Comparative Assessment of Legume-Based Crop Rotations for Soil Health Improvement

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Received: 27 May 2021
Revised: 14 Jun 2021
Accepted: 01 Jul 2021
Published: 22 Jul 2021

E-ISSN: 2989-5340
DOI: https://doi.org/10.54660/jafi.2021.1.2.28-31

ABSTRACT

Background: Monoculture of cereal crops has made the decline in soil organic matter content, nutrient reserves, and microbial function among agro-ecosystems faster, thus threatening the agricultural productivity base of sustainable agriculture in the long run. As biological nitrogen fixation and residue carbon input make legume-based crop rotation one of the recommended tools of enhancing soil and agricultural sustainability.

Methods: The comparative study was aimed at studying three rotation systems based on legumes versus monoculture of cereals, in order to assess their impact on soil health indicators as well as agricultural productivity.

Methodology: The two-season randomized block experiment with replicated blocks compared soybean-maize, cowpea-maize and groundnut-maize crop rotations versus monoculture, with the measurement of soil properties, such as soil organic carbon content, nitrogen, phosphorus, potassium content, microbial biomass carbon content, basal soil respiration, bulk density, soil water holding capacity, aggregate stability and yield of cereals.

Results: Rotations of legumes have improved significantly the parameters of soil organic carbon, nutrients, microbial biomass, and soil aggregation, and resulted in lowering the soil density. The cowpea-maize combination was found to provide the most positive results concerning microbial biomass and carbon respiration, while soybean-maize system yielded the highest total production of cereals as well as a higher nitrogen content.

Conclusions: The application of legumes in crop rotation proves to be useful for enhancing a range of soil quality characteristics and can contribute positively to the overall sustainability of the agricultural approaches.

Keywords: Legume-based crop rotation; Soil health; Soil organic carbon; Microbial biomass carbon; Biological nitrogen fixation; Sustainable agriculture

1. Introduction

Soil health is defined as the ability of the soil to function as a living system, thus making it possible for plant, animal, and human productivity to be reached. This means that soil health is crucial for successful sustainable agricultural intensification [1]. Increasing cropping intensity due to the use of cereal monocultures has led to a decrease in organic carbon levels in the soil, changes in nutrient cycles, and diminished microbial diversity [2, 3]. Consequently, all the processes lead to a drop in nutrient availability in the short run. One of the features of legumes is that they have a special connection with rhizobial bacteria that allows them to fix nitrogen (BNF) and produce an ample amount of nitrogen available for plants without applying fertilizers. What is more, legumes exhibit a low carbon-nitrogen ratio which allows them to decompose quicker thereby providing a higher amount of nitrogen for plants.

There is considerable research discussing the benefits of this, yet little evidence exists from field trials to show how various legumes and crop rotation practices have impacted the soil [9, 10]. The current literature tends to look at a limited number of soil characteristics such as soil organic matter or grain yield rather than concentrating on the entire measurement of soil health. The present project aims to provide more information in this regard and compare the efficiency of soybean-maize, cowpea-maize, and groundnut-maize systems against conventional maize monoculture system, thus contributing to more balanced assessment of different agricultural practices' performance.

Materials and Methods

Experimental Site and Climate

The field experiment was conducted over two consecutive cropping cycles at a research farm situated in a semi-arid agroecological zone characterized by a mean annual rainfall of approximately 850 mm and mean temperatures ranging from 18°C to 34°C. The soil was classified as a sandy clay loam (Alfisol) with slightly acidic to neutral reaction.

Pre-Experimental Soil Characteristics

Baseline composite soil samples (0–15 cm depth) indicated low-to-medium SOC, medium available nitrogen, and low-to-medium available phosphorus and potassium, consistent with soils under prolonged cereal monocropping (Table 2, pre-treatment values).

Experimental Design and Treatments

A randomized complete block design with three replications was used, comprising four treatments (Table 1): three legume-cereal rotations and a continuous maize monoculture as control. Standard recommended agronomic packages, including seed rate, spacing, and irrigation scheduling, were uniformly applied; only crop sequence and residue management differed among treatments. Legume residues were incorporated into the soil after harvest in all rotation treatments.

