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Decadal Impact of an Integrated Farming System on Soil Organic Carbon Stock and Carbon Sequestration across Diverse Land Use Systems

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

Integrated farming systems (IFS) may improve soil carbon storage by diversifying biomass inputs and reducing reliance on continuous cereal cultivation. This field study assessed depth-wise soil organic carbon (SOC) stock and surface-layer carbon sequestration in a decade-old IFS model at the Farming System Research Centre, SKUAST-Jammu, Chatha, relative to an adjoining existing farmer's farming system (EFFS) under continuous rice–wheat cultivation. Composite soil samples were collected from four depths (0–15, 15–30, 30–45 and 45–60 cm) and analysed for organic carbon using the Walkley–Black method, while bulk density was determined by the core method. Carbon stock and sequestration were calculated from SOC concentration, bulk density and soil depth, and the data were analysed using a randomised block design. Soil carbon stock decreased with increasing depth across all land uses. The highest SOC stock up to 60 cm was recorded under boundary plantation with turmeric intercropping (46.64 Mg C ha^{-1}), followed by fodder, horticulture and crop blocks, while the lowest occurred under EFFS (26.34 Mg C ha^{-1}). Overall, the IFS model accumulated 38.91 Mg C ha^{-1} up to 60 cm, representing about 48% greater carbon storage than in EFFS. Surface-layer carbon sequestration ranged from 2.94 Mg C ha^{-1} under perennial fodder to 7.90 Mg C ha^{-1} under boundary plantation, whereas EFFS showed a negative value (–0.65 Mg C ha^{-1}). Over ten years, the IFS model achieved an overall carbon sequestration of 4.47 Mg C ha^{-1}, demonstrating its greater potential for soil carbon accumulation compared with continuous rice–wheat cultivation.

Keywords: *Integrated farming system; soil organic carbon; carbon stock; carbon sequestration; land use systems; rice–wheat cropping system.*

1. Introduction

Climate change and food insecurity are widely regarded as the two most pressing challenges of the present century, and both are intimately linked to the terrestrial carbon cycle (Lal, 2011). Atmospheric CO_2 concentration has continued its upward trajectory well past 400 ppm (Lal, 2018), and soils, which hold two to three times more carbon than the atmosphere, act simultaneously as a major source and sink of this carbon, so that even small management-driven shifts in soil organic carbon (SOC) can have disproportionate effects on the global carbon balance. Enhancing soil carbon sequestration through improved land use and management is therefore recognised internationally as one of the most accessible and cost-effective routes to climate change mitigation, underpinning initiatives such as the '4 per mille' soil carbon programme and various national carbon-farming incentives (Timilsina *et al.*, 2025).

Land use change is among the strongest determinants of SOC dynamics. Conversion between cropland, pasture, agroforestry and forest systems alters organic matter inputs, root biomass, litter turnover and soil physical protection of carbon, and can drive SOC either upward or downward depending on the direction and intensity of the change (Guo & Gifford, 2002; Shuai *et al.*, 2024). Continuous, intensive cereal-based cropping of the kind still widely practised by smallholders in the North-Western Himalayan foothills tends to deplete SOC through repeated tillage, residue removal and limited return of organic inputs, whereas diversified systems that integrate perennial components such as horticulture, fodder trees and boundary plantation tend to build carbon through greater and more continuous biomass return, root turnover and reduced soil disturbance (Rumpel & Kögel-Knabner, 2011; Saha *et al.*, 2014; Li *et al.*, 2007). Recent field evidence from India also indicates that land-use systems with greater tree integration can favour soil carbon build-up relative to purely agricultural land uses (Bhalawe *et al.*, 2024). Integrated Farming System (IFS) approaches, in which crop, horticulture, livestock, fishery, poultry, mushroom, biogas and boundary-plantation enterprises are combined on a single farm unit, have gained renewed attention as a means of simultaneously improving farm income and soil quality without the land-use trade-offs associated with pure monocultures (Jayanthi *et al.*, 2000; Babu *et al.*, 2023). Long-term, decadal IFS installations provide a rare opportunity to track how the carbon-building potential of individual farm enterprises compares with conventional practice under identical agro-climatic conditions. In the wider literature, integrated crop–livestock–forest and agroforestry systems have consistently been shown to outperform conventional cropping or pasture systems in SOC accumulation: integrated crop–livestock–forest management in Brazilian Ferralsols increased SOC across aggregate size classes relative to continuous cropping (Schiavo *et al.,* 2025), and integration of pasture with crop–livestock–forest components in tropical systems achieved SOC accumulation rates several-fold higher than conventional pasture or no-till management alone (Molina *et al.*, 2026). Similarly, deep-soil national baseline surveys have shown that management intensity and land use jointly control SOC stocks, underlining the need for depth-resolved rather than surface-only assessment (Castellón Meyrat *et al.*, 2026). A recent meta-analysis of studies from India likewise showed that carbon-building agricultural practices generally enhance soil organic carbon, while the magnitude of response varies with management practice, duration and agroecological context (Patil *et al.*, 2025).

