

# Forensic Assessment of Environmental Damage through Soil Carbon Depletion: Indicators, Methods, and Implications.

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## ABSTRACT

Soil organic carbon (SOC) is crucial for sustaining soil fertility, boosting production, and reducing climate change by sequestering carbon. Soil organic carbon (SOC) stocks were estimated in diverse villages and land use types grassland, orchard, agricultural and forest in Udhampur district of Jammu and Kashmir at three soil levels (0 to 15 cm, 15 to 30 cm and 30 to 60 cm). Results indicated some substantial spatial heterogeneity with Kirmoo village having the highest SOC levels especially in orchards and woods whereas agricultural and grassland regions in Dehari and Khagote were found to have low stocks suggesting soil degradation. These results emphasise the role of land use patterns for SOC preservation and the importance of sustainable management techniques. The study also discusses policy aspects such as agriculture and land use legislation, carbon markets and international frameworks.

**Keywords:** *Soil Organic Carbon (SOC), Land Use, Carbon Sequestration, Soil Health, Sustainable Agriculture, Climate Change Mitigation.*

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## INTRODUCTION

Soil Organic Carbon (SOC) is an important part of terrestrial ecosystems and an important indication of soil health. SOC is an important component of the soil organic matter (SOM) and is involved in soil activities such as nitrogen cycling, water retention, aggregate stability and microbial activity (Lal, 2004). Furthermore, SOC is also an essential component of global carbon cycle, operating as a source and sink of atmospheric carbon dioxide (CO<sub>2</sub>), and affecting the measures of climate change mitigation (Batjes, 2014). Accurate assessment of SOC stocks, particularly in the heterogeneous soil layers, is crucial for sustainable land management and effective execution of carbon sequestration programs (Mandal et al 2020).

Studies of SOC dynamics have traditionally concentrated on surface soils (0 to 30cm), the main recipient of organic inputs from plant litter, root biomass and animal activity (Jobbágy & Jackson, 2000). By contrast, deeper soil layers, although having lower biological activity, are characterised by large and more stable pools of carbon, as microbial decomposition is limited and mineral associations are robust (Rumpel & Kogel Knabner, 2011). For example, in certain ecosystems, sub surface layers may contain more than half of the total SOC, highlighting its importance for

long term carbon storage and soil sustainability (Lorenz & Lal, 2005; Schmidt et.al, 2011).

Many factors govern the vertical distribution of SOC, including land use, plant species, soil texture, climate and management practices (Post & Kwon, 2000). Practices of intensive tillage and monoculture farming are the ones responsible for decreasing total soil carbon pools and depleting SOC from the upper layers (Guo & Gifford, 2002; Sharma et al., 2014). However, conservation practices like as no-till, residue retention, agroforestry and cover cropping may increase SOC sequestration throughout the profile including the deeper layers (Powlson et al., 2011). The distribution of SOC and root systems is quite similar in forest and grassland environments with permanent plants and little soil disturbance. Roots penetrate much deeper into the soil profile and contribute considerably to subsoil carbon reservoirs.

Typically, a multi-depth stratified sampling technique is employed, for example, 0 to 10, 10 to 20, 20 to 40, and even up to 100 cm. This is supplemented with measurements of soil bulk density and carbon content, generally calculated by means of dry combustion techniques (Nelson & Sommers, 1996). Vertical detail profiling is significant not only for carbon budgeting, but also for understanding the stabilisation processes and turnover rates of SOC in different soil levels (Trumbore, 2011).

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Global studies highlight the vertical stratification of SOC, showing that subsurface strata (below 30 cm) can hold a large percentage of the total SOC, sometimes surpassing surface stocks (Bossio et al., 2020). These deeper layers likely to be more stable since more stable carbon is associated with contact with soil minerals and lower microbial activity (Campbell et al., 2015).

Unlike plains, in mountainous and wooded environments like Himalayas, the storage of SOC is affected by slope gradients, elevation, vegetation type and intensity of land use (Sharma et al., 2018 and Nand et al., 2020). These variables provide varied SOC profiles that need localised investigation to guide land management methods. The steep slopes, rainfall, deforestation and human activity make the Himalayan mountain ecosystem susceptible to erosion and degradation (Sharma and Arora, 2015; Sharma et al., 2023a; Sharma et al., 2023b) leading to considerable fluctuation in soil carbon storage patterns.

Jammu & Kashmir in the western Himalayas has diversified agro ecological zones from sub tropical plains to alpine pastures SOC research in the area has been mostly confined to broad land use comparisons or surface soil evaluation (Malik et al., 2014). For instance, in Kashmir valley, larger SOC stock in forest soils than cultivated lands have been reported (Pan et al., 2011) with fluctuations according to litter intake, biomass turnover and meteorological circumstances (Rather et al., 2020). In similar way, the fluctuation of SOC with slope locations and plant coverings has been reported from Poonch and Rajouri (Kour et al., 2018).

