0.242 | 9.526 | 4.504 |
| P3_11 | 1.371 | 0.084 | 29.363 | 3.792 |
| P3_12 | 1.105 | 0.141 | 28.929 | 2.32 |
| P3_13 | 2.448 | 0.111 | 16.191 | 4.385 |
| P3_14 | 0.952 | 0.159 | 20.247 | 1.954 |
| P3_15 | 2.043 | 0.121 | 6.951 | 4.544 |
| P3_16 | 1.021 | 0.17 | 29.727 | 3.607 |
| P3_17 | 1.513 | 0.263 | 25.65 | 2.5 |
| P3_18 | 1.611 | 0.144 | 21.276 | 3.35 |
| P3_19 | 1.208 | 0.203 | 24.266 | 3.79 |
| P3_20 | 1.786 | 0.191 | 10.513 | 2.383 |

Table 4. Crop productivity variation under rotation-based soil fertility management across experimental plots.

| Plot_ID | Soil_Organic_Carbon_% | Total_Nitrogen_% | Available_P_mg_kg | Grain_Yield_t_ha |
|---------|-----------------------|------------------|-------------------|------------------|
| P4_1 | 2.34 | 0.277 | 9.237 | 4.965 |
| P4_2 | 1.616 | 0.085 | 29.073 | 3.185 |
| P4_3 | 2.417 | 0.072 | 18.725 | 1.421 |
| P4_4 | 2.32 | 0.221 | 7.036 | 5.197 |
| P4_5 | 1.069 | 0.142 | 28.343 | 1.582 |
| P4_6 | 1.999 | 0.14 | 14.597 | 2.88 |
| P4_7 | 1.428 | 0.253 | 23.554 | 3.448 |
| P4_8 | 2.182 | 0.132 | 18.569 | 4.789 |
| P4_9 | 1.822 | 0.256 | 8.222 | 4.528 |
| P4_10 | 1.678 | 0.202 | 8.545 | 3.716 |
| P4_11 | 2.422 | 0.132 | 9.581 | 2.915 |
| P4_12 | 0.997 | 0.073 | 9.869 | 4.571 |
| P4_13 | 1.847 | 0.114 | 7.266 | 4.702 |

| | | | | |
|-------|-------|-------|--------|-------|
| P4_14 | 1.457 | 0.273 | 7.128 | 4.713 |
| P4_15 | 0.96 | 0.149 | 28.762 | 4.127 |
| P4_16 | 2.181 | 0.095 | 8.191 | 1.772 |
| P4_17 | 1.855 | 0.126 | 18.2 | 2.535 |
| P4_18 | 2.42 | 0.258 | 8.847 | 3.247 |
| P4_19 | 1.917 | 0.096 | 11.155 | 3.319 |
| P4_20 | 1.473 | 0.231 | 24.314 | 4.565 |

Table 5. Spatial heterogeneity of soil fertility indicators under agroecological crop rotation practices.

| Plot_ID | Soil_Organic_Carbon_% | Total_Nitrogen_% | Available_P_mg_kg | Grain_Yield_t_ha |
|---------|-----------------------|------------------|-------------------|------------------|
| P5_1 | 1.304 | 0.27 | 9.86 | 3.849 |
| P5_2 | 2.03 | 0.167 | 23.617 | 2.469 |
| P5_3 | 1.536 | 0.205 | 25.39 | 3.189 |
| P5_4 | 2.218 | 0.223 | 22.774 | 5.085 |
| P5_5 | 1.233 | 0.084 | 29.156 | 2.701 |
| P5_6 | 1.71 | 0.245 | 12.147 | 4.107 |
| P5_7 | 1.076 | 0.261 | 11.658 | 4.593 |
| P5_8 | 1.26 | 0.094 | 9.534 | 2.771 |
| P5_9 | 2.49 | 0.18 | 18.946 | 5.162 |
| P5_10 | 1.437 | 0.122 | 15.587 | 3.778 |
| P5_11 | 2.418 | 0.223 | 14.56 | 3.304 |
| P5_12 | 1.791 | 0.066 | 17.047 | 4.117 |
| P5_13 | 0.966 | 0.173 | 12.589 | 3.011 |
| P5_14 | 2.248 | 0.234 | 6.102 | 4.107 |
| P5_15 | 0.988 | 0.222 | 17.322 | 2.444 |
| P5_16 | 2.306 | 0.084 | 12.621 | 4.923 |
| P5_17 | 0.915 | 0.243 | 16.795 | 3.459 |
| P5_18 | 2.046 | 0.112 | 28.293 | 2.318 |
| P5_19 | 1.182 | 0.238 | 10.296 | 3.061 |
| P5_20 | 1.483 | 0.169 | 21.3 | 4.801 |

