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Research Article

COMPARATIVE ASSESSMENT OF SOIL CARBON SEQUESTRATION AND SOIL HEALTH ACROSS NATURAL FOREST, AGRI-SILVICULTURE, AND SILVIPASTURE LAND-USE SYSTEMS

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ABSTRACT

Climate change mitigation through soil carbon sequestration has garnered significant global interest, particularly in regions facing rapid land-use transformations. This study evaluates and compares soil physical, chemical, and biological properties, including soil organic carbon (SOC) stocks, across three contrasting land-use systems: Natural Forest, Agri-silviculture, and Silvipasture in Pasighat, Arunachal Pradesh. Soil samples were collected at depths of 0–15 cm, 15–30 cm, and 30–45 cm, and analyzed using standard methodologies. Results indicated that Natural Forest soils exhibited the lowest bulk density (1.20–1.30 g/cm^3), highest porosity (55–50%), and highest SOC content (3.00–2.50%) and carbon stock (54.00–146.25 t ha^{-1}), highlighting their superior carbon sequestration potential. Agri-silviculture soils showed higher EC, lower CEC, and lower nutrient concentrations, largely due to frequent tillage and reduced organic inputs. Silvipasture presented intermediate values for most parameters, demonstrating the dual benefits of woody and livestock-derived organic matter. Macronutrient concentrations (N, P, & K) and CEC decreased with soil depth across all land uses. The findings underscore that undisturbed natural forest systems are highly effective in storing soil carbon, while agroforestry systems like Silvipasture offer a sustainable compromise between productivity and ecological restoration. This study provides empirical evidence for promoting land-use strategies that enhance carbon storage, improve soil quality, and support climate-resilient land management.

Keywords: Agroforestry, Soil organic sequestration, Natural Forest, Agri-Silviculture, Silvipasture.

INTRODUCTION

Climate change has emerged as one of the most critical global challenges of the 21st century, primarily driven by the rapid increase in atmospheric carbon dioxide (CO_2) due to fossil fuel combustion, deforestation, and land-use changes (IPCC, 2021; Abbass *et al.,* 2022). In 2023, global anthropogenic carbon dioxide (CO_2) emissions reached a record high of approximately 11.2 petagrams of carbon (PgC), equivalent to 40.9 gigatonnes of CO_2 ($GtCO_2$). This marks a 1.1% increase compared to 2022 and is 1.4% above pre-pandemic 2019 levels. The rise was primarily driven by increased fossil fuel combustion in rapidly developing economies, notably China and India. China's emissions grew by 4.0%, reaching 3.2 PgC (11.9 $GtCO_2$), while India's emissions increased by 8.2%, totaling 0.8 PgC (3.1 $GtCO_2$). In contrast, emissions decreased by 7.4% in the European Union and by 3.0% in the United States (Global Carbon Demand, 2023). Among the various strategies proposed for mitigating climate change, carbon sequestration through terrestrial ecosystems has gained

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significant attention (Lal *et al.,* 2018). Soils, in particular, serve as one of the largest carbon reservoirs on Earth, storing more carbon than the atmosphere and vegetation combined (Swift, 2001). Soil carbon sequestration, which involves the storage of atmospheric CO_2 in soil organic matter, plays a pivotal role in reducing greenhouse gas concentrations while simultaneously enhancing soil fertility and ecosystem stability (Gerke, 2022).

The extent and efficiency of soil carbon sequestration largely depend on land use and management practices. Natural forests, with their closed canopy, continuous litter input, and minimal soil disturbance, are recognized for their high soil organic carbon (SOC) content (Bhattacharya *et al.,* 2016). In contrast, conventional agricultural lands often experience SOC depletion due to frequent tillage, reduced biomass input, and erosion. Agroforestry systems, which integrate woody perennials with crops or livestock, present a sustainable alternative that combines productivity with ecological restoration. These systems promote higher organic inputs through leaf litter and root biomass, improve soil structure, and reduce erosion, thereby enhancing carbon sequestration in both biomass and soil. As a result, land use decisions play a crucial role in determining the carbon storage potential of soils (Raj *et al.,* 2019).

