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Role of agroforestry systems in enrichment of soil organic carbon and nutrients: A review

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ABSTRACT

Monocropping systems have intensively exploited natural resources in recent decades, and the indiscriminate use of inorganic fertilizers, combined with agro-chemicals, has resulted in the deterioration of natural resources such as soil and water, resulting in the loss of soil fertility. Agroforestry is an ideal scientific strategy for eco-restoration of degraded areas and sustainable resource management when compared to mono cropping systems. It is a land management and farming strategy that aims to not only produce food from marginal agricultural land, but also to significantly improve the quality of the environment and soil. When compared to regular crop removal in a solo cropping system, leaf litters and their breakdown under tree-based vegetation favour nutrients enrichment. The adoption of an agroforestry system resulted in the accumulation of soil organic carbon, increased the availability of macronutrients and micronutrients, and improved the microenvironment for plant growth. As a result, pairing suitable tree species with agricultural crops can contribute in the maintenance or enhancement of soil fertility. Based on these findings, it is advised that farmers adopt agroforestry systems since they have enormous potential to improve soil fertility, leading to increased crop output and food security.

Introduction

Agroforestry is a specialized form of land use that combines trees with livestock or agricultural crops to provide enhanced ecological and environmental advantages. It's an ideal scientific practice for restoring degraded lands and managing resources in an efficient manner (Sileshi *et al.,* 2020). In both rural and urban environments, trees in general can offer a wide range of environmental advantages, and they are crucial to the ecosystem services provided by natural areas (, Barrios *et al.,* 2018; Mexia *et al.,* 2018; Blanco *et al.,* 2020). Despite the fact that the advantages that trees can offer on rural properties, such as food security, household income, economic stability, and thermal comfort (shade), are frequently connected to their goods, such as fruit, timber, or other items, trees may additionally enhance the cycling of nutrients and have beneficial impacts on soil physical and chemical characteristics when they are included in agricultural systems (Isaac *et al.,* 2007; Torralba *et al.,* 2016; Rodriguez*et al.,* 2021). Concerns regarding agriculture's long-term viability are rising. The environment has been harmed by overuse and underuse of fertilizers, as well as poor

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resource management. Harsh weather conditions, population pressure, land limits, and the adoption of conventional soil management practices have all lowered soil fertility in developing countries (Henao and Baanate, 1999). The process of reducing soil erosion results in an increase in soil fertility (Garcia *et al.,* 2017) and reduce runoff (Mu *et al.,* 2018) and maintain soil organic matter (Bonanomi*et al.,* 2020)This results inimprovement of the soil's physical, chemical, and biological qualities, increased nitrogen (N) input from N-fixing plants, excavation of minerals from deeper horizons by roots, and recycling of those minerals through litter fall on the ground. Based on the current population status expansion and higher demand on agricultural areas, there is a desire for more intensive land usage (Wang *et al.,* 2018). Crop residue burning is the least expensive way to prepare ground for planting, but it might interfere with Ncycling and deposition processes, resulting in a loss of soil fertility (Jusoch *et al.,* 2013; Bhutiani and Ahamad, 2019) and, as a result, reducing the recovery of natural vegetation during fallow periods. Phosphorus (P) and N being the most limiting elements for crop productivity in the cropping land (Reza *et al.,* 2019), and the high price of inorganic fertilizers prevents most small-holder farmers from using them in sufficient quantities (Akpan *et al.,* 2012). Many crops have been observed to be deficient in macronutrients, and the severity of these deficiencies varies based on agroecological systems, soil types, farming practices and human activities (Shukla and Behera, 2014).Organic matter, physical properties, and nutrient levels must all be sustained in order for soil fertility to be maintained. Changes in soil properties, such as pH, soil organic carbon (SOC), soil structure, macronutrients (Aluko and Fagbenro, 2000) and micronutrients (Dhaliwal and Walia, 2008) influenced soil fertility and production. Agroforestry systems based on *Populus, Eucalyptus* and *Melia* have developed as an alternative option for crop diversification in north-west India, boosting soil fertility, productivity, and net profitability while also helping to mitigate the negative effects of climate change (Chaudhari *et al.,* 2014; add one more citation here). Trees contribute to soil fertility preservation by fixing Nand returning organic content through leaf fall (Rosenstock *et al.,* 2014), resulting in a high proportion of organic-P in the soil. According to Wood *et al.* (2007) soil fertility is linked to the amount of litter fall, the quality of the litter, the rate of nutrient mineralization and breakdown. In comparison to solo cropping or traditional farming systems, research have shown that including diverse tree species such as *Acacia, Eucalyptus* and *Poplar and Mahogany* improves pH, electrical conductivity (EC), organic matter, available macro and micronutrients in soil (Rosenstock *et al.,* 2014; Dinesha and Dey, 2023). As a result, better methods of farming not only improve soil fertility and productivity, but they also have the potential to make soil a net sink for carbon, lowering CO_2 levels in the atmosphere (Naik *et al.,* 2017).