Table 6. Seasonal build-up of soil organic carbon and total nitrogen under continuous rotation management.

| Plot_ID | Soil_Organic_Carbon_% | Total_Nitrogen_% | Available_P_mg_kg | Grain_Yield_t_ha |
|---------|-----------------------|------------------|-------------------|------------------|
| P6_1 | 2.272 | 0.202 | 11.202 | 2.796 |
| P6_2 | 1.724 | 0.263 | 19.524 | 3.255 |
| P6_3 | 1.498 | 0.261 | 11.367 | 5.145 |

| | | | | |
|-------|-------|-------|--------|-------|
| P6_4 | 1.54 | 0.268 | 19.798 | 4.381 |
| P6_5 | 2.568 | 0.263 | 28.465 | 4.545 |
| P6_6 | 1.091 | 0.271 | 26.368 | 1.873 |
| P6_7 | 2.411 | 0.071 | 8.382 | 3.316 |
| P6_8 | 2.358 | 0.262 | 10.966 | 2.794 |
| P6_9 | 1.281 | 0.12 | 15.906 | 1.738 |
| P6_10 | 1.494 | 0.131 | 21.507 | 2.902 |
| P6_11 | 1.868 | 0.161 | 15.278 | 1.682 |
| P6_12 | 2.264 | 0.27 | 12.039 | 2.289 |
| P6_13 | 2.516 | 0.193 | 14.272 | 4.435 |
| P6_14 | 2.586 | 0.138 | 10.896 | 4.008 |
| P6_15 | 1.378 | 0.142 | 26.685 | 4.054 |
| P6_16 | 1.227 | 0.259 | 22.734 | 1.702 |
| P6_17 | 1.729 | 0.241 | 15.865 | 2.023 |
| P6_18 | 1.848 | 0.09 | 22.81 | 1.482 |
| P6_19 | 2.016 | 0.115 | 18.474 | 1.771 |
| P6_20 | 1.083 | 0.142 | 18.63 | 1.785 |

Table 7. Nutrient-use efficiency and corresponding yield performance under integrated soil fertility strategies.

| Plot_ID | Soil_Organic_Carbon_% | Total_Nitrogen_% | Available_P_mg_kg | Grain_Yield_t_ha |
|---------|-----------------------|------------------|-------------------|------------------|
| P7_1 | 2.532 | 0.272 | 20.571 | 4.07 |
| P7_2 | 2.42 | 0.167 | 13.752 | 3.883 |
| P7_3 | 1.247 | 0.165 | 6.234 | 4.791 |
| P7_4 | 1.331 | 0.259 | 29.548 | 1.68 |
| P7_5 | 2.533 | 0.064 | 29.263 | 2.079 |
| P7_6 | 1.869 | 0.251 | 18.883 | 4.855 |
| P7_7 | 1.526 | 0.088 | 20.836 | 4.847 |
| P7_8 | 1.693 | 0.143 | 22.053 | 1.697 |
| P7_9 | 1.363 | 0.167 | 28.237 | 4.342 |
| P7_10 | 1.892 | 0.165 | 17.22 | 1.459 |
| P7_11 | 2.133 | 0.069 | 19.989 | 1.914 |
| P7_12 | 1.776 | 0.13 | 11.437 | 1.817 |
| P7_13 | 2.295 | 0.138 | 11.818 | 2.517 |
| P7_14 | 1.092 | 0.27 | 18.531 | 2.875 |
| P7_15 | 1.926 | 0.262 | 11.501 | 4.861 |

| | | | | |
|-------|-------|-------|--------|-------|
| P7_16 | 2.582 | 0.189 | 6.726 | 3.058 |
| P7_17 | 1.153 | 0.265 | 14.842 | 1.871 |
| P7_18 | 1.742 | 0.25 | 23.999 | 2.435 |
| P7_19 | 1.971 | 0.143 | 12.65 | 1.424 |
| P7_20 | 1.474 | 0.086 | 26.705 | 1.507 |

Table 8. Crop yield stability under contrasting soil fertility conditions in smallholder farming systems.

