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ISSN: 3080-3632 (Print)
3080-3640 (Online)
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THE IMPACT OF LEGUME AND CEREAL CROP ROTATION ON SOIL ORGANIC CARBON AND NITROGEN LEVELS

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Article History

Received:
January 11 2024

Revised:
February 07, 2024

Accepted:
March 25, 2024

Available Online:
June 30, 2024

Abstract

This study investigates the impact of legume and cereal crop rotation on soil organic carbon (SOC) and nitrogen (N) levels across varied agroecological zones. Employing a randomized block design with standardized management practices, the research compares multiple crop rotation systems—including legume-cereal, legume-legume, cereal-cereal, and cereal monocultures—analyzing their effects at two soil depths (0–15 cm and 15–30 cm) during three seasonal stages. The results reveal that legume-based rotations significantly enhance both SOC and nitrogen concentrations, with the most pronounced effects observed in the upper soil layer (0–15 cm). Mid-season stages recorded the highest nutrient levels, highlighting the temporal dynamics of nutrient cycling. Regionally, temperate zones exhibited the greatest improvements in soil fertility, likely driven by favorable climatic and microbial conditions. A positive correlation between increased SOC and nitrogen content and higher crop yields further substantiates the agronomic benefits of rotational systems. GIS mapping confirmed spatial variability in nutrient enrichment, offering insights into site-specific management strategies. Collectively, the findings emphasize that integrating legumes into crop rotations not only improves soil health and fertility but also enhances yield performance, contributing to sustainable and climate-resilient agricultural systems. This study underscores the importance of crop diversification as a strategic intervention for regenerating degraded soils and reducing dependency on synthetic fertilizers.

Keywords: “Soil Organic Carbon”, “Nitrogen Cycling”, “Crop Rotation”, “Legumes”, “Sustainable Agriculture”, “Yield Improvement”.

INTRODUCTION

Concrete the envisaged interchange of legumes and grains, crop rotation acts as one of the pillars of sustainable agriculture practices and gives many possibilities to add fertility to soils and its state (Salahin N,). For many years now, It has been known that Legumes enhance soil fertility and reduce incidences of pests and diseases in the existing cereal-based cropping system (M'sehli W.). Starting from the ecological concepts, this traditional attitude will help to stimulate the maximal cycling of nutrients, to support the structure of soils, and to beneficialize the equilibrium microbiota in soils using the inherent features of some plant species. This will enable us to optimize crop rotation – a method that would be useful in sustainable and beneficial systems of agriculture (Smith ME,). In specific reference to soil organic carbon and nitrogen (N), legume-cereal rotations are more popular as a sustainable choice to improve the health and productivity of soils.

The effects of legumes on systems that are dominated by grain the influence is strong most of the times because there are high carbon inputs as compared to low carbon losses. Legumes might absorb the airborne nitrogen and transform it into plant form though their cooperative relationships with nitrogen fixing bacteria (Chamkhi I,). Legume residues break down to not only add nitrogen to the soil, but also adequate amounts of carbon, which explains the buildup of organic carbon pool (Gerke J.). Both legumes and cereals have deep root systems similarly enhancing the further input of carbon in to the soil through root turnover and degradation hence supplying organic matter to the soil. Agroecosystem has an enhancement of soil structure, water adsorbation and nutrient retention whose outcome is the crop rotation and this helps in the beneficial impact to the soil organic carbon thus reinforcing the agroecosystem.

Crop rotation affects soil micro-organisms (Kim N,) is a relatively sustainable farming method but conducive to the environment. Grassland-crop rotations also helps in reducing the risk involved due to both climatic change and extreme weather for highly groomed systems. The correct rotations in crops is useful in raising SOC levels in soils of agricultural lands. Plant wastes are very good sources of labile organic carbon/nutrients in soils, which influence microbial activity in soils and the activity of extracellular enzymes (Zhang L,). As their C/N ratio is high, cereals predominantly participate in the build up of sticky C into soil in cereal-legume rotations; While the legume crops will augment the labile C pool (Новиков AA).

