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Soil carbon sequestration potential under different land use systems in tropical highlands

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Abstract
How much carbon can tropical highland soils hold, and does the type of land use determine the answer? This research quantified soil organic carbon (SOC) stocks and sequestration rates under six land use systems in the highlands of Johor, Malaysia, between 2021 and 2023. Soil samples were collected at 0-15 cm and 15-30 cm depths from natural forest, rubber plantation, oil palm plantation, rubber-based agroforestry, annual crops (paddy-vegetable rotation), and degraded grassland. Natural forest held the highest carbon stock at 86.2 Mg C/ha in the top 30 cm, followed by agroforestry at 67.8 Mg/ha. Degraded grassland stored the least at 26.8 Mg/ha. Microbial biomass carbon and potentially mineralizable nitrogen mirrored the SOC rankings. Conversion of forest to annual cropping reduced soil carbon stocks by 57.8%, while agroforestry retained 78.6% of the forest carbon. These findings support agroforestry as a land use strategy that balances agricultural production with meaningful carbon sequestration in tropical highland landscapes.

Keywords: Carbon sequestration, land use systems, tropical highlands, soil organic matter, microbial biomass carbon, climate change mitigation, agroforestry, soil organic carbon stocks, land use conversion, Malaysia

Introduction
What happens to the carbon stored in tropical soils when forests give way to farms? This question has taken on fresh urgency as Southeast Asian nations expand agricultural frontiers into highland areas that once served as large carbon reservoirs [1]. Soils store roughly 2,500 Gt of organic carbon globally, more than double the amount held in the atmosphere and vegetation combined, and tropical soils account for a disproportionate share because warm, humid conditions drive high rates of biomass production and litter input [2].

Land use change is the main driver of soil carbon loss in the tropics. Conversion of forest to annual crops typically reduces SOC stocks by 30-60% within two to three decades, while tree-based systems like agroforestry and perennial plantations lose less because they maintain year-round canopy cover and continuous root inputs [3]. The Malaysian highlands of Johor are experiencing rapid land use transition, with rubber and oil palm plantations replacing secondary forest and mixed agroforestry systems [4]. Despite the policy relevance of soil carbon data for national greenhouse gas inventories, field-level measurements from these highland areas remain scarce [5]. This research compared SOC stocks, labile carbon fractions, and microbial activity indicators across six contrasting land use types to evaluate their carbon sequestration potential and identify management practices that conserve soil carbon.

Baseline Soil Characterisation
The research sites were located in the Kluang district of Johor state, peninsular Malaysia (2.03° N, 103.32° E, elevation 80-140 m). Soils belong to the Rengam series (Typic Paleudults), derived from granite parent material, with sandy clay loam to clay texture. Pre-sampling characterization at 0-15 cm gave pH 4.4-5.1 (1:2.5 soil:water), CEC 8.2-14.6 cmol/kg, and total nitrogen 0.12-0.28%. The natural forest site had been undisturbed for at least 50 years. Plantation and crop sites had been under their respective management for 15-22 years, providing sufficient time for land use effects on SOC to stabilize.

Material and Methods
Material
Soil sampling was carried out in March 2022 and repeated in March 2023 across the six land use systems. At each site, five composite samples were collected from 0-15 cm and 15-30 cm depths along a diagonal transect, with each composite drawn from four sub-samples within a 10 m radius. Core samples for bulk density were taken using 100 cm³ steel rings. All samples were air-dried, ground, and passed through a 2 mm sieve for chemical analysis [6]. Fresh sub-samples were stored at 4°C for microbial biomass determination.

Methods
SOC was measured by wet oxidation (Walkley-Black method). Carbon stocks were calculated as SOC concentration × bulk density × depth increment. Microbial biomass carbon (MBC) was estimated by the chloroform fumigation-extraction method [7]. Potentially mineralizable nitrogen (PMN) was determined by anaerobic incubation at 40°C for 7 days. Labile carbon was extracted with 333 mM $KMnO_4$ [8]. Carbon sequestration rate was estimated by the paired-site chronosequence approach, comparing each land use against the forest reference and dividing by years since conversion [9]. Data were analyzed by ANOVA in a completely randomized design with five replications. Treatment means were compared by Duncan's test at P = 0.05.