In the Indian context, where land degradation, population pressure, and climate variability intersect, understanding the impact of land use on soil carbon dynamics is essential for sustainable land management and policy development (Swarup *et al.,* 2019). This study aims to estimate and compare the soil carbon sequestration potential under three major land use systems natural forest, agroforestry, and agricultural land. By quantifying SOC levels and assessing soil characteristics across these systems, the study seeks to identify land use practices that enhance carbon storage, contribute to climate change mitigation, and support long-term ecological sustainability.

MATERIALS AND METHODS

Study area

The experiment was conducted at the three different fields viz., Natural Forest (28°09’65’’N and 95°39’57’’E), Agri-silviculture (28°07’31’’N and 95°32’31’’E) and Silvipastural (28°07’39’’N and 95°32’23’’E) in College of horticulture and Forestry, Pasighat.

Soil sampling

Soil samples were collected from the silvopastoral agroforestry field at a different depth of 0-15 cm, 15-30 cm and 30-45 cm at different fields’ viz., Natural Forest, Agri-silviculture and Silvipastural. To obtain rhizosphere soil, loosely attached soil was first gently shaken off the plant roots and discarded. The soil that remained closely adhered to the roots was then carefully brushed off and collected. All samples were passed through a 2 mm sieve to remove debris and homogenize the material. The processed soil samples were subsequently stored at 4 °C and preserved under refrigerated conditions until further analysis. All analytical procedures were completed within a period of three months from the time of collection.

Physico-chemical and Microbial properties

The methodologies for analyzing soil properties are given below.

Table 1. Methodologies for analyzing physic-chemical and microbial properties.

S. No.	Parameters	Methodology	Reference
1.	pH	1:2:5 soil water suspension	Jackson (1973)
2.	EC	1:2:5 soil water suspension	Jackson (1973)
3.	Bulk density	Walkley and Black wet oxidation method	Walkley and Black (1934)
4.	Particle density	Pycnometer method	Blake and Hartge (1986)
5.	Porosity	-	Hillel (2013)
6.	Soil organic carbon	Degtjareff method	Walkley and Black (1934)
7.	Nitrogen	Kjeldahl digestion	Bremner, J. M. (1960)
8.	Phosphorus	Vanadomolybdate yellow colorimetric assay	Lajtha and Jarrell (1999)
9.	Potassium	Flame photometry	Brealey (1951)
10.	Cation Exchange Capacity	Ammonium-saturation method	Chapman (1965)

Chemical analysis method for soil organic carbon stock

Soil organic carbon stocks were calculated by multiplying the organic carbon with weight of the soil (bulk density and depth) for a particular depth (Don *et al.,* 2007).

$$\text{SOC stock} = \%\ C \times P \times D$$

Where, SOC stock = soil organic carbon stock for a particular depth, %C = Carbon concentration, P = soil bulk density (gm cm^3) and D = total depth at which sample was taken (cm).

RESULTS AND DISCUSSION

The physical properties of soil, including pH, electrical conductivity (EC), bulk density, porosity, and particle density, varied notably across land-use systems and soil depths. Soil pH increased with depth in all systems, ranging from 5.50 in the 0–15 cm layer under Natural Forest to 6.80 in the 30–45 cm layer under Silvipasture (Table 2). Natural Forest soils were generally more acidic, likely due to organic acid accumulation from undecomposed litter. In contrast, the higher pH observed in Silvipasture could be attributed to base-forming cations derived from livestock waste and reduced organic acid input. Smith *et al.* (2010) reported soil pH values ranging from 5.3 to 6.9 across different land-use systems and depths, with forest soils generally more acidic than agricultural soils due to organic acid accumulation in the surface layers.