Within agroforestry-type land uses, boundary and block plantations occupy a distinctive niche: because they combine minimal soil disturbance with continuous woody biomass and litter input along field margins, they have repeatedly been reported to sequester carbon at rates exceeding those of pure agricultural blocks in the North-Western and Central Himalayan region (Bhardwaj *et al.*, 2024; Singh *et al.*, 2024; Kaith *et al.*, 2023). Boundary and block plantation systems in the Indo-Gangetic plains have been reported to sequester carbon at annualised rates in the range of about 5.5 to 9.2 Mg C ha^{-1} yr^{-1}, exceeding many pure agricultural systems (Chavan *et al.*, 2023). Diversified, tree-integrated farming models incorporating boundary plantation alongside conservation agriculture and agroforestry have also been shown to raise soil carbon stocks and microbial functioning relative to traditional farming in multi-year on-farm trials in Central India (Pradhan *et al.*, 2026). Traditional agroforestry systems of the Garhwal Himalaya similarly show a consistent decline in SOC with depth, mirroring root density and biological activity gradients (Kumar *et al.*, 2025). Recent India-focused literature further identifies agroforestry-based land-use diversification as relevant to both carbon sequestration and climate adaptation (Prabakaran *et al.*, 2025). A bias-aware global synthesis of agroforestry meta-analyses also supports the capacity of tree-integrated systems to improve soil organic carbon and broader soil-health attributes, while recognising variation among systems and environmental contexts (Rubeaud *et al.*, 2026). Accurate depth-wise carbon accounting depends critically on reliable bulk density data, since even small errors in bulk density propagate directly into carbon stock estimates; recent methodological work has therefore emphasised standardised sampling and equivalent-soil-mass corrections when comparing carbon stocks across land uses or over time (Chirol *et al.*, 2025; Dubeux *et al.*, 2024), and continental-scale bulk density–organic carbon databases and models have been developed precisely to reduce this source of uncertainty (Chen *et al.*, 2024; Hou *et al.*, 2024). Land-use-driven changes in soil organic carbon have also been shown to interact strongly with bulk density and soil aggregation, with global meta-analyses confirming that both the direction and magnitude of soil organic carbon change following land use conversion are highly context-dependent (Huang *et al.,* 2024; Shuai *et al.,* 2024), and site-level studies from the Loess Plateau of China and semi-arid Ethiopia reporting parallel gains in aggregate-associated carbon and structural stability under less-disturbed land uses (Pan *et al.*, 2024; Kahsay *et al.*, 2025).

Within India specifically, and in the temperate and dry-temperate zones of Jammu and Kashmir in particular, land use has repeatedly been identified as the principal driver of soil organic carbon pools, fractions and the resulting carbon stocks: studies from the Kashmir valley have shown that converting fallow land to forest, orchard or vegetable land uses significantly raises total organic carbon at both surface and sub-surface depths (Khenrab *et al.*, 2026), findings echoed by carbon-pool and carbon-management-index assessments across the wider North-Western Himalaya (Mir *et al.*, 2023; Tiwari & Joshi, 2022; Blair *et al.*, 1995) and by district-level nutrient-mapping studies linking organic carbon status to land use in Jammu and Kashmir (Renuka *et al.*, 2022). Similar land-use-driven variability in soil organic carbon pools has also been reported from the dry-temperate belt of the North-Western Himalayas (Kumar *et al.*, 2024) and from the north-eastern hill region of India (Yadav *et al.*, 2024). At the policy level, India's growing emphasis on climate-smart nutrient management and soil-health-based interventions (Datta *et al.*, 2022; Balkrishna *et al.*, 2026; Verma *et al.*, 2026) further underscores the practical relevance of quantifying which farm-level land uses build soil carbon most effectively. Despite this body of evidence, quantitative, depth-wise soil carbon stock and sequestration data from a single, decade-old IFS model that spans crop, horticulture, fodder, perennial-fodder and boundary-plantation blocks side-by-side under North-Western Himalayan foothill conditions remain scarce. Most available studies report either surface-only carbon values or compare only two or three land uses at a time, so that the relative carbon-building performance of an entire farm-scale enterprise mix against conventional practice is not well established for this agro-ecological region. The present study was therefore undertaken to (i) quantify depth-wise soil organic carbon stock across the thirteen land use systems of a decadal IFS model at SKUAST-Jammu, Chatha, (ii) compute the corresponding carbon sequestration and carbon sequestration potential relative to the initial (2010) baseline, and (iii) compare these outcomes against an adjoining existing farmer's field under continuous rice–wheat cultivation, so as to identify which farm enterprises within the IFS framework contribute most to long-term soil carbon gain.

2. Materials and Methods

2.1 Study Area and Experimental Site

The study was conducted at two adjoining sites: (i) the live Integrated Farming System (IFS) research model established under AICRP-IFS at the Farming System Research (FSR) Centre on the main campus of Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu (SKUAST-Jammu), Chatha, and (ii) an adjacent farmer's field maintained under conventional rice–wheat cultivation, representing the existing farmer's farming system (EFFS). Both sites lie at 32°40′ N latitude and 74°58′ E longitude at an altitude of 332 m above mean sea level in the Shiwalik foothills of the North-Western Himalayas and experience a sub-tropical climate with hot, dry summers, a humid monsoon and cold, dry winters; the ten-year mean annual rainfall of the area is about 1234 mm, of which roughly 70% is received between June and September.