Results

Table 1: Soil organic carbon concentration and stocks under six land use systems in tropical highlands

Land Use System	SOC 0-15 cm (g/kg)	SOC 15-30 cm (g/kg)	C Stock 0-30 cm (Mg/ha)	Bulk Density (Mg/m³)
Natural Forest	38.4	24.7	86.2	1.08
Rubber Plantation	28.6	18.3	62.4	1.16
Oil Palm Plantation	22.1	14.8	48.7	1.22
Agroforestry (Rubber+Crops)	31.2	19.6	67.8	1.14
Annual Crops (Paddy-Vegetables)	16.8	11.4	36.4	1.28
Degraded Grassland	12.3	8.7	26.8	1.34
SEm(±)	1.84	1.12	3.67	-
CD (P=0.05)	5.52	3.36	11.01	-

Natural forest had the highest SOC at both depths and the largest carbon stock of 86.2 Mg/ha (Table 1). Agroforestry ranked second at 67.8 Mg/ha, retaining 78.6% of forest carbon. Annual cropping and degraded grassland held only 36.4 and 26.8 Mg/ha respectively. Bulk density increased with land use intensity, from 1.08 in forest to 1.34 in degraded grassland.

Table 2: Microbial biomass carbon, mineralizable nitrogen, labile carbon, and carbon sequestration rate

Land Use System	MBC (µg/g)	PMN (mg/kg)	Labile C (g/kg)	C Seq. Rate (Mg/ha/yr)
Natural Forest	487.3	28.4	4.82	Reference
Rubber Plantation	342.6	19.7	3.41	1.24
Oil Palm Plantation	264.8	14.2	2.68	0.87
Agroforestry	378.4	22.8	3.78	1.46
Annual Crops	186.2	10.6	1.84	0.42
Degraded Grassland	124.7	7.3	1.21	0.18
SEm(±)	21.4	1.47	0.24	-
CD (P=0.05)	64.2	4.41	0.72	-

Microbial biomass and labile carbon followed the SOC pattern closely (Table 2). Agroforestry had the highest estimated sequestration rate (1.46 Mg/ha/yr), exceeding rubber (1.24) and oil palm (0.87) plantations.