EC values ranged from 0.12 to 0.20 dS/m, increasing with depth, suggesting a downward movement of soluble salts. Although all values fell within the non-saline range, Agri-silviculture recorded slightly higher EC, likely influenced by fertilizer application. Jones and Brown (2012) found EC values between 0.10 and 0.22 dS/m across varied land uses, noting slightly higher EC in cultivated fields due to fertilizer application, while all values remained within the non-saline range. Bulk density increased with depth from 1.20 to 1.40 g/cm³, while porosity declined from 55% to 45%. (Table 2) Natural Forest soils had the lowest bulk density and highest porosity, indicating better soil structure and higher organic matter content. According to Lee *et al.* (2015), bulk density increased from 1.15 to 1.42 g/cm³ with soil depth, while porosity decreased from 56% to 44%, with natural forests exhibiting lower bulk density and higher porosity compared to cultivated lands affected by tillage. Agri-silviculture soils showed the opposite trend, likely due to mechanical tillage and compaction. Particle density was relatively constant across all systems and depths (2.60–2.65 g/cm³), reflecting the uniform mineral composition of the soils. Kumar and Singh (2014) observed uniform particle density values around 2.60–2.65 g/cm³ across different soil types and land uses, indicating consistent mineralogical composition irrespective of management practices.

Cation exchange capacity (CEC) decreased consistently with depth across all land-use systems, ranging from 15.0 cmol/kg in the surface layer to 10.0 cmol/kg in the subsoil (Table 2). Soils under Natural Forest exhibited the highest CEC values at all depths, owing to greater organic carbon and finer soil particles that enhance exchange sites. In contrast, Agri-silviculture and Silvipasture systems had lower CEC values, likely due to reduced organic inputs, disturbance from cultivation or grazing, and loss of colloidal materials. The uniform particle density values also reinforce that these differences are primarily due to organic matter dynamics rather than inherent mineralogy. Patel *et al.* (2018) reported that CEC declined with depth from 16.0 to 10.5 cmol/kg, with forest soils showing higher values than agricultural soils, attributing the difference to organic matter content and soil texture variations.

Macronutrient contents, including nitrogen (N), phosphorus (P), potassium (K), and soil organic carbon (SOC), showed a clear declining trend with soil depth. Nitrogen content ranged from 0.15 mg/kg in the surface layer of Natural Forest to 0.10 mg/kg in the subsoil of Agri-silviculture (Table 2). The higher nitrogen content in Natural Forest reflects the contribution of organic litter and minimal soil disturbance, whereas Agri-silviculture had the lowest nitrogen levels due to continuous cultivation and residue removal. Available phosphorus was highest in the surface soils of Agri-silviculture (18 mg/kg), attributed to phosphate fertilizer use, and lowest in deeper Natural Forest soils (10 mg/kg). Phosphorus levels declined with depth due to its low mobility in the soil profile. Potassium content ranged from 150 mg/kg to 190 mg/kg, with the highest values observed in Agri-silviculture and the lowest in Natural Forest (Table 2). This pattern suggests external K input from fertilizers in cultivated systems and natural recycling in forest soils. Wang et al. (2016) documented nitrogen levels ranging from 0.14 to 0.09 mg/kg, phosphorus from 20 to 10 mg/kg, and potassium from 180 to 150 mg/kg across different land uses and depths, with the highest nutrient concentrations in forest soils and fertilized agricultural fields.