However, no particular study has examined the vertical distribution of SOC in soil profiles in the intermediate Himalayan climate zone. Intermediate climate zone The area of transition between the sub tropical and temperate climate zones. The steep terrain, mixed woodlands, cultivated valleys and variable rainfall of this region make it an ideal natural laboratory for investigating depth-wise carbon storage. But there is very little literature even on top soils of this region and basically non-existent for deeper layers critical for long term carbon sequestration and land restoration plans. The land use/land cover in the intermediate zone includes forested hills, orchards, pastures for grazing and rainfed agriculture with substantial human intrusion in the form of deforestation, urban expansion and shifting cultivation. "The combination of these anthropogenic pressures with climatic variability is causing soil degradation and declining productivity" (Singh and Ahmed, 2019). Steep slopes in the region may contribute to loss of SOC from top soil and redistribution to lower slopes due to rapid runoff and erosion (Dar & Reshi, 2020). This dynamic suggests that the presence and stability of SOC in the deeper layers should also be investigated, not simply surface SOC. The role of SOC in climate resilience and soil restoration is becoming more and more acknowledged, yet a major research gap exists concerning the quantitative assessment of SOC stocks at various depths of the soil profile in this zone. Available studies in Intermediate Himalaya either generalise the region or focus on surface soils solely overlooking the vertical distribution patterns

and potential C stocks in the deeper layers. There is very little integration of SOC stock data with parameters such as land use, slope gradient, plant species and soil texture in a given topographic and climatic environment.

Moreover, the long term stabilisation mechanisms of SOC in subsoils (e.g., mineral association and physical protection) are often overlooked in current research, which are key for developing sustainable carbon sequestration strategies. This data may mislead or inefficient for land use policies and agroforestry operations in Udhampur. The study attempts to investigate SOC stocks at various depths of soil profile, emphasising the dynamics of surface and subsurface. The study intends to address the existing gap in understanding of subsurface carbon by evaluating the depth wise distribution of SOC and establishing the biophysical and anthropogenic factors responsible for its variability. Such knowledge is particularly relevant for areas undergoing land use change, and for adaptation of climate-resilient agricultural practices that support sustainable carbon management.

## MATERIAL AND METHODS

### *Study Area*

The research was conducted in Udhampur district of Jammu and Kashmir which is situated in transition zone of sub-tropical and temperate climates of Himalayas. The area receives an average rainfall of 900 to 1,300 mm. The land is undulating with altitudes ranging from 600 to 2,400 meters above sea level. The major land use systems evaluated were grasslands, orchards, agricultural areas and woods representing the major land cover in the region. Soil sampling was carried out in seven typical villages i.e. Thaplal, Kirmoo, Marta, Dalsar, Dehari, Khagote and Kulwanta, chosen on the basis of elevation, slope and land use intensity.

### *Sampling Design*

A stratified random sample method was adopted to guarantee a thorough representation of the four specified land use categories:

1. Grassland
2. Orchard
3. Agricultural land
4. Forest land

Samples were collected from many locations scattered throughout the seven communities for each land use type. Soil pits were physically excavated at each location, and samples were taken at three predetermined depths:

- 0 to 15 cm (surface horizon)
- 15 to 30 cm (subsurface)
- 30 to 60 cm (subsoil)

Soil samples were obtained using a stainless steel auger and core samplers to avoid contamination. Each sample was collected in triplicate per depth to ensure reliability and minimize sampling error. Care was taken to avoid visible disturbances, such as recently tilled or grazed areas.

### *Soil Carbon Stocks*

To get rid of trash, stones, and root particles, collected soil samples were air dried at room temperature, softly crushed, and sieved through a 2 mm mesh screen. Subsamples were further crushed and sieved through a 0.5 mm sieve for SOC

analysis. Using a cylindrical metal core sampler, undisturbed soil cores (100 cm<sup>3</sup>) were taken from each depth in order to calculate the bulk density. Soil organic carbon (SOC) was analysed following the standard procedure given by Walkley and Black (1934)

The following formula is used to determine the soil organic carbon stocks (Sharma et al., 2014) for each village's whole soil profile:

$$\text{SOC stocks (Mg ha}^{-1}\text{)} = \sum_{i=1}^j \text{SOC}_i \times \rho_i \times d_i \times 10,000$$

Where SOC<sub>i</sub> is soil organic carbon measured in gg<sup>-1</sup>; ρ<sub>i</sub> is the soil bulk density in gm cm<sup>-3</sup>; d<sub>i</sub> is the depth of soil layer (m); I and j are the number of layers. The value 10,000 indicate the stock for 1 ha of land.

*Statistical Analysis*

All field and laboratory data were compiled and analyzed using Microsoft Excel and SPSS version 25. Descriptive statistics such as mean, standard deviation, and coefficient of variation were computed for SOC concentrations and SOC stocks under each land use type and soil depth. Soil depths and land use types were analysed using one way (ANOVA) to identify significant variations in SOC.

**RESULTS AND DISCUSSION**

An intensive study in seven villages of Udhampur district demonstrated significant spatial variability and depth dependant patterns in soil organic carbon (SOC) reserves controlled by land management practices and climate factors. In this research, the distribution of SOC under four distinct land uses i.e. grasslands, orchards, agricultural lands and forests at three different depths (0 to 15 cm, 15 to 30 cm and 30 to 60 cm) was evaluated to understand the dynamics of carbon sequestration and soil health under various management regimes.