Soil Sampling and Laboratory Analysis

Soil samples were collected at 0–15 cm depth before initiation and after completion of the second rotation cycle. SOC was determined by the Walkley-Black wet oxidation method; available nitrogen by alkaline permanganate distillation; available phosphorus by Olsen's method; available potassium by flame photometry; microbial biomass carbon (MBC) by chloroform fumigation-extraction; soil respiration by alkali absorption; bulk density by the core method; water holding capacity (WHC) by Keen-Raczkowski apparatus; and wet aggregate stability by the wet-sieving method.

Statistical Analysis

Data were subjected to analysis of variance (ANOVA) appropriate to the randomized block design, and treatment means were compared using the least significant difference (LSD) test at $p<0.05$, using standard statistical software.

Table 1: Experimental crop rotation treatments

Treatment	Rotation sequence	Legume component	Residue management
T1 (Control)	Maize–Maize (continuous)	None	Residue removed
T2	Soybean–Maize	Soybean	Residue incorporated
T3	Cowpea–Maize	Cowpea	Residue incorporated
T4	Groundnut–Maize	Groundnut	Residue incorporated

Results and Performance Evaluation

All three legume-based rotations produced statistically significant improvements over the monoculture control across nearly every measured soil health indicator (Table 2). Soil organic carbon increased most under the cowpea-maize system, followed closely by soybean-maize, while the control showed a marginal decline over the two-season period, reflecting continued carbon mining under monocropping.

Available nitrogen rose most sharply under soybean-maize, consistent with its comparatively higher biological nitrogen fixation potential, whereas available phosphorus and potassium showed the greatest gains under cowpea-maize, likely linked to enhanced microbial-mediated mineralization. Microbial biomass carbon and basal soil respiration, indicators of biological activity, increased by the widest margin under cowpea-maize, indicating a more metabolically active soil microbial community.

Physical indicators also responded favorably to legume inclusion: bulk density declined and water holding capacity and wet aggregate stability improved under all rotation treatments relative to the control, with soybean-maize and cowpea-maize showing statistically comparable improvements that exceeded groundnut-maize (Table 3).

Cereal-phase (maize) grain yield was significantly higher under all legume rotations than the monoculture, with soybean-maize recording the highest yield advantage, followed by cowpea-maize and groundnut-maize. Considered together, these results indicate that while all legume rotations meaningfully enhanced soil health relative to continuous monocropping, cowpea-maize delivered the most pronounced biological and chemical gains, whereas soybean-maize offered the strongest productivity response.

Table 2: Soil health indicators before and after two cycles of crop rotation (mean values)

Indicator	Baseline (all plots)	T1 Control (after)	T2 Soybean-Maize	T3 Cowpea-Maize	T4 Groundnut-Maize
SOC (g/kg)	6.8	6.5	8.1	8.6	7.7
Available N (kg/ha)	182	170	224	212	201
Available P (kg/ha)	14.2	13.6	18.9	20.1	17.4
Available K (kg/ha)	168	160	195	203	188
MBC (µg/g soil)	142	138	205	224	189
Bulk density (Mg/m^3)	1.48	1.49	1.38	1.35	1.41

Table 3: Comparative performance of legume-based cropping systems (percentage change over control)

Parameter	Soybean-Maize	Cowpea-Maize	Groundnut-Maize
SOC increase (%)	+24.6	+32.3	+18.5
WHC increase (%)	+15.8	+17.2	+11.4
Aggregate stability increase (%)	+19.1	+22.7	+14.6
Maize grain yield increase (%)	+28.4	+24.9	+19.2