Crop productivity is mostly influenced by soil fertility. Since soil fertility and farm productivity tend to be strongly correlated, addressing the issue will have a direct impact on agricultural yields. It has been proven that using chemical fertilizers along with organic source on newly created high-yielding crop types can increase crop yields by a ratio of three to five or more (Mamnabi *et al.*, (2020)). It has, however, fallen into a number of issues. Fertilizers are expensive to create in terms of energy resources, and their continued widespread use has a negative impact on the environment. Because of physical soil deterioration or a lack of micronutrients, for instance, yield responses to fertilizers have decreased. Above all, a significant portion of underprivileged farmers are unable to pay for expensive fertilizers and other purchased inputs, nor do they have the resources to assume the associated risk. Farmers have also had to spend a lot of money buying chemical fertilizers due to their high cost and limited availability. An economic analysis confirms that this method of farming is neither sustainable nor profitable. Thus, there is a need for proper farming techniques that would reduce inputs while boosting yields by conserving the natural fertility of the soil. Rapidly growing and N-fixing plant species can be used in agroforestry as a quick approach to add organic matter to the soil.

Effect of agroforestry systems on soil organic carbon and nutrient availability

The fertility of the soil is almost solely responsible for crop productivity. This in turn has an impact on household food security. Soil fertility levels must rise in order to maintain good crop productivity and

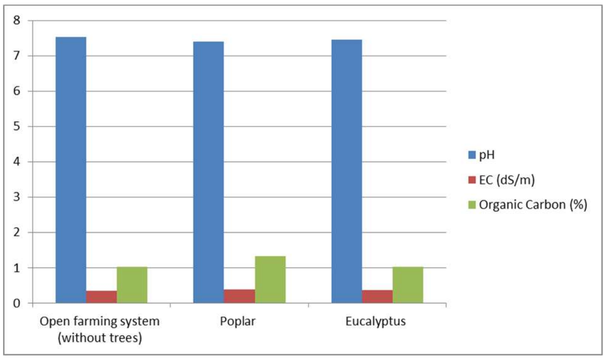

Figure 1: Effect of various agroforestry and open agricultural systems on soil pH, EC and SOC at a depth of 0–30 cm (Sharma *et al.,* 2022)

food security. However, soil infertility has been caused by subpar agricultural methods as well as other occurrences like soil erosion. By controlling the site's microclimate, trees and growing crops help to improve the environment. Organic matter can accumulate in the soil and nutrient cycling is made possible by litter fall, root elongation, and crown expansion, resulting in improved root zone characteristics and soil fertility (Laganiere *et al.,* 2010; Dinesha and Dey, 2023). According to Jobbage and Jackson (2001) micronutrient profiles are mainly characterized by rooting depth and distribution. Large amounts of nutrients can be absorbed below the rooting zone of crops by trees with deep and extensive root systems, which can then redistribute those nutrients to the topsoil (Allen *et al*., 2004). Through litter fall and root turnover, which varies with the type of tree, intercrops, plantation age, decomposing rate, season, and spacing, significant amounts of nutrients are returned to the soil. (Singh 2009, Laik *et al.,* 2009, Singh and Singh, 2016).