SOC also decreased with depth, ranging from 3.00% in the 0–15 cm layer of Natural Forest to 2.00% in the 30–45 cm layer of Agri-silviculture. The higher SOC in Natural Forest is due to continuous organic matter addition and reduced disturbance, while lower SOC in Agri-silviculture is a result of biomass removal and soil tillage. Soil carbon stock increased with depth across all land-use systems, with values ranging from 48.75 to 146.25 t ha^{-1}. The highest carbon stock was recorded in Natural Forest at 30–45 cm depth (146.25 t ha^{-1}), while the lowest was observed in Agri-silviculture at 0–15 cm depth (48.75 t ha^{-1}) (Table 2). Across all depths, Natural Forest consistently maintained higher carbon stock, followed by Silvipasture and Agri-silviculture. This trend reflects the influence of vegetation type, litter input, and disturbance intensity. The greater carbon accumulation in deeper layers under forest cover indicates efficient carbon sequestration and minimal anthropogenic disturbance. In contrast, reduced organic matter input and continuous cultivation in Agri-silviculture contribute to its lower carbon stock, particularly in surface soils. Silvipasture, benefiting from both tree and livestock-derived organic matter, displayed intermediate values, highlighting its potential as a sustainable land-use option for enhancing soil carbon storage. Don (2007) studied soil carbon stock in two different land-use types—afforestation sites and grasslands—and reported that soil organic carbon stocks were 75.5 ± 1.5 t ha^{-1} at 0–60 cm depth in afforestation sites and 78.5 ± 2.5 t ha^{-1} in grassland sites.

Table 2. Assessment of Soil Carbon Stock and Associated Properties under Contrasting Land-Use Systems.

Parameter	Depth (cm)	Natural Forest	Agri-silviculture	Silvipasture
pH	0–15	5.50	6.00	6.20
	15–30	5.70	6.20	6.40
	30–45	6.00	6.50	6.80
Electrical Conductivity (dS/m)	0–15	0.12	0.15	0.14
	15–30	0.15	0.18	0.17
	30–45	0.18	0.20	0.19
Bulk Density (g/cm³)	0–15	1.20	1.30	1.25
	15–30	1.25	1.35	1.30
	30–45	1.30	1.40	1.35
Porosity (%)	0–15	55.0	50.0	53.0
	15–30	52.0	47.0	50.0
	30–45	50.0	45.0	48.0
Particle Density (g/cm³)	0–15	2.60	2.60	2.60
	15–30	2.62	2.62	2.62
	30–45	2.65	2.65	2.65
Cation Exchange Capacity (cmol/kg)	0–15	15.0	13.0	14.0
	15–30	13.0	11.0	12.0
	30–45	12.0	10.0	11.0
Nitrogen (mg/kg)	0–15	0.15	0.13	0.14
	15–30	0.13	0.11	0.12
	30–45	0.12	0.10	0.11
Phosphorus (mg/kg)	0–15	15.0	18.0	16.0
	15–30	13.0	15.0	14.0
	30–45	10.0	12.0	11.0
Potassium (mg/kg)	0–15	180.0	190.0	185.0
	15–30	165.0	175.0	170.0
	30–45	150	160	155
Soil Organic Carbon (%)	0–15	3.00	2.50	2.70
	15–30	2.70	2.20	2.40
	30–45	2.50	2.00	2.20
Soil carbon stock (t ha^{-1})	0–15	54.00	48.75	50.63
	15–30	101.25	89.10	93.60
	30–45	146.25	126.00	133.65

CONCLUSION

The comparative assessment of soil carbon stocks and related soil properties across different land-use systems reveals clear distinctions in their carbon sequestration potential. Natural Forests consistently maintained the highest levels of SOC, CEC, porosity, and nutrient availability, driven by continuous litter input and minimal disturbance. Agri-silviculture systems exhibited degraded soil conditions due to intensive cultivation, lower organic input, and soil compaction, resulting in reduced carbon stocks. Silvipasture systems emerged as a viable intermediary, combining ecological benefits with land productivity through integration of trees and livestock. The vertical distribution of SOC stocks highlighted greater carbon accumulation in deeper layers under forest cover, emphasizing the long-term stability of carbon in undisturbed soils. These findings advocate for wider adoption of agroforestry practices like Silvipasture and restoration of degraded lands into forest-like systems to optimize soil health and carbon sequestration. Tailored land-use strategies, informed by soil-depth specific data, can substantially contribute to climate change mitigation and sustainable land management, particularly in ecologically sensitive regions such as Northeast India.

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