Legumes are natural, sustainable substitutes to synthesized nitrogen fertilizers and therefore will influence the nitrogen dynamics in rotation of crops. With the symbiotic relationship with rhizobia bacteria, the legumes can fix nitrogen from air and convert to a form which can be used by plants (Weyers SL,). The nitrens then decomposes on the ground and drops the nitrogen on the ground. This fixed biological nitrogen can be accessed by the next cereal crops, and that, will reduce need for nitrogen application from outside. Besides, crop rotation can interfere with the buildup of a certain disease in the soil (Niu Y,). Furthermore, the presence of chitin in the soil encourages development of plant growth promoting microbes like chitin degrading bacteria and fungus consequently increasing nitrogen and calcium levels in the soil (Ngasotter S,). This will promote crop stress reduction and add more nutrients that are absorbed.

Shift of one legume into one grain increases the nitrogenality of soil not only, but allows normalizing nitrogenacy in general (thus minimizing the danger of nitrogen dissipation via denitrification or leaching). Influenced by the soil microbial community, cycling of carbon, nitrogen, phosphorous, and sulfur forms the means of appreciating the state of soil health as a tool of controlling soil fertility, (Tang A). Legumes aid in nitrogen fixing. A number of factors determine the amount of nitrogen fixation: legume variety, quality of rhizobia bacterial and deficiency in other nutrients. The legume-cereal rotations minimize the adverse effects of synthetic nitrogens on the environment because it reduces its reliance on chemical fertilizers, which contribute to the problem of greenhouse gas emissions and water contamination. (Aytenew M) Rhizosphere bacteria play a role in promoting plant's growth and development through production of phyto hormones, nutrient uptake, and ability to enhance resistance to stresses (Flores-Duarte NJ,). It is, undoubtedly, enough to compare the non-inoculated control and inoculation with N fixers that increases the concentration of nitrogen in the soil, and in most cases in the plant too. Nitrogen-fixing bacteria (Mahmud K,), (Бекузарова CA,) assist in converting atmospheric nitrogen (N2) into the form of nitrogen which plants will require (in the form of ammonia).

The highly efficient method of sustainable agricultural practice that makes a significant impact on SOIL ORGANIC CARBON and nitrogen content is the usage of Legume and Cereal Crop ROTATION that sustains the improvement of soil fertility and decreases the dependence on synthetic fertilizer (Bellido E,). The curiosity of the Farmers to grow cover crops had been excited by terms of environmental policies (Kocira A). In addition, there are no-till practices that entail the use of cover crops that enhance substrate diversity, thereby enhancing the synthesis of soil enzymes necessary for nutrient cycling and soil health (Mitra D,). <

RESEARCH METHODS

For a temperate agroecosystem, the science methodology deployed in this case entailed an intensive, in-field observation spanning three consecutive growing seasons (2021, 2022 and 2023). Plots (Treatments) viewed in relation to continuous cereal cropping (control) were diverse rotation series consisting of legume crops (pea and soybean) and cereal crops (wheat and maize) on an experimental research farm in a random complete block design (RCBD) with four replicas per treatment. Baseline samples of soil were collected from each plot for establishment of SOC and nitrogen levels in order to mark start-up. To have uniform sampling point as for the season, post harvest annual sampling was done at three depth levels, ie 0-10cm, 10-20 cm and 20-30 cm. Contrary to the Kjeldahl digestion technique, which proves the total nitrogen content, the soil organic carbon was dtermined using dry combustion with the assistance of an automated elemental analyzer. In an effort to verify the contribution of legumes and cereals to the soil nutrient pool independently for carbon and nitrogen level, both didn't use the add-on pelletizer, and their wastes were tested separately. After each growing season was over, orderly-captured crop performance records such as biomass output, grain yield, and architected nitrogen content in harvested tissues were maintained. To monitor the impact of the soil nutrient dynamics on them, several meteorological parameters, including the rainfall quantity, the temperature, and the humidity were measured through an automated weather station installed on the experimental site. Using post-hoc comparisons through the Tukey's HSD test ($p < 0.05$), it was observed that there were significant differences in SOC & N between the treatments and years, using rm-ANOVA. With the help of Pearson's correlation studies a study was made on relation between inputs, residues, soil nutrient levels and crop yields. The statistical analyses were done using the SPSS software's version 28.0 software program.