Effect of agroforestry on soil organic carbon

The mineral soil can be penetrated by the deep root systems of trees. Significant sources of SOC in deeper soil layers come from root-derived C inputs (Kell, 2012). In deeper soil layers close to trees, agroforestry systems accumulate more carbon than they do in shallower soil layers away from trees (Nair *et al*., 2010). Peichl *et al*. (2006) studied carbon sequestration in a poplar intercropping system that is 13 years old and found that it was four times higher than in a solo cropping system. He compared the carbon concentrations in soil from solo cropping sites, poplar intercropping sites, and spruce intercropping sites. Carbon concentrations were higher in poplar intercropping than in other intercroppings, according to the findings. According to Chauhan *et al*. (2012), soil enrichment through litter and roots increased organic carbon in the surface layer of soil under poplar-based agroforestry compared to a no-tree control. Stefano and Jacobson (2018) conducted a meta-analysis of the literature recently published. They discovered that switching from non-tree systems to agroforestry systems boosted SOC storage in general. In a 28-year-old long term experiment under Eastern Himalayas, Yadav *et al*. (2021) studied the effect of agroforestry system on different carbon fractions in 0-15 cm of soil depth and they revealed that very labile, labile, less labile and non labile fractions were significantly higher under sisoo+pineapple system (6.44, 4.45, 5.38 and 5.86 mg/h) as compared to sole cropping of pinapple (3.19, 4.41, 2.75 and 2.42 mg/h).

In subtropical plantations in China, Wang *et al.* (2013) studied the effect of different tree species mixture on organic carbon stocks of soil and found that SOC stocks were 14.3 and 8.1% higher in mixed plantations than that of *Pinus massoniana* and *Castanopsis hystrix* plantations in 0-20 cm soil depth. These differences in SOC stocks among plantations were attributed to root biomass, leaf litter fall input and soil Nstock. The results show that silvicultural approach of mixture of *C. hystrix* versus *P. massoniana*can be a better option for soil organic carbon (SOC) sequestration as compared to monoculture plantations in subtropical China. Guo *et al*. (2018) investigated seasonal and vertical variations of SOC in five different planting systems, a pure wheat (*Trticum aestivum*) field, a pure ginkgo (*Gingko biloba*) system, a pure metasequoia (*Metasequoia glyptostroboides*) seedling system, a ginkgo and metasequoia-based agroforestry system.. The results showed that the ginkgo and wheat agroforestry system had significantly higherSOC throughout the year when compared to other systems at varying soil depths i.e., 0-10 and 10-20 cm. SOC concentration was lower in the pure *Metasequoia* and pure *Ginkgo* planting systems than in the other planting systems. The cause for this decline was a reduction in tree input and a reduction in fine root biomass. This demonstrates that agroforestry systems are more efficient and resulted in a higher soil C sink buildup. Matos *et al*. (2011) investigated the impacts of changing land use from silvopasture to arable land, grassland, continuous arable land, and silvopasture on the dynamics of (SOC). Carbon stocks decreased by 47% on average from upper soil depth (0-10) cm to lower soil depth (10-20 cm). In comparison to silvopasture-arable land and arable land systems, soils under silvopasture had the highest total organic carbon in the upper layers.

Effect of agroforestry on soil macronutrients

The most important benefit of the agroforestry system is the improvement in soil fertility maintenance (Singh, 2010). In addition to reducing soil carbon loss due to erosion, agroforestry systems aid in nutrient replenishment, which is lost when biomass is harvested (Vallejo *et al.,* 2012). In India, a poplar-based agroforestry system and rice-wheat, maize-wheat, and cotton-wheat rotation farmlands were compared to examine P availability and speciation by Prakash *et al.* (mention year) and they concluded that in comparison to other conventional land uses agroforestry produced more organic P and less inorganic P as well as having a higher SOC content. Due to lesser P availability, intercropping appeared to reduce P nutrition. In temperate climatic conditions in Belgium, Pardon *et al*. (2017) evaluated the impact of tree rows bordering arable fields and alley cropping on nutrient availability in a plough layer (0-23 cm) at different distances from the tree rows and with different tree ages and sizes. The average increase in soil nutrient stocks in the agroforestry system was 86, 108, 45 and 16 kg/h of P, K, Mg, and Na, respectively. Arora *et al.,* (2021) assessed the effects of different land use systems on soil chemical characteristics in the 0–15 m of soil depth in the Shiwalik foothills of northwest India. They reported that under cultivated land available P and available K (27.9 and 189.9 kg/h) were comparatively higher than in agri-horticulture (21.0 and 151.2 kg/h) and agroforestry (22.2 and 156.0 kg/h) systems, respectively. The continual addition of inorganic fertilizers might have been the reason for the higher availability of P and K in farmed systems.