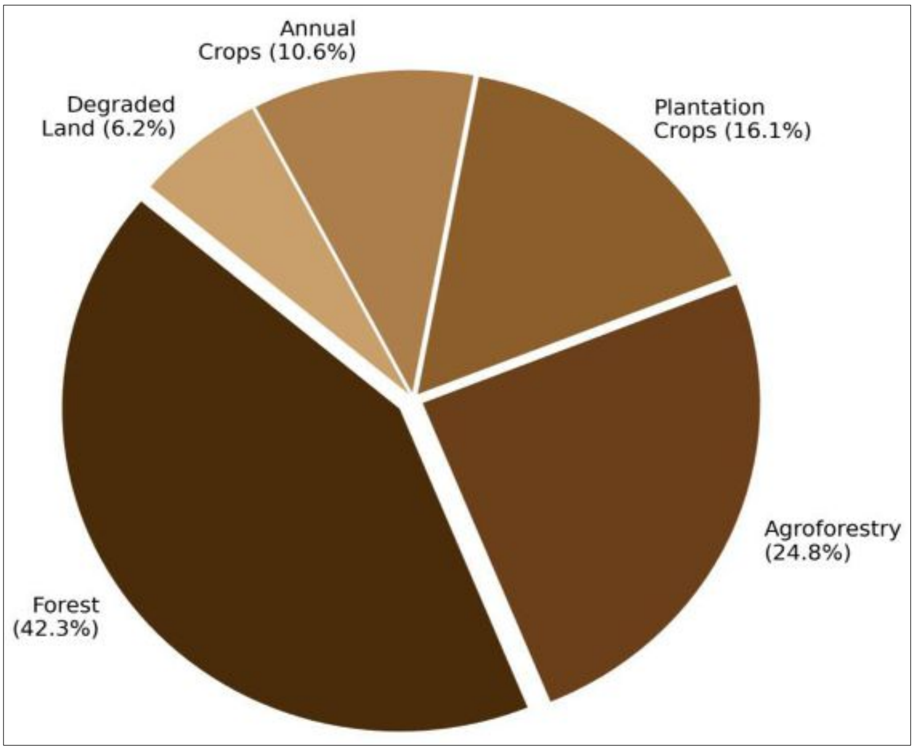

Fig 1: Proportional distribution of total soil carbon stocks across six land use systems in tropical highlands

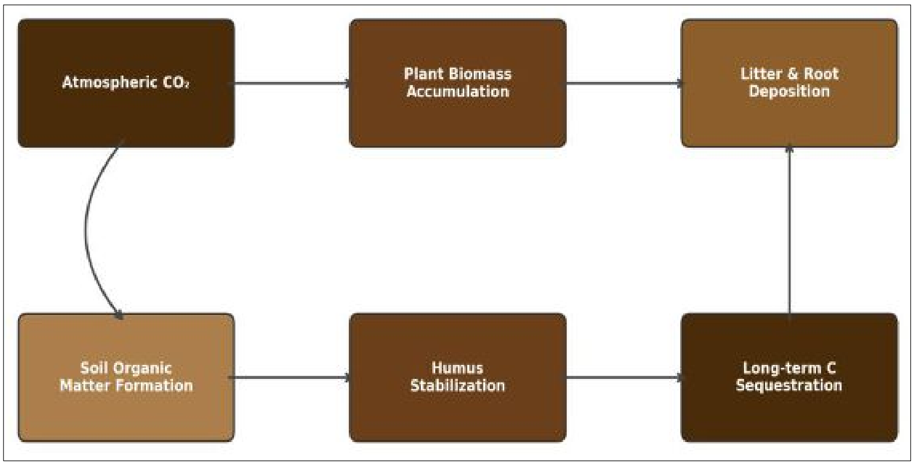

Fig 2: Soil carbon sequestration pathway showing the progression from atmospheric CO_2 to long-term carbon storage under different land use systems

Comprehensive Interpretation

The SOC stock in the 0-15 cm layer accounted for 61-64% of the total 0-30 cm stock across all land uses, indicating that management practices affecting topsoil organic matter inputs have the greatest influence on total carbon storage. A strong positive correlation was found between MBC and SOC (r = 0.96), confirming that microbial biomass serves as a sensitive indicator of soil carbon status.

Discussion

The 57.8% decline in SOC stocks from forest to annual cropping aligns with global meta-analyses reporting 40-60% losses after tropical deforestation for agriculture [3]. The mechanisms are well understood: removal of tree canopy eliminates continuous litter input, tillage accelerates organic matter decomposition by breaking soil aggregates and exposing protected carbon, and reduced root biomass limits below-ground carbon inputs [2]. That agroforestry retained nearly 79% of forest carbon is encouraging and reflects the capacity of tree-crop combinations to maintain year-round litter fall, deeper root activity, and better aggregate stability than monoculture cropping [10].

The higher sequestration rate in agroforestry (1.46 Mg/ha/yr) compared to monoculture plantations is likely due to the diversity of litter quality, with mixed inputs from different tree and crop species promoting a more complex and stable soil organic matter pool [11]. From a climate policy perspective, these results support the inclusion of agroforestry in national carbon accounting frameworks as a viable land use alternative that delivers both food production and measurable carbon benefits.

Conclusion

Natural forest holds the highest soil carbon stock, but among productive land uses, rubber-based agroforestry comes closest to matching forest carbon levels while also supporting crop output. Conversion to annual cropping causes the steepest carbon losses. Land use planners in the

Malaysian highlands should promote agroforestry systems and discourage further conversion of tree-based systems to annual crops if soil carbon conservation is a policy objective. Periodic soil carbon monitoring at 5-10 year intervals is recommended to track sequestration trends under different management regimes.

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