2.2 Land Use Systems and Experimental Details

The one-hectare IFS model, established in 2010, comprised thirteen land use systems organised into a crop block (CLU1–CLU3: rice–wheat–green manure, rice–potato–black gram, and rice–mustard–fodder rotations), a horticulture block (HLU4–HLU8: okra intercropped with broccoli, cauliflower and cabbage, a fodder sorghum–berseem rotation, and a fallow sole-horticulture unit), a fodder block (FLU9: maize + sorghum–berseem + oat), a boundary plantation block (BPLU10 and BPLU11: two turmeric cultivation strips raised beneath compatible forest tree species along the field margins) and a perennial fodder unit on the pond dyke (PGLU12: hybrid Napier grass). Of the 1-ha model, 0.82 ha was under these cultivated land uses, with the remaining 0.20 ha allocated to non-cultivable, non-soil enterprises (animal husbandry, fishery-cum-poultry, mushroom and vermi-compost units). The adjoining 1-ha EFFS plot (FFLU13) was maintained under a conventional rice–wheat cropping system representative of prevailing farming practice in the area.

2.3 Soil Sampling and Bulk Density Determination

Composite soil samples were collected from all thirteen land use systems at four depths (0–15, 15–30, 30–45 and 45–60 cm), air-dried, processed and analysed for organic carbon content by the Walkley-Black wet oxidation method (FAO, 2020). Bulk density at each depth in each land use was determined by the core method, consistent with recommended practice for depth-resolved carbon stock estimation (Gray *et al.*, 2015; Chen *et al.*, 2024). Baseline (initial, 2010) soil organic carbon and bulk density values for the site, recorded at the time of IFS model establishment, were used as the reference for computing carbon sequestration over the subsequent decade.

Plate 1. Aerial (drone) view of the study site showing the Integrated Farming System (IFS) model with its horticulture, crop and boundary-plantation blocks alongside the pond and the adjoining farmer's rice–wheat field (EFFS)

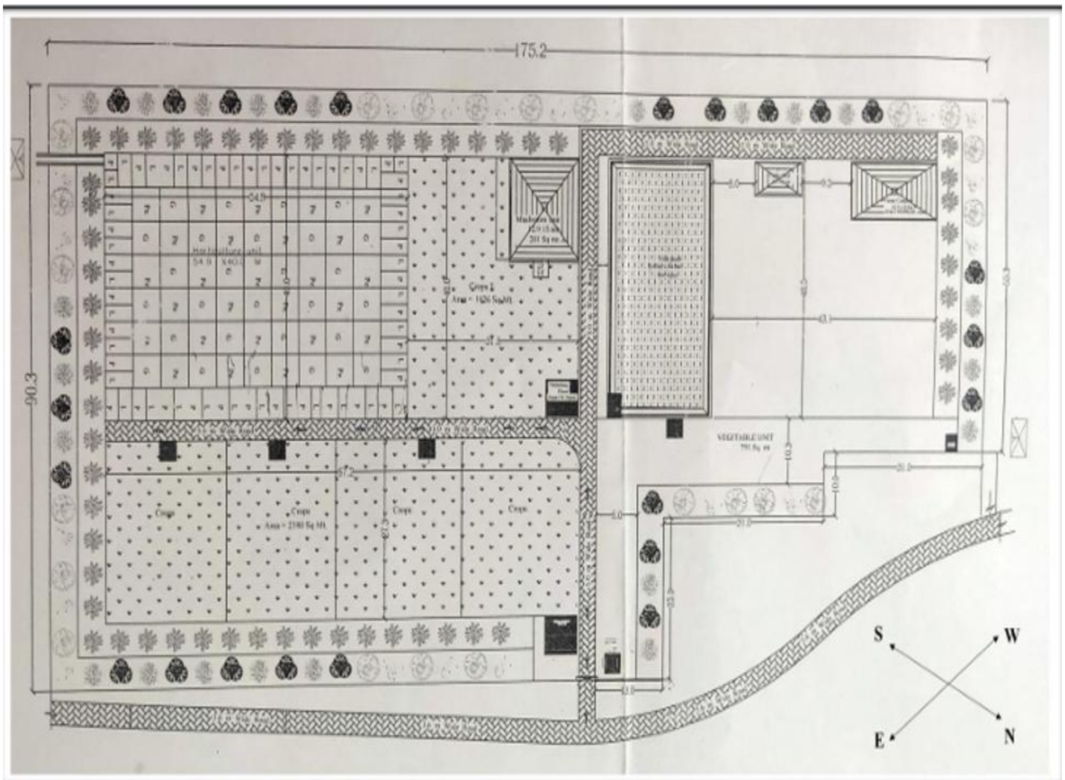

Plate 2. Layout plan of the IFS research model showing the horticulture unit, crop blocks, boundary plantation, vegetable unit and other component enterprises, with soil sampling locations distributed across the constituent land use systems

2.4 Computation of Soil Carbon Stock, Sequestration and Sequestration Potential

Soil carbon stock at each depth was computed following Bhardwaj *et al.* (2022) as:

$$C\ stock\ (Mg\ C\ ha^{-1}) = C\ content\ (\%) \times Bulk\ density\ (g\ cm^{-3}) \times Depth\ (cm)$$