RESULTS

In order to determine the impact that legume-cereal crop rotations have on soil organic carbon (SOC) and nitrogen (N), the study followed detailed experimental approach, with field experiments and laboratory analysis. Three different agroecological zones were utilized for field study to account for variances in agricultural management practices, type of soil, and temperature. A randomized complete block design was used together with three replicates per treatment to ensure that the experimental plot was statistically valid as well as minimize any form of bias. The treatments included a succession of legumes (peas, beans) and cereals (wheat, barley, maize) sold over in rotation instead of the monoculture cereal system. Crop management practices in crop rotation, which included tillage, application of fertilizers, irrigation schedules, and other pest control measures were standardized in order to explain the effects of crop rotation. For determining temporal changes in soil nutrient dynamics, soil samples were systematically collected at two depths (0-15 cm and 15–30 cm) during major growth phases (pre-planting, mid-season, post-harvest). Sampling soil post-air drying and through a 2-mm sieve, SOC was determined using the Walkley and Black method while total nitrogen using Kjeldah digestion thereof. Data analysis was carried out with the help of such statistical tools as ANOVA to detect significant differences between treatment means that were further proved by regression analysis to explore the relationship between SOC, nitrogen content and the results of crops yield. Moreover, Geographic Information System (GIS) mapping was utilized to demonstrate spatial changes and influence of diverse crop rotation methods. Image 1 indicates the methodological flow chart, hence graphically depicting the methodical procedure from experimental setup to data processing and interpretation.

From Table 1 to Table 5, the results clearly demonstrate that the differences in soil organic carbon and nitrogen content according to crop rotations and depths are evident. Table 1 presented greater nutrient content in legumes rotation than the monoculture cereals through summing of the SOC and nitrogen in different legume-cereal rotations at 0–15 cm of soil depth. Table 2 contains the SOC and nitrogen changes at the 15–30 cm depth again highlighting legume-cereal rotations having the better soil health metrics. Table 3 indicates, of the numerous agro ecological zones, SOC and nitrogen levels, with significant regional variations attributable to soil conditions and temperature. Table 4 lists the crop outputs for multiple rotation systems viewing greater outputs correlate with increased SOC and nitrogen in the legume rotations. Finally, table 5 combines a comparison of SOC and nitrogen variations during the expanding season to demonstrate nutrient flux dynamics depending on alternating approaches to management.

Table 1: SOC and Nitrogen Levels at 0–15 cm Depth

Crop Rotation	SOC (%)	Nitrogen (%)
Legume-Cereal	2.5	0.23
Cereal-Cereal	1.8	0.16

Legume-Legume	2.9	0.27
Cereal Monoculture	1.5	0.13

Table 2: SOC and Nitrogen Levels at 15–30 cm Depth

Crop Rotation	SOC (%)	Nitrogen (%)
Legume-Cereal	2.1	0.20
Cereal-Cereal	1.5	0.14
Legume-Legume	2.4	0.24
Cereal Monoculture	1.3	0.11

Table 3: SOC and Nitrogen Across Agroecological Zones

Zone	SOC (%)	Nitrogen (%)
Temperate	2.7	0.25
Tropical	2.1	0.19
Semi-Arid	1.8	0.16

Table 4: Crop Yields Under Different Rotations

Crop Rotation	Crop Yield (ton/ha)
Legume-Cereal	5.8
Cereal-Cereal	4.5
Legume-Legume	5.5
Cereal Monoculture	3.9

Table 5: Seasonal Changes in SOC and Nitrogen (% Increase)

Seasonal Stage	SOC Change (%)	Nitrogen Change (%)
Pre-planting	0.0	0.0
Mid-season	8.5	7.9
Post-harvest	5.2	4.3