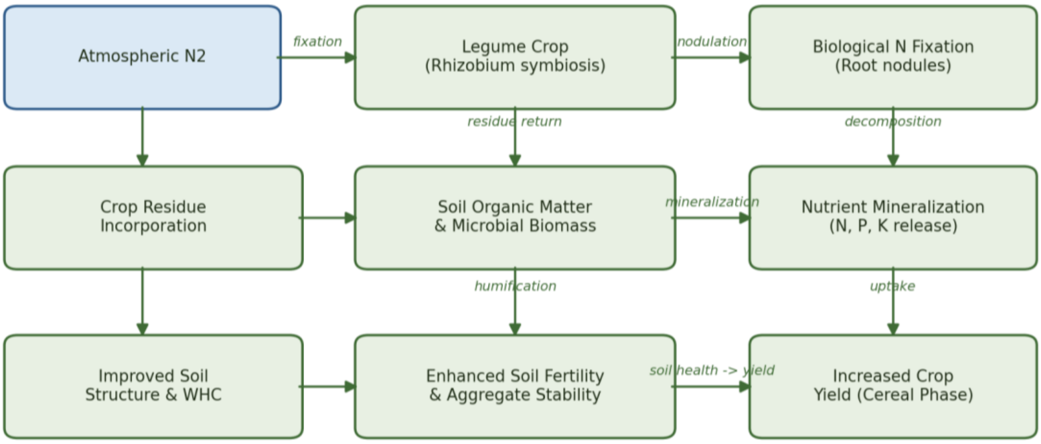

Fig 1: Schematic illustration of nutrient cycling and soil improvement pathways under legume-based crop rotations, from biological nitrogen fixation through residue decomposition, mineralization, and resultant gains in soil fertility, structure, and cereal-phase yield.

As illustrated in Figure 1, the soil health benefits observed in Tables 2 and 3 arise from a cascading biological pathway: atmospheric nitrogen fixed within legume root nodules is partly retained in residues, which upon incorporation elevate soil organic matter and microbial biomass; subsequent microbial mineralization releases plant-available nutrients that jointly improve soil structural properties and cereal productivity.

Discussion

The observed improvements in SOC, nutrient availability, and biological activity under legume-based rotations are consistent with the established mechanistic role of biological nitrogen fixation and residue quality in shaping soil fertility trajectories [11, 12]. The narrower C:N ratio typical of legume residues, particularly cowpea, favors rapid microbial colonization and turnover, which explains the comparatively larger MBC and respiration responses recorded under the cowpea-maize treatment relative to soybean-maize and groundnut-maize [13, 14].

The divergence between cowpea-maize's biological superiority and soybean-maize's yield superiority suggests that nitrogen supply capacity, rather than overall microbial activity, is the more proximate driver of cereal-phase productivity in nitrogen-limited soils [15]. This distinction has practical significance: farmers prioritizing immediate yield gains may favor soybean-based rotations, whereas those targeting longer-term structural and biological soil restoration may derive greater benefit from cowpea inclusion [16].

The consistent decline in bulk density and gains in aggregate stability and water holding capacity across all legume treatments reinforce the role of root architecture and organic matter accumulation in improving soil physical resilience, a mechanism of particular relevance to climate-smart agriculture under increasingly erratic rainfall patterns [17, 18]. Diversified legume rotations additionally reduce reliance on synthetic nitrogen fertilizer, lowering both input costs and the associated greenhouse gas footprint of nitrous oxide emissions from fertilizer manufacture and application [19].

Economically, the marginal yield advantage observed under legume rotations, combined with reduced fertilizer expenditure, suggests favorable returns, although this study did not conduct a formal cost-benefit analysis, representing a limitation. Additional limitations include the two-season duration, single-site setting, and absence of long-term multi-year data capturing rotation effects across variable climatic years. Future research should extend these comparisons across multiple agroecological zones and longer durations, incorporate economic and life-cycle assessments, and examine below-ground microbial community composition using molecular approaches to more precisely characterize the mechanisms underlying the observed soil health gains [20, 21, 22].

Conclusion

The comparative analysis has shown that growing legumes in rotations improves soil organic carbon, nutrient availability, microbial biomass and physical properties of soil. Legume crops not only enhance soil health indicators but also increase yield of the cereal. The analysis indicates that cowpea-maize rotation yields the biggest improvement in biological and chemical indicators of soil health, while soybean-maize rotation delivers the highest production output, suggesting that choices of crops for rotation depend on soil restoration and yield priorities. The results highlight the agricultural importance of the legume diversification as the low-cost and climate-resilient method of sustainable soil management. Support for the increased dissemination of such technique needs extensive field testing in the long-term and at various locations to demonstrate the effectiveness of such approach under varying conditions.

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