Carbon sequestration over the study period was calculated as the difference between the final (2020) and initial (2010) carbon stock:

$$C\ sequestration\ (Mg\ C\ ha^{-1}) = Final\ C\ stock - Initial\ C\ stock$$

The annualised carbon sequestration potential was derived as:

C sequestration potential (Mg C ha⁻¹ yr⁻¹) = (Final C stock – Initial C stock) / Time (years)

Area-weighted carbon stock and sequestration for the IFS model as a whole were computed by combining the per-hectare values of each land use system with its proportional area within the 0.82-ha cultivated area of the 1-ha model and were compared with the corresponding values for the 1-ha EFFS plot.

2.5 Statistical Analysis

Data on soil carbon stock and sequestration were analysed using a randomised block design (RBD) in the Statistical Package for the Social Sciences (SPSS), with treatment means compared at $p < 0.05$.

3. Results and Discussion

3.1 Depth-wise Distribution of Soil Carbon Stock

Soil carbon stock declined progressively with increasing soil depth across all thirteen land use systems, consistent with the general pattern of surface accumulation and subsurface decline in organic carbon reported for both agricultural and agroforestry soils (Table 1, Fig. 1). At the surface depth (0–15 cm), carbon stock ranged from a low of 14.22 Mg C ha^{-1} under perennial fodder on the pond dyke to a high of 19.18 Mg C ha^{-1} under boundary plantation (BPLU10), against an initial (2010) baseline of 11.29 Mg C ha^{-1}, representing an improvement of nearly 70% over the decade. Carbon stocks in the crop block (14.41–15.67 Mg C ha^{-1}) and horticulture block (15.21–16.27 Mg C ha^{-1}) were intermediate, while the fodder block (18.03 Mg C ha^{-1}) approached the boundary plantation values. In contrast, the surface carbon stock of EFFS (10.63 Mg C ha^{-1}) remained below even the 2010 baseline, indicating a net carbon loss under continuous rice–wheat cultivation over the same period.

Table 1. Depth-wise soil carbon stock (Mg C ha^{-1}) under different land use systems of the IFS model and the existing farmer's farming system (EFFS)

Land use systems in IFS model	Area (ha)	0–15 cm (Mg C ha^{-1})	15–30 cm (Mg C ha^{-1})	30–45 cm (Mg C ha^{-1})	45–60 cm (Mg C ha^{-1})	Total up to 60 cm (Mg C ha^{-1})
Crop Block – CLU1	0.22	14.41	10.86	5.41	3.59	34.27
Crop Block – CLU2	0.06	15.67	11.51	5.87	4.13	37.18
Crop Block – CLU3	0.10	15.03	11.49	5.66	3.87	36.05
Horticulture Block – HLU4	0.08	15.91	12.79	6.85	4.62	40.16
Horticulture Block – HLU5	0.07	15.72	12.10	6.40	4.39	38.60
Horticulture Block – HLU6	0.04	16.27	12.92	7.05	4.90	41.58
Horticulture Block – HLU7	0.08	15.55	12.54	6.03	4.15	38.27
Horticulture Block – HLU8	0.03	15.21	10.09	5.45	3.89	34.64
Fodder Block – FLU9	0.07	18.03	12.15	6.60	4.10	40.88
Boundary Plantation – BPLU10	0.04	19.18	14.37	7.73	5.36	46.64
Boundary Plantation – BPLU11	0.04	18.94	13.75	7.44	5.10	45.23
Perennial fodder (pond dyke) – PGLU12	0.00	14.22	10.30	5.32	3.63	33.47
IFS model – Total[a]	0.82	16.18	12.07	6.32	4.31	38.91
Farmer's field (EFFS) – FFLU13	1.00	10.63	8.09	4.48	3.13	26.34
Initial (2010)	–	11.29	–	–	–	–

CLU1: Rice–Wheat–Green manure; CLU2: Rice–Potato–Black gram; CLU3: Rice–Mustard–Fodder (Maize + Sorghum); HLU4: Okra–Broccoli; HLU5: Okra–Cauliflower; HLU6: Okra–Cabbage; HLU7: Fodder (Sorghum–Berseem); HLU8: Fallow (sole horticulture block); FLU9: Maize + Sorghum–Berseem + Oat; BPLU10 and BPLU11: Turmeric cultivation strips 1 and 2 under boundary plantation; PGLU12: Hybrid Napier on the pond dyke; FFLU13: Rice–Wheat cropping system under the existing farmer's field (EFFS). Sub-surface (15–30, 30–45, 45–60 cm) and total-to-60-cm carbon stock values are current-status measurements; depth-wise sequestration derived from these layers was inferred from the surface (0–15 cm) baseline trend, as detailed under Limitations

[a] 0.82 ha of the 1-ha IFS model was under cultivated land uses; the remaining 0.20 ha was allocated to non-cultivable enterprises (animal, fishery-cum-poultry, mushroom and vermi-compost units)