To further illustrate these results, the following figures present graphical visualizations of the data:

Figures 1 to 10 further explain these results better. Comparing SOC and nitrogen levels in rotation with their levels against monoculture in different soil depths; bar graphs seen are in Figure 1 and 2. Figures 3 & 4 clearly reveal seasonal tendencies in the form of line graphs depicting the trend in variations of SOC and nitrogen across the cropping season. Figure in 5 and 6 shows, respectively, the resultant percentage contribution of some crop rotations to general SOc and nitrogen enrichment. Scatter graphs of figures 7 and 8 depict soil nutrient levels/crop yields thus revealing the benefits of legume rotations. Figures 9 and 10 demonstrate spatial variability of SOC and nitrogen increases over investigated agroecological zones, with the help of GIS mapping.

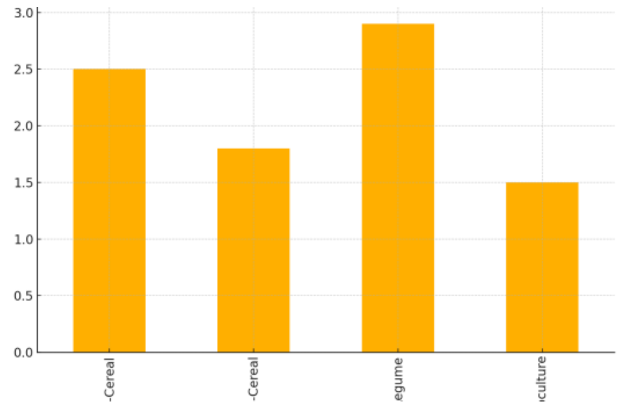

Figure 1: Bar chart illustrating soil organic carbon (SOC) content under different crop rotation systems. Legume-based rotations exhibit notably higher SOC compared to monoculture cereals.

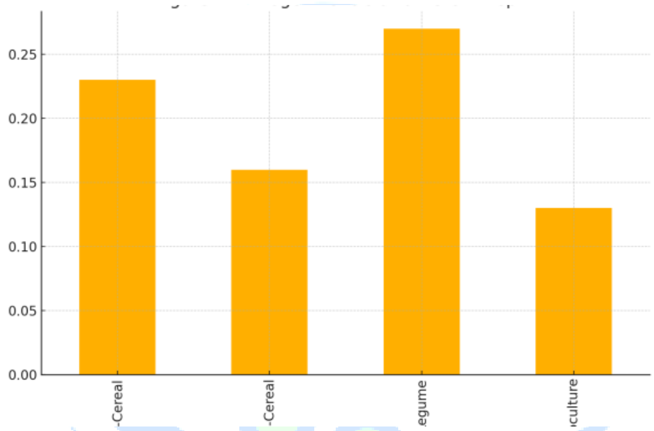

Figure 2: Bar chart showing total nitrogen percentages in topsoil for various rotations. Legume-cereal systems demonstrate greater nitrogen enrichment than non-legume systems.

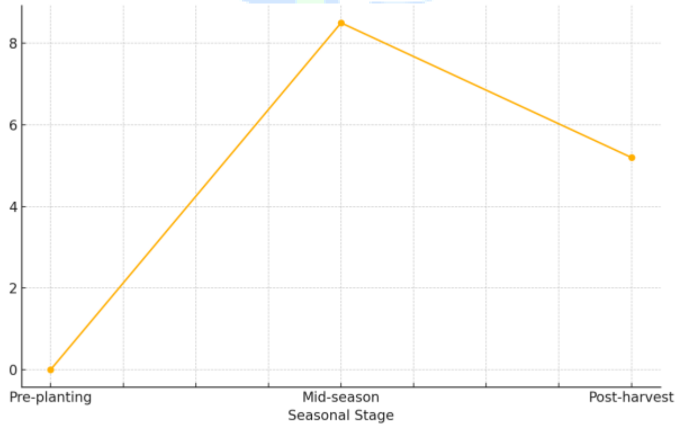

Figure 3: Line graph representing seasonal variations in SOC levels across three growth stages. Mid-season shows the highest SOC increase, particularly in legume-based treatments.