Sarvade *et al.* (2014) studied the effect of intercropping of four tree species viz., *Populus deltoides* (T1), *Eucalyptus camaeldulensis* (T2), *Leucaena leucocephala* (T3) and *Melia azedarach* (T4) planted at 3.0×1.0 m^2 (S1), 3.0×1.5 m^2 (S2), 3.0×2.0 m^2 (S3), 3.0×2.5 m^2 (S4) spacing with wheat (*Triticum aestivum L*) variety PBW-502 on Available soil N, P and K. The results showed that available N and P were significantly influenced by tree species and their spacing treatments whereas K_2O was non-significant. The highest available soil N (83.8 mg/kg), P (7.04 mg/kg) and K (73.4 mg/kg) were recorded under *Leucaena leucocephala*. The S3 tree spacing recorded highest available soil N (81.8 mg/kg), P_2O_5 (7.05 mg/kg) and K_2O (72.1 mg/kg). The findings showed that highest values for soil nutrients were recorded from T3×S3 treatment combination. Mineralization of organic forms and atmospheric Nfixation are the key ways in which these nutrients are made available to plants in agroforestry systems. In *Melia dubia*-wheat agroforestry system, Narender *et al.* (2021) studied the effect of agroforestry system on SOC , Nand potassium (K) in surface and sub-surface soil layers under semi-arid region of Haryana. They observed that available N, available P and available K were significantly higher under tree based system (128.65, 11.88 and 293.15 kg/h) as compared to sole cropping wheat without tree (108.89, 10.58 and 246.41 kg/h), respectively. Similar results were observed forSOC. Also, it was revealed that SOC, available N, available P and available K were significantly higher in surface soil layer (0-15 cm) as compared to sub-surface soil layer (15-30 cm). So, in order to make the soil enrich in nutrients agroforestry system can be considered as suitable option as compared to sole cropping system. An experiment was conducted by Sharma *et al.* (2022) to demonstrate the effect of agroforestry system on soil available N, P and K in 0-30 cm of soil depth (Figure 2) and concluded that available N and K_2O was significantly higher under popular and eucalyptus based agroforestry system as compared to open farming system. While P_2O_5 was not significantly affected by the different land uses, although highest P_2O_5 was observed under eucalyptus-based agroforestry system (20.2 kg/h) followed by popular (19.6 kg/h) and least under open farming system (17.7 kg/h). Pardon *et al.* (2017) studied the effect of alley cropping and arable fields bordered by tree row on nutrient availability with in a plough layer (0-23 cm) in temperate climatic conditions of Belgium having different distances from the tree rows and with

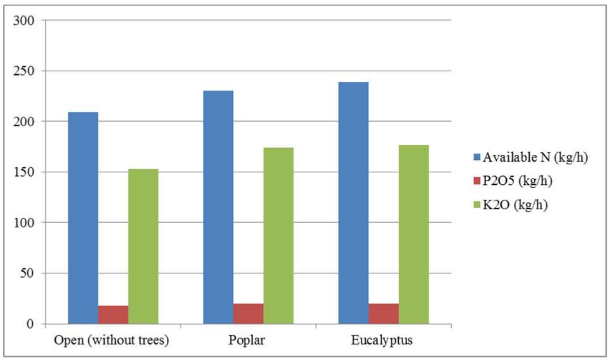

Figure 2: Effect of various agroforestry and open agricultural systems on soil available N, P and K at a depth of 0–30 cm (Sharma *et al.,* 2022)

different tree ages and sizes. The results revealed that average increase in soil nutrient stocks in agroforestry system was 86, 108, 45 and 16 kg/h of P, K, Mg and Na respectively when compared to control. The average total N stock increased by 56 kg/h in 0-23 cm soil layer of transects closer to the tree row. This increased soil Nconcentrations appeared to be strongly linked with buildup of SOCconcentrations. Yang *et al.* (2018) found that total Pcontent was higher under trees than abandoned land which can be due to organic acids (secreted by roots) activating P and improving P availability.