This depth-wise decline mirrors reports from diversified farming systems and agroforestry stands elsewhere, where the highest SOC and carbon stock values consistently occur in the uppermost soil layer owing to concentrated root density, litter deposition and biological activity, with a steady decrease as depth increases (Kumar *et al.*, 2025). The higher subsurface carbon stock recorded under boundary plantation at all four depths in the present study is consistent with the recognised role of tree-based land uses in promoting deeper root systems and reduced disturbance, which favour retention of recalcitrant, deep-soil carbon relative to annually tilled cropland (Rumpel & Kögel-Knabner, 2011). A comparable surface-to-subsurface decline, together with clear land-use separation in carbon stock, has also been reported for the soils of Jammu and Kashmir (Kumar *et al.,* 2026a*;* Kumar *et al.,* 2026b*;* Khenrab *et al.*, 2026; Kumar *et al.*, 2024) and for other North-Western Himalayan carbon-pool assessments (Mir *et al.,* 2023), lending regional support to the present depth-wise pattern.

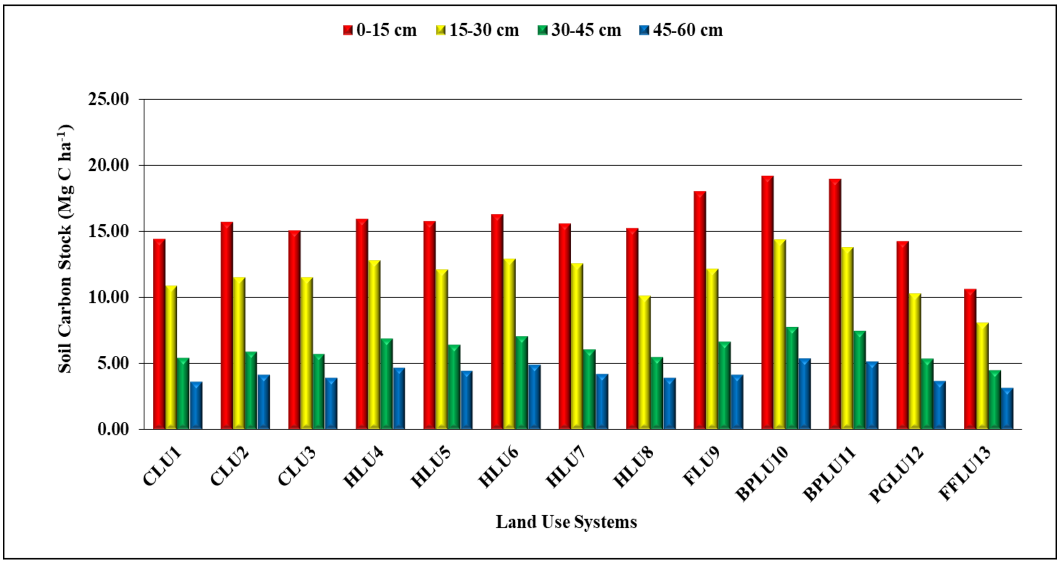

Fig. 1. Graph showing Depth-wise soil carbon stock (Mg C ha⁻¹) under different land use systems of the IFS model and the existing farmer's farming system (EFFS)

3.2 Total Carbon Stock: IFS Model vis-à-vis Existing Farmer's Field

Summed across the four depths up to 60 cm, total carbon stock was highest under boundary plantation (46.64 and 45.23 Mg C ha^{-1} for BPLU10 and BPLU11, respectively), followed by the fodder block (40.88 Mg C ha^{-1}), horticulture block (34.64–41.58 Mg C ha^{-1}) and crop block (34.27–37.18 Mg C ha^{-1}), with the lowest value recorded under EFFS (26.34 Mg C ha^{-1}). Averaged over the 0.82-ha cultivated area of the IFS model, total soil carbon stock up to 60 cm was 38.91 Mg C ha^{-1}, about 48% higher than the 26.34 Mg C ha^{-1} recorded in the adjoining EFFS plot managed under continuous rice–wheat cultivation (Fig. 3).

The clear advantage of the IFS model over EFFS reflects the cumulative effect of continuous, diversified organic matter return through crop residues, horticultural biomass, fodder cuttings and, notably, leaf litter and root turnover under boundary plantation relative to a cereal system in which residues are frequently removed and tillage is repeated every season. This finding is consistent with reports that tree–crop interfaces and integrated crop–livestock–forest systems enhance below-ground carbon accumulation and soil fertility relative to conventional or continuous cropping systems (Pradhan *et al.*, 2026; Schiavo *et al.*, 2025), and with broader evidence that management intensity, alongside land use, is a key determinant of national and regional SOC stock differences (Castellón Meyrat *et al.*, 2026). The consistently negative departure of EFFS from even its own historical baseline reinforces earlier observations that intensive tillage accelerates the mechanical breakdown of soil aggregates and the loss of physically protected carbon, whereas minimising soil disturbance favours carbon accumulation (Saha *et al.*, 2014). Comparable land-use contrasts in total carbon stock have been reported from tropical pasture-to-integrated-system conversions in Brazil (Molina *et al.*, 2026), from semi-arid land use gradients in northern Ethiopia (Kahsay *et al.*, 2025), and from the Brazilian Cerrado agricultural frontier (Nwaogu *et al.*, 2024), all of which confirm that diversified or reduced-disturbance systems consistently outperform conventional, continuously cropped systems in total soil carbon stock regardless of geography.