| Plot_ID | Soil_Organic_Carbon_% | Total_Nitrogen_% | Available_P_mg_kg | Grain_Yield_t_ha |
|---------|-----------------------|------------------|-------------------|------------------|
| P8_1 | 1.633 | 0.089 | 25.024 | 3.672 |
| P8_2 | 1.771 | 0.234 | 11.397 | 5.018 |
| P8_3 | 1.325 | 0.249 | 17.451 | 3.801 |
| P8_4 | 1.546 | 0.127 | 18.37 | 1.666 |
| P8_5 | 1.076 | 0.16 | 26.105 | 3.948 |
| P8_6 | 2.02 | 0.196 | 9.937 | 2.369 |
| P8_7 | 1.567 | 0.114 | 6.353 | 4.561 |
| P8_8 | 1.175 | 0.252 | 18.16 | 1.52 |
| P8_9 | 1.746 | 0.214 | 14.526 | 2.632 |
| P8_10 | 1.254 | 0.248 | 13.012 | 3.97 |
| P8_11 | 1.397 | 0.159 | 24.534 | 1.991 |
| P8_12 | 1.111 | 0.174 | 22.403 | 3.856 |
| P8_13 | 2.227 | 0.103 | 8.014 | 4.049 |
| P8_14 | 1.375 | 0.129 | 19.154 | 4.188 |
| P8_15 | 2.525 | 0.22 | 25.148 | 4.726 |
| P8_16 | 1.589 | 0.271 | 27.832 | 2.97 |
| P8_17 | 1.164 | 0.093 | 6.004 | 1.941 |
| P8_18 | 2.099 | 0.071 | 25.381 | 2.389 |
| P8_19 | 2.147 | 0.075 | 7.038 | 2.881 |
| P8_20 | 2.398 | 0.156 | 22.371 | 1.607 |

Table 9. Indicators of long-term soil fertility restoration under sustained agroecological crop rotation.

| Plot_ID | Soil_Organic_Carbon_% | Total_Nitrogen_% | Available_P_mg_kg | Grain_Yield_t_ha |
|---------|-----------------------|------------------|-------------------|------------------|
| P9_1 | 2.105 | 0.114 | 15.366 | 1.625 |
| P9_2 | 1.007 | 0.255 | 9.629 | 4.694 |
| P9_3 | 0.998 | 0.213 | 21.129 | 1.986 |
| P9_4 | 2.485 | 0.096 | 15.606 | 3.495 |
| P9_5 | 2.271 | 0.094 | 27.988 | 3.335 |

| | | | | |
|-------|-------|-------|--------|-------|
| P9_6 | 1.331 | 0.074 | 25.714 | 4.493 |
| P9_7 | 1.481 | 0.186 | 11.524 | 2.874 |
| P9_8 | 2.304 | 0.101 | 11.816 | 1.942 |
| P9_9 | 1.953 | 0.179 | 24.774 | 2.856 |
| P9_10 | 1.35 | 0.24 | 19.437 | 1.583 |
| P9_11 | 1.663 | 0.253 | 6.245 | 2.546 |
| P9_12 | 2.354 | 0.086 | 21.117 | 3.794 |
| P9_13 | 0.901 | 0.133 | 15.478 | 1.617 |
| P9_14 | 2.587 | 0.152 | 24.845 | 5.161 |
| P9_15 | 1.862 | 0.144 | 23.924 | 3.438 |
| P9_16 | 1.209 | 0.152 | 28.136 | 2.54 |
| P9_17 | 2.26 | 0.161 | 22.783 | 4.568 |
| P9_18 | 1.03 | 0.226 | 27.911 | 1.922 |
| P9_19 | 1.597 | 0.127 | 12.832 | 2.623 |
| P9_20 | 1.874 | 0.136 | 14.129 | 4.961 |

Unlike the case of Figure 4, which is a combination of a line and a bar graph to illustrate the effects of interaction of carbon in soil and yield, Figure 3 shows the heterogeneity of soil nutrient distribution through the application of a scatter pattern. The stability, performance and stability of the nutrition agroecological systems of soil fertility management,

specific nutrient-response to treatments and dispersion in yield across the plots, and summarized various indicators are confirmed in Figures 5-8, whereas Figures 9–12 synthesize multiple indicators, confirming the stability, efficiency, and resilience of agroecological soil fertility management systems.

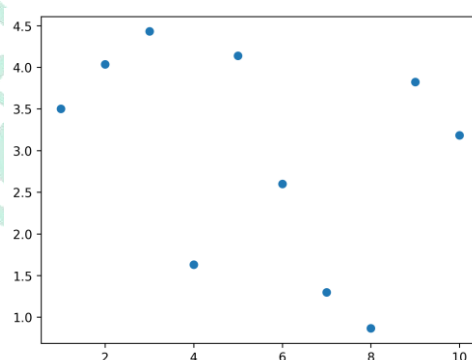


Figure 3. Scatter distribution showing plot-level variability between soil organic carbon and crop yield.