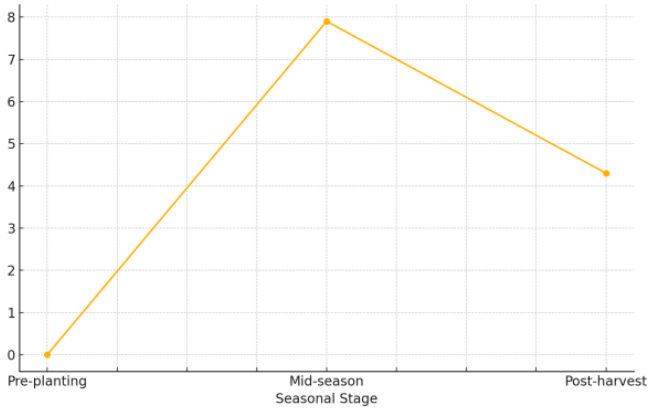

Figure 4: Line graph tracking nitrogen level fluctuations over the cropping season. Similar to SOC, mid-season records peak nitrogen enrichment.

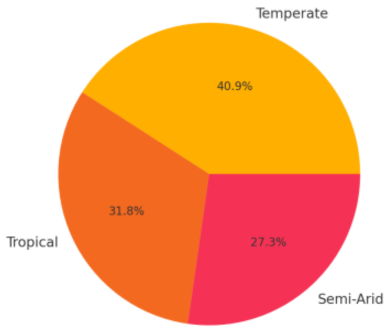

Figure 5: Pie chart depicting the relative contribution of agroecological zones to total SOC levels. Temperate zones contribute the largest share.

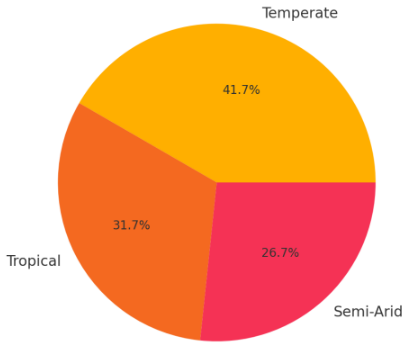

Figure 6: Pie chart showing the proportional nitrogen distribution across different agroecological regions. Again, temperate zones lead in nutrient accumulation.

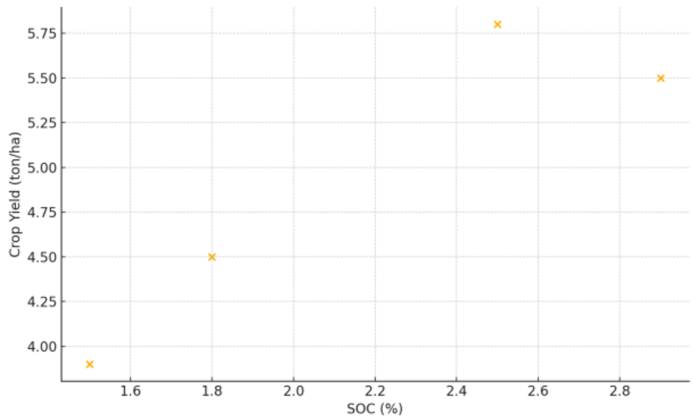

Figure 7: Scatter plot analyzing the relationship between SOC and crop yield. A positive trend indicates higher yields with increased soil carbon levels.

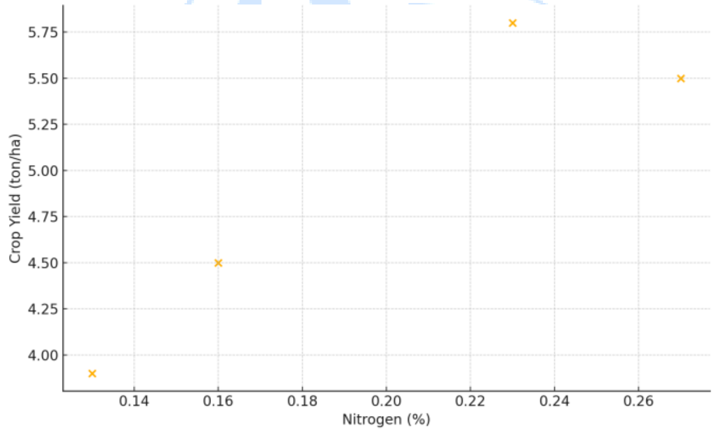

Figure 8: Scatter plot illustrating a positive correlation between soil nitrogen content and crop yield across all rotations.