3.3 Soil Organic Carbon Sequestration

At the surface depth (0–15 cm), carbon sequestration over the ten-year period ranged from 2.94 Mg C ha^{-1} under perennial fodder on the pond dyke to a maximum of 7.90 Mg C ha^{-1} under boundary plantation (BPLU10), followed by the fodder block (6.74 Mg C ha^{-1}), horticulture block (3.92–4.99 Mg C ha^{-1}) and crop block (3.12–4.39 Mg C ha^{-1}) (Table 2, Fig. 2). In marked contrast, EFFS recorded a negative sequestration value of –0.65 Mg C ha^{-1}, indicating a net decline in surface soil carbon relative to the 2010 baseline under continuous rice–wheat cultivation. Overall, the IFS model sequestered 3.66 Mg C over its 0.82-ha cultivated area, equivalent to 4.47 Mg C ha^{-1} over the decade.

The consistently higher carbon sequestration recorded under boundary plantation and fodder-based land uses is in line with the broader agroforestry literature from the North-Western and Central Himalayan region, where boundary and block plantation systems have been reported to sequester carbon at markedly higher rates than pure agricultural systems owing to their combination of continuous woody biomass input and minimal soil disturbance (Chavan *et al.*, 2023; Bhardwaj *et al.*, 2024; Kaith *et al.*, 2023). Higher soil organic matter content, greater leaf litterfall and faster decomposition relative to purely agricultural fields have similarly been proposed as the principal mechanisms driving elevated sequestration under tree-integrated systems (Rajput *et al.*, 2017), while the negative sequestration recorded under EFFS is consistent with the well-documented depletion of SOC under continuous cereal cultivation through accelerated mineralisation, leaching and erosion combined with limited residue return (Li *et al.,* 2007).

Table 2. Soil organic carbon sequestration and its potential at surface depth (0–15 cm) under different land use systems of the IFS model and EFFS

Land use systems in IFS model	Area (ha)	C sequestration (Mg C unit area⁻¹)	C sequestration (Mg C ha⁻¹)	C sequestration potential (Mg C ha⁻¹ yr⁻¹)
Crop Block – CLU1	0.22	0.69	3.12	0.31
Crop Block – CLU2	0.06	0.26	4.39	0.44
Crop Block – CLU3	0.10	0.37	3.75	0.37
Horticulture Block – HLU4	0.08	0.37	4.62	0.46
Horticulture Block – HLU5	0.07	0.31	4.43	0.44
Horticulture Block – HLU6	0.04	0.20	4.99	0.50
Horticulture Block – HLU7	0.08	0.34	4.27	0.43
Horticulture Block – HLU8	0.03	0.12	3.92	0.39
Fodder Block – FLU9	0.07	0.47	6.74	0.67
Boundary Plantation – BPLU10	0.04	0.27	7.90	0.79
Boundary Plantation – BPLU11	0.04	0.26	7.65	0.77
Perennial fodder (pond dyke) – PGLU12	0.00	0.00	2.94	0.29
IFS model – Total	0.82	3.66	4.47	–
Farmer's field (EFFS) – FFLU13	1.00	–	–0.65	–0.07

CLU1: Rice–Wheat–Green manure; CLU2: Rice–Potato–Black gram; CLU3: Rice–Mustard–Fodder (Maize + Sorghum); HLU4: Okra–Broccoli; HLU5: Okra–Cauliflower; HLU6: Okra–Cabbage; HLU7: Fodder (Sorghum–Berseem); HLU8: Fallow (sole horticulture block); FLU9: Maize + Sorghum–Berseem + Oat; BPLU10 and BPLU11: Turmeric cultivation strips 1 and 2 under boundary plantation; PGLU12: Hybrid Napier on the pond dyke; FFLU13: Rice–Wheat cropping system under the existing farmer's field (EFFS)

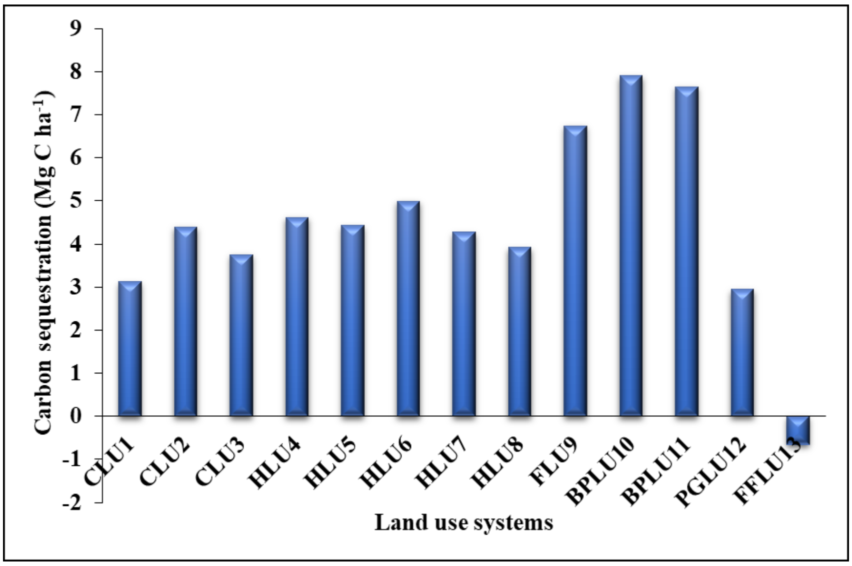

Fig. 2. Graph showing Soil organic carbon sequestration (Mg C ha⁻¹) at the surface depth (0–15 cm) under different land use systems of the IFS model and EFFS