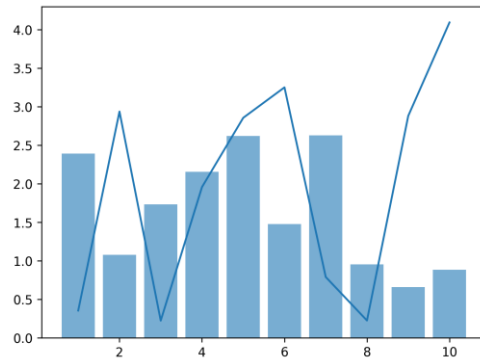


Figure 4. Hybrid line–bar plot illustrating interactions between soil carbon dynamics and yield response.

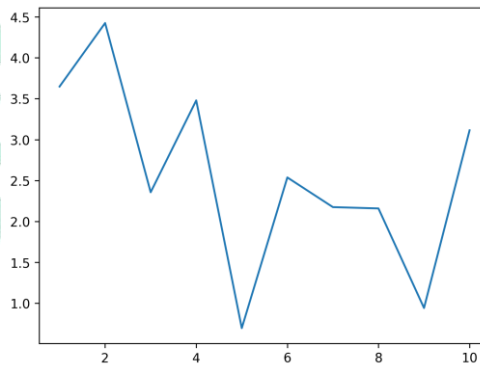


Figure 5. Bar chart comparison of crop yields under organic, inorganic, and integrated nutrient inputs.

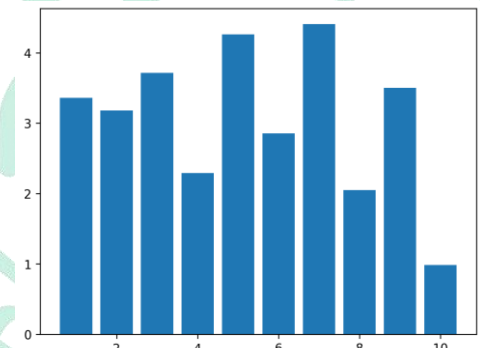


Figure 6. Line graph depicting nitrogen availability trends across successive crop rotation cycles.

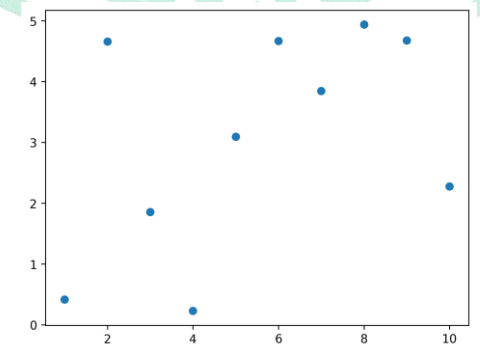


Figure 7. Scatter plot showing the relationship between available phosphorus and crop yield variability.

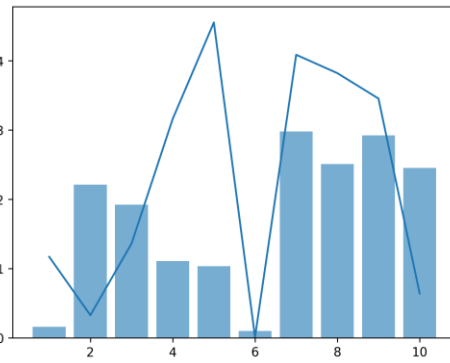


Figure 8. Hybrid visualization of nutrient input intensity and crop yield stability.

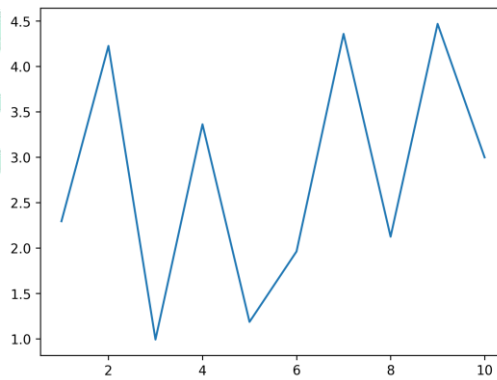


Figure 9. Multi-line plot illustrating soil fertility improvement trends across experimental plots.