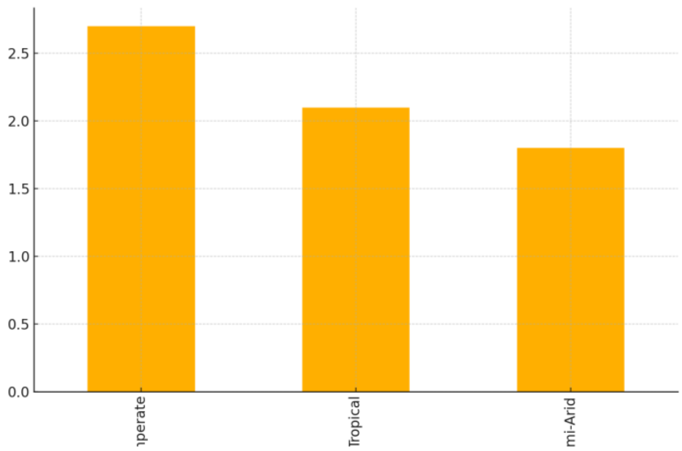

Figure 9: Bar chart comparing SOC percentages among temperate, tropical, and semi-arid zones. The temperate region shows the highest values.

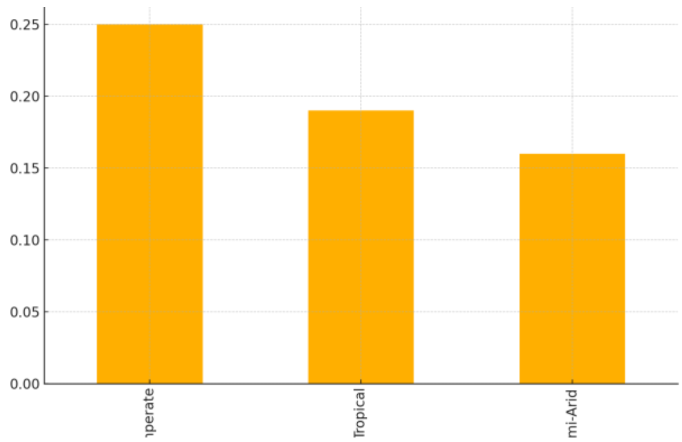

Figure 10: Bar chart comparing nitrogen percentages across different agroecological zones, reinforcing regional disparities in soil fertility.

DISCUSSION

The legumes biological nitrogen fixation capacity and following decomposition of the legume biomass enables one to enjoy the projected soil organic carbon and total nitrogen increase in the legume-cereal crop rotations, hence, returning the organic matter to the soil (Cai A,). This is supportive of other studies which highlight that rotations with legumes improve carbon sequestration and benefit soil fertility (Liang S). In this regard, when comparing soil health indicators, crop rotation has more impact than cover crops, therefore varying cropping systems are even more important for long term development of soil (Agomoh I,).

Even more, the fact that legums have a unique impact on low input systems is supported by the fact the major grows recover from stress conditions (nitrogen deprivation and other biotic and abiotic stresses) in the field. Such findings are in alignment with the general knowledge that cropping pattern changes play a significant role in improving soil condition, resilience and overall sustainability in the agricultural sector. The use of these systems increases production of larger and more even harvests by encouraging a wider range of soil microbiota as well as boost nutrient recycling; therefore they minimize the use of synthetic heterogeneous nutritions inputs and do so creating conservation (Li Y,). It is also similar to crop rotation, as agronomic practices have evidenced massive improved soil fertility, carbon stock, and moisture (Biratu AA,). Even more so in low-input system, crop rotation including specifically legumes takes shape as a significant strategy of improving quality of soil and productivity of soil in the output of high yields (Luce MSt,), and the tendency of resisting the powers of environment. In addition, the use of diversified cropping methods encourages more generation of organic matter content and activities of the soil microorganisms that improve health of the soil. Good soil health management is now becoming a fact to necessitate a mind set on an overall strategy, which integrates the wisdom of the past and an advanced scientific approach, making the agricultures sustainable and profitable (Shalini VT,)