3.4 Carbon Sequestration Potential

Annualised carbon sequestration potential followed the same pattern as absolute sequestration, ranging from 0.29 Mg C ha⁻¹ yr⁻¹ under perennial fodder to a maximum of 0.79 Mg C ha⁻¹ yr⁻¹ under boundary plantation (BPLU10), with the fodder block (0.67 Mg C ha⁻¹ yr⁻¹) and horticulture block (0.39–0.50 Mg C ha⁻¹ yr⁻¹) intermediate. EFFS, by contrast, showed a negative carbon sequestration potential of –0.07 Mg C ha⁻¹ yr⁻¹, attributable to continued adoption of a rice–wheat cropping system over the study period without any compensating woody or perennial component (Fig. 3).

These sequestration-potential values fall within the range reported for boundary and block plantation agroforestry systems elsewhere in India; for example, boundary plantation systems in the Indo-Gangetic plains have been reported to sequester carbon at annualised rates of around 5.5 Mg C ha⁻¹ yr⁻¹ under intensively managed poplar- or eucalyptus-based systems (Chavan *et al.*, 2023), though the present values are naturally more modest, reflecting the shorter turmeric-under-tree-canopy component and the smaller scale of the boundary strips relative to dedicated block plantations. Nevertheless, the consistent, positive sequestration potential recorded across every land use of the IFS model, set against the negative value for EFFS, underscores the climate-mitigation value of diversifying conventional cereal-dominated farms with horticultural, fodder and boundary-plantation components—a conclusion that aligns with recent calls to treat regenerative, diversified farming practices as a practical and immediately deployable lever for cropland carbon sequestration (Abrar *et al.*, 2025; Villat & Nicholas, 2024; Uludere Aragon *et al.*, 2024).

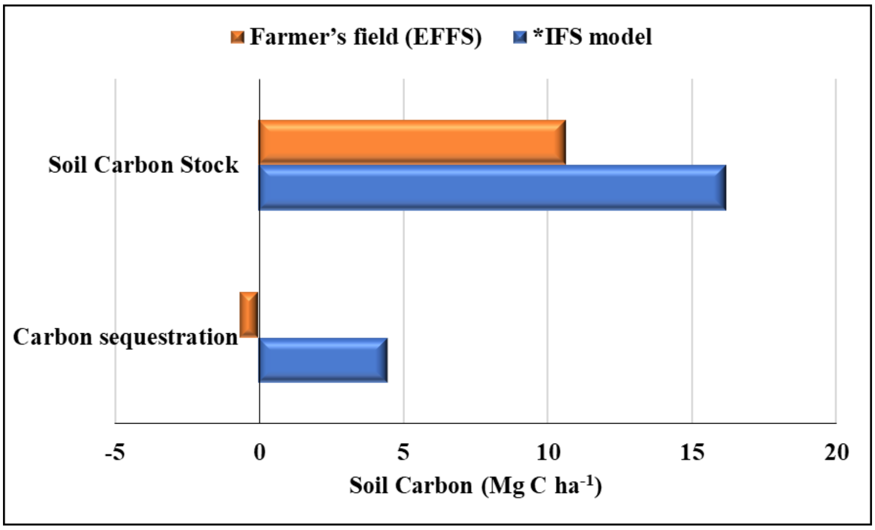

Fig. 3. Overall soil carbon stock and carbon sequestration (Mg C ha^{-1}) in the IFS model versus the existing farmer's farming system (EFFS) over ten years

It is worth noting that the profitability, resource-use efficiency and general soil-health performance of this same decadal IFS model have been reported separately by the co-authors (Thakur *et al.,* 2025); the present analysis is confined specifically to depth-wise soil carbon stock, sequestration and its annualised potential, and is presented here as a distinct, non-overlapping contribution to that broader evaluation of the model.

3.5 Relationship of Soil Carbon Stock with Soil Properties

Soil carbon stock (SCS) at the surface depth (0–15 cm) was negatively and highly significantly correlated with bulk density (r = –0.85**), pH (r = –0.87**) and electrical conductivity (r = –0.73**), and positively and highly significantly correlated with available nitrogen (r = 0.96**), potassium (r = 0.91**) and the DTPA-extractable micronutrients Fe, Mn, Zn and Cu (r = 0.91**, 0.93**, 0.83** and 0.90**, respectively), while its correlation with available phosphorus, though positive, was comparatively weaker (r = 0.71**) (Table 3). No significant relationship was found between SCS and the sand, silt or clay fractions.