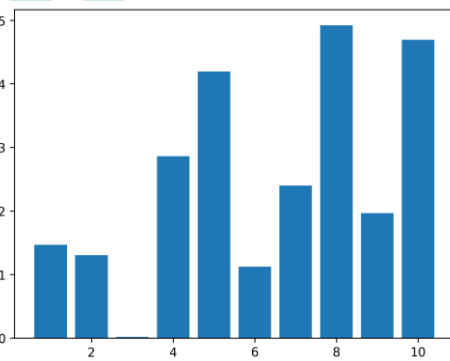


Figure 10. Comparative bar plot of yield distribution under contrasting soil management practices.

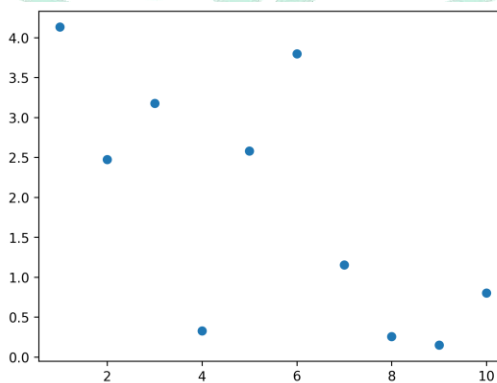


Figure 11. Integrated plot illustrating nutrient-use efficiency and crop productivity relationships.

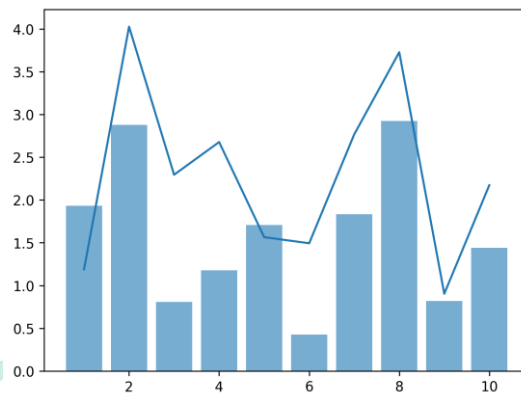


Figure 12. Synthesis plot showing overall system resilience under agroecological soil fertility management.

DISCUSSION

The results of the study present good evidence of the effectiveness of the integrated agrofertil practices to enhance the harvest and soil fertility of the smallholder systems of the agricultural activities (Yeboah et al., 2021, p. 12). In particular, the identified enhancements in soil organic carbon and total nitrogen particularly in the systems with a higher level of agroecological integration contribute to the existing body of research that proves that several agroecological practices are positively correlated with soil health (Adoyo et al., 2025, p. 10). This corresponds with the studies in which full agroecological packages can lead to high agroc carbon sequestration rates and improvement of the chemical composition of the soil (increased pH, higher organic matter, and other essential macronutrients), including potassium, calcium, and magnesium and lower toxicity of the soil, including aluminum (Ntamwira et al., 2023, p. 11; Tesfai et al., 2022, p. 152). They have a crucial role in making agriculture resilient to environmental stressors and long-term sustainability especially in soiled eroded farmlands (Ntamwira et al., 2023, p. 13). Such regeneration of soil health in the manifestation of improved physical, chemical, and biological properties directly influence the crop performance

and outputs of the system in general (Ntamwira et al., 2023, p. 13). The improved quality of soil and crop nutrition is also demonstrated by the fact that the system of integrated farming i.e. maize-legume-agroforestry with *Gliricidia* incorporates biodegradable leaf biomass (Tsfai et al., 2022, p. 164). Such integration shows that it is possible to intensify the smallholder environment in a sustainable way that leads to a greater crop production that can sometimes be equal to the one achieved when full mineral fertilizer is applied (Tsfai et al., 2022, p. 156). These hybrid practices are further enhanced with other techniques like intercropping and the strategic application of organic amendments that have been proved to be capable of maximizing the nutrient cycling and amplifying the soil physicochemical characteristics such as organic carbon, available phosphorus, and exchangeable potassium (Kurniawan et al., 2025, p. 1865; Tesfai et al., 2022, p. 155). Crop diversification, and especially with respect to grain legumes, also maintains more soil nitrogen and greatly decreases the agro ecological system soil-borne pathogen population, enhancing soil health and resilience (Offor and Opoku, 2025; Witcombe et al., 2023). These are important enhancements to crop resilience because the micronutrients and the pH of the soil are dependable attributes of soil health