Effect of agroforestry on soil micronutrients

Micronutrients are essential for plants to complete their life cycle; they are utilised in small amounts to promote healthy plant growth, improve soil quality, boost crop yield, and supply balanced nutrition to crops (Lal, 2009). The long-term cultivation of a specific type of soil system changes the physical and chemical qualities of the soil, as well as the micronutrient content in the soil, making it available for plant growth. Different land uses alter micronutrient availability and redistribution through changes in soil chemistry and OM (Doran, 2002). Ram *et al.* (2022) concluded that among different land use systems higher zinc, iron, copper, and manganese soil were found under agroforestry-based systems (poplar+turmeric and eucalyptus+turmeric) as compared to fallow uncultivated land and sole cropping system in 0-20 cm of soil depth (Figure 3). In deep loamy alluvial soils, Kaur *et al.* (2020) conducted an experiment to study the impact of agroforestry system of different ages on micronutrient availability. They observed that availability of Zn, Cu, Fe and Mn was significantly higher under 30 year-old popular based agroforestry system as compared to 10 and 20 years old system. The availability of micronutrients in surface soils of agroforestry land use systems was also found to be higher when compared to fodder-fodder and fallow land because of higher organic matter content, which results in proper aeration and protection of micronutrients in bound forms from oxidation and precipitation, and supplied soluble chelating agents, increasing the solubility of micronutrient contents (Saha *et al.,* 2019).

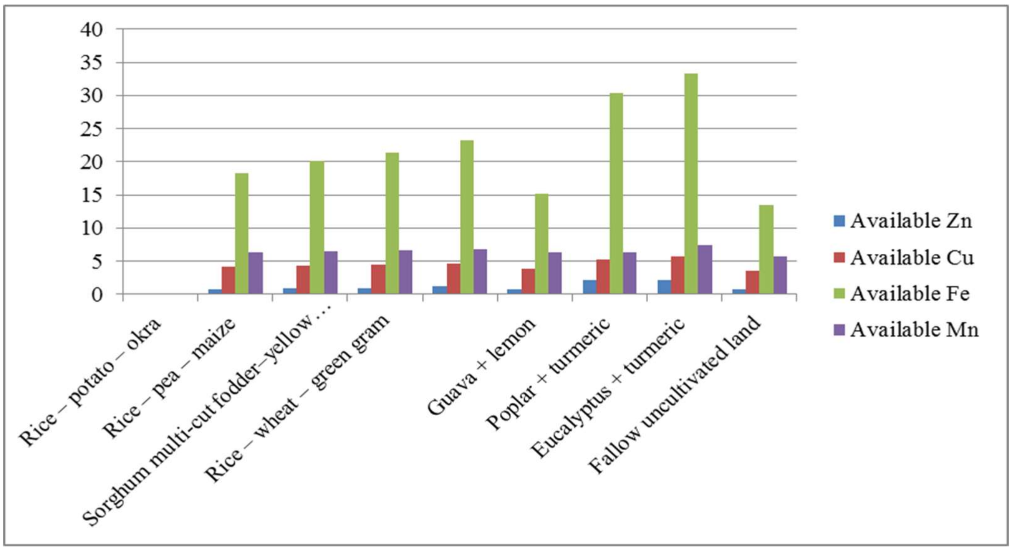

Figure 3: Micronutrient concentration (mg/kg) in soil at 0–20 cm depth under various land-use systems (Ram *et al.,* 2022)

Conclusion

The reviewed research suggests that agroforestry systems have a lot of potential for improving soil fertility. In comparison to monocropping, combining trees with agricultural crops increased N, P and K availability. Under tree-based land use patterns, there was an overall increase in SOC and carbon fractions. Also, under tree-based systems, an increase in soil organic matter boostedN and have a better micronutrient status in the soil than solo cropping systems and barren lands. So, adopting a tree-based farming system can be a sustainable way to reduce chemical fertilizer use, improve nutrient cycling, and increase soil carbon.

Conflict of interest

The authors declare that they have no conflict of interest.

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