Table 3. Pearson correlation coefficients (r) between soil carbon stock (SCS) and soil physico-chemical properties at 0–15 cm depth

Soil property	Sand	Silt	Clay	Bulk density	pH	EC	Avail. N	Avail. P	Avail. K	Fe	Mn	Zn	Cu
Soil carbon stock (SCS)	0.15	0.06	-0.27	-0.85**	-0.87**	-0.73**	0.96**	0.71**	0.91**	0.91**	0.93**	0.83**	0.90**

*Values are Pearson correlation coefficients (r) at the 0–15 cm depth (n = 13 land uses); ** significant at P = .01*

The strong negative association between SCS and bulk density confirms the widely reported inverse relationship between soil compaction and carbon storage, whereby land uses that minimise tillage and mechanical disturbance—such as boundary plantation and fodder blocks in the present study—sustain lower bulk density and correspondingly higher carbon stock (Hou *et al.*, 2024; Chen *et al.*, 2024). This pattern is consistent with regional evidence from the temperate and dry-temperate zones of Jammu and Kashmir, where land-use type has similarly been identified as a primary driver of both total soil organic carbon and its bulk-density-mediated stock (Khenrab *et al.*, 2026; Kumar *et al.*, 2024), and with carbon-management-index studies from the wider North-Western Himalaya that report the highest carbon pools and lowest bulk density under the least-disturbed, tree-dominated land uses (Mir *et al.*, 2023; Tiwari & Joshi, 2022; Blair *et al.*, 1995). The strong positive correlation of SCS with available N, K and micronutrients mirrors the well-documented role of soil organic carbon as a reservoir and chelating agent for plant nutrients, and is consistent with nutrient-mapping studies from other districts of Jammu and Kashmir that report higher organic carbon and associated nutrient status under less-disturbed, tree-based land uses relative to intensively cultivated soils (Renuka *et al.*, 2022).

4. Limitations of the Study

This study is subject to certain limitations that should be considered when interpreting the results. First, carbon sequestration and its annualised potential were computed against a single, surface-depth (0–15 cm) initial (2010) baseline, as depth-wise baseline values for the 15–30, 30–45 and 45–60 cm layers were not available; sequestration at sub-surface depths could therefore not be independently verified and was inferred from the surface trend. Second, the comparison rests on a single, one-hectare IFS model and a single adjoining EFFS plot without independent field-level replication of either land use system, so that observed differences, though internally consistent across land uses and statistically treated under a Randomized Block Design, cannot fully rule out confounding from pre-existing site-specific variation in soil properties predating the 2010 establishment of the model. Third, organic carbon was estimated by the Walkley–Black wet oxidation method, which does not fully oxidise more recalcitrant carbon fractions and may therefore underestimate absolute carbon stock, particularly at greater depths; a complementary gravimetric (loss-on-ignition/ash-content) estimate could be used in future work to cross-validate the wet-oxidation values reported here. Fourth, the study reflects a single decadal time point (2010–2020) at one agro-climatic location in the Shiwalik foothills of the North-Western Himalayas, and the carbon stock and sequestration values reported may not be directly transferable to other soil types, climatic zones or shorter/longer management periods without further validation. Finally, non-soil enterprises of the IFS model (animal husbandry, fishery-cum-poultry, mushroom and vermi-compost units, together 0.20 ha) were outside the scope of this soil-carbon assessment, so the reported area-weighted IFS values pertain only to its 0.82 ha of cultivated land uses. Future studies could also examine variation in carbon stock and sequestration under such IFS models across altitudinal/spatial gradients and different cropping patterns; these comparisons were beyond the scope of the present single-site assessment.

5. Conclusion

Depth-wise assessment over a decade-old Integrated Farming System model in the North-Western Himalayan foothills showed that soil carbon stock declined consistently with depth across all land uses, and was substantially higher under boundary plantation and fodder-based systems than under crop or horticulture blocks. Averaged over its cultivated area, the IFS model accumulated about 48% more total soil carbon (38.91 Mg C ha^{-1} up to 60 cm) than the adjoining existing farmer's field (26.34 Mg C ha^{-1}) under continuous rice–wheat cultivation, and sequestered a net positive 4.47 Mg C ha^{-1} over ten years compared with a net negative value for the farmer's field. Boundary plantation with turmeric intercropping emerged as the single most effective enterprise for building soil carbon stock and sustaining positive carbon sequestration potential, followed closely by the fodder block. These findings support the wider promotion of tree-integrated, diversified farming system models rather than continuous cereal monocropping as a practical, farm-scale strategy for enhancing soil carbon sequestration and climate change mitigation in hill and foothill agriculture, while simultaneously diversifying farm income. Beyond its direct carbon benefit, such tree-boundary and fodder-integrated diversification offers smallholders in the Shiwalik foothills an additional, low-input avenue for improving long-term soil fertility and resilience without displacing food-crop area, since the gains were realised on boundary and marginal niches of the same 0.82 ha cultivated block rather than through land-use conversion. Wider adoption would benefit from location-specific extension support on tree-crop spacing and species choice, and from policy incentives, such as carbon credits or green cess support, linked to on-farm carbon stock, to encourage smallholders to adopt such models at scale across similar hill and foothill agro-ecologies.

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Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. Grammarly and ChatGPT were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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