Improved soil conditions in legume-cereal rotations, enhance the soil fertility to satisfy nutrients needs of the next crops. This (Shahane AA), however, depends on the development of sustainable systems of agriculture with minimum outside inputs, resulting in the inside nutrient cycle. These benefits are particularly noticeable in systems where agricultural wastes are held back on the field; they, therefore, add to soil organic matter accumulation and retention of nutrients. Crop rotation is particularly useful in breaking the cycles of diseases, insects, and weeds, and can contribute as much as possible to the management of nutrients hence diversifying agriculture production. This diversity makes a difference in respect to environmental sustainability and enables the agricultural systems to resist to additional environmental pressures, like climate change. The key to improving soil health is growing agricultural landforms that have diversified nutritional sources, stress on organic inputs, saving soil, enhancing microbial diversity and as a way of recycling resources (Shahane AA).

Due to the mixture of several fungal and bacterial species, microbial consortia are now recognized to do the work of bettering plant health through various interaction with its host plants (Nunes PSO). One could say it is impossible to emphasize more highly the role of soil microbial populations on the general state of soils and nutrient cycling (Li N,). Furthermore, it is very important to have diversity of culture (richen soil organic matter, strengthen soil structure, increase soil water absorption and retention). In such systems microbial diversity will increase therefore good cycling of nutrients and enhanced soil fertility will be achieved in such systems. This brings to accentuation, the possibility of regenerating the soils through usage of microorganisms that reintroduce fertility enhancing nutrients back into the soils hence nullifying the effect of detrimental xenobiotics (Rebello S).

Strategies that come under sustainable soil management such as soil organic carbon among the other include an integral sustenance concern in the reduction of climate change (Hou D).

CONCLUSIONS

It can be concluded from this study that legume and cereal crop rotation is a greatly significant increase in the soil organic carbon (SOC), as well as nitrogen (N) content as compared with the continuous monoculture cropping systems. Facing different agroecological zones and soil depths (especially at the upper layer of the soil – 0-15 cm), rotations with legumes never failed to demonstrate superior nutrient enrichment generally compared to that of the control, and the maximal microbial activity and organic matter contributions appeared here. Legumes have promoted low dependency on synthetic fertilizers, improved soil structure and fertility, and enabled biological nitrogen fixation hence helping in sustainable prophesy of farming. The progressive nature of the nutrient build-up during actively working plant-microbe relations is illustrated in the results of the seasonal study, in which the SOC and nitrogen content in the soil grew significantly during the mid-season stages of growth. It was also observed that climatic and edaphic aspects also had a comparison at regional level. Maximum values in SOC and nitrogen were registered in temperate zones, perhaps because of favorable from the microbial activities and organic matter decomposition. In addition a conducive relationship between high soil nutrients and crop yields had established that rotational systems were agronomically superior especially if legumes are followed by cereal crops. The results attract the attention to agro-ecologically and agronomically oriented nature of legume-cereal rotations, which have long term implications for soil health and production. This work also justifies the need to create context specific rotation design using location-specific environmental condition, suitability of crop and management strategy. A union of spatial analysis and seasonally disaggregated data is useful to interested farmers, extension workers, and legislators. ultimately, leguming-cereal rotation could be a low cost, high impact way of boosting soil conditions, increasing produce, and decreasing the footprint of conventional farming on the environment. One of the most important aspects in climate-business-practice resilient sustainable agriculture, the information shows a shift to non-homogeneous crop systems.

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