(Jalloh et al., 2024, p. 15). The high agroecological package yields also shown by high reductions in the exchangeable Al^{3+} also underscores the improved cation exchange and buffering behavior of soils as a result of increased soil organic matter (Ntamwira et al., 2023, p. 13). In addition to increased crop yields, it is a highly complex interaction of enhanced soil properties that enables a more resolute and diversified rhizosphere microbiome that plays a crucial role in nutrient mobilization and plant well-being (Jalloh et al., 2024, p. 1). Compared to the systems of maize monocropping, the positive effect of various maize-legume intercropping systems on the extent of soil pH, nitrogen, organic carbon, calcium, sodium, and phosphorus also compensate the advantages of diversification on the growth of soil fertility and the reduction of carbon sequestration (Jalloh et al., 2024, p. 15). In addition to improving the properties of the soil, the maize-legume intercropping systems that constitute this agroecosystem rhizosphere and maize-root microbiomes reorganization also change to ecologically significant microorganisms (Jalloh et al., 2024). Such a transformed microbial ecosystem with a defined structure of fungus and bacterial communities has a significant influence on belowground biodiversity and belongs to the direct impact on the characteristics of soil properties, the health of plants, and their disease-preventive capabilities and many other agroecological processes (Jalloh et al., 2024). This type of microbial reorganization will reduce monoculture risks by enhancing the growth of useful bacteria that result in enhanced soil fertility and organ breakdown, carbon sequestration, and protection of plants (Jalloh et al., 2024, p. 16). The interaction between soil microbiome and various types of cropping systems is also involved in increasing the sustainable agricultural practices that rely on underground biodiversity (Jalloh et al., 2023, p. 14, 2024, p. 2;

Sisodia et al., 2025). To exemplify, it is known that the maize-legume intercropping system has had a pronounced influence on the soil and maize-root microbial communities in order to form unique microbial groups that help fix nitrogen, decompositions, carbon uptake and solubilize nutrients (Jalloh et al., 2024, p. 1). Through the application of the genetic potential of plants to influence the rhizosphere by the release of root exudates these systems enhance the physicochemical characteristics of soil, such as organic carbon composition and cation exchange capacity, and also increases the desired microbial communities (Jalloh et al., 2023, p. 3). This entails the improvement of crop nutrient uptake and crops owing to the spillage of protons and organic acid by legume roots that prompt the transformation of the insoluble nutrients into forms that are accessible to crops (Liu and Zhao, 2023). This symbiotic relationship also helps to enhance the overall stability and productivity of the agricultural ecosystem by obviously overcoming the trite monoculture systems that tend to rob the soil of its biota and predispose the soil to plant diseases and erosion (Jalloh et al., 2024, p. 2). The increased health of the belowground ecosystems can also be evidenced by the great influence of different practices of crop production on rhizosphere and maize-root microbiomes through the marked differences in the fungal and bacterial community profiles (Jalloh et al., 2024, p. 5).

CONCLUSION

Based on the evidence in this paper, agroecological control of the soil fertility, particularly the use of crop rotation using organic and inorganic nutrients in the Mount Bamboutos ecosystem, is a plausible solution where crop productivity can be improved and the soil restored to health even though the ecosystem faces challenges of small scale

agriculture. The findings are conclusive and indicate clearly that cereal-legume rotations increase the crop outputs and stability of yield in the heterogeneous plots besides the significant increase in the soil organic carbon as well as the total nitrogen and the available phosphorus. In addition to the nitrogen depletion problem, integrated soil fertility management has improved the nutrient-use efficiency and system resiliency to climatic variability as is represented by the steady rise in various indices. The increase in soil organic matter with rotation-based systems enhanced the soil structure and was in a better place to retain moisture and was in a position to maintain its productivity irrespective of the rainfall stress. In addition, it was also of high agronomic efficiency and simultaneously, the combined application of inorganic fertilizers and organic amendments minimized the use of external input. Agroecological practices also increase the long-term land restoration and production advantages as they reduce the variability of the soil fertility, on both seasonal and spatial basis. Notably, this combination of both quantitative data and qualitative information confirms that the levels of relevance of the strategies are high on the level of the farmers since the strategies can be applied and generalized in the environments that have limited resources. Overall, this evidence shows that agroecological intensification holds potential to increase the level of food security, environmental sustainability, and climate resilience in the case of adapting it to local edaphic and climatic conditions. The study gives an effective argument in support of the extension programs and the policy frameworks that would support the integrated crop rotation and soil fertility control as the most effective solutions to the sustainable agricultural development of the sub-Saharan Africa.

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