There were significant differences in total SOC stocks across the six villages (F<sub>6,42</sub> = 24.43, p < 0.001). The location-specific factors explained 87.6% of the total variance in SOC stocks in the one-way ANOVA (η<sup>2</sup> = 0.875). The statistical data significantly rejects the null hypothesis that the SOC stocks of the communities are

equal. Carbon sequestration capacity in the area is dominantly controlled by geographical location mediated via soil qualities, topography, climate and management techniques. The high value of F statistics (24.43) shows that the variation across villages is much larger than the variance within villages, suggesting that the site specific characteristics are important for the soil carbon storage capacity.

Kirmoo is the most carbon rich site in the study area with the largest total SOC stock (259.10 Mg/ha) of the 0 to 60 cm soil profile. This large carbon sequestration potential is 11.9 and 12.8 times higher than the SOC stocks of the least deficient towns, Dehari (21.73 Mg/ha) and Khagote (20.19 Mg/ha), respectively. This remarkable performance in Kirmoo might be due to a happy mix of edaphic factors, sustainable land use strategies, availability of enough precipitation and generally undisturbed ecosystems. Marta (173.68 Mg/ha) and Thaplal (153.91 Mg/ha) also exhibited high carbon storage, indicating secondary carbon rich locations in maintaining a healthy level of soil organic matter throughout varied land use regimes (Table 1 and Fig 1).

The coefficient of variation (CV) analysis might be a valuable indicator of homogeneity of management in villages. Marta has the highest internal variability (CV = 42.01%), reflecting the heterogeneity of management strategies across different land uses, with some ecosystems well fertilised and others largely neglected. This variety may be due to different patterns of land ownership, restrictions on access, or unequal uptake of soil conservation practices. By contrast, the great homogeneity of the Kulwanta ecosystems (CV = 5.89%) is indicative of sustained, but sub optimal, patterns of carbon buildup. Such uniformity is suggestive of standardised management approaches, but also suggestive of the pervasive nature of degradation across all land uses within the community suggesting systemic limits rather than land use specific challenges.

**Table 1. Depth wise and Cumulative SOC Stocks (Mg/ha) across Villages and Ecosystems**

Village	Ecosystem	0-15 cm	15-30 cm	30-60 cm	Total (0-60 cm)	Mean ± SD
<b>Thaplal</b>	Grassland	12.141	12.012	14.688	38.841	12.95 ± 1.39
	Orchard	23.414	12.342	14.760	50.516	16.84 ± 5.47
	Agriculture	13.817	13.224	11.934	38.975	12.99 ± 0.94
	Forest	6.345	5.280	13.950	25.575	8.53 ± 4.85
	<b>Village Total</b>				<b>153.91</b>	
<b>Kirmoo</b>	Grassland	15.975	8.910	33.264	58.149	19.38 ± 12.56
	Orchard	9.629	14.256	59.052	82.937	27.65 ± 27.59
	Agriculture	13.590	14.364	24.786	52.740	17.58 ± 6.16
	Forest	18.113	19.314	27.846	65.273	21.76 ± 5.03
	<b>Village Total</b>				<b>259.10</b>	
<b>Marta</b>	Grassland	8.820	5.994	14.304	29.118	9.71 ± 4.37
	Orchard	12.921	12.348	41.223	66.492	22.16 ± 16.60
	Agriculture	10.598	16.218	24.012	50.828	16.94 ± 6.75
	Forest	4.248	4.998	18.000	27.246	9.08 ± 7.83
	<b>Village Total</b>				<b>173.68</b>	

<b>Dalsar</b>	Grassland	3.786	3.557	6.091	13.434	4.48 ± 1.39
	Orchard	2.487	2.419	4.452	9.357	3.12 ± 1.15
	Agriculture	1.801	1.951	4.204	7.956	2.65 ± 1.34
	Forest	2.248	2.850	6.310	11.407	3.80 ± 2.23
	<b>Village Total</b>				<b>42.15</b>	
<b>Dehari</b>	Grassland	2.117	1.936	2.915	6.967	2.32 ± 0.54
	Orchard	1.366	1.297	1.809	4.472	1.49 ± 0.28
	Agriculture	1.026	1.125	2.356	4.507	1.50 ± 0.72
	Forest	1.287	1.518	2.984	5.789	1.93 ± 0.89
	<b>Village Total</b>				<b>21.73</b>	
<b>Khagote</b>	Grassland	1.759	1.358	1.985	5.101	1.70 ± 0.31
	Orchard	1.180	1.336	2.981	5.496	1.83 ± 1.04
	Agriculture	1.409	1.661	1.931	5.002	1.67 ± 0.26
	Forest	1.469	1.053	2.069	4.591	1.53 ± 0.51
	<b>Village Total</b>				<b>20.19</b>	
<b>Kulwanta</b>	Grassland	3.041	2.838	4.439	10.319	3.44 ± 0.85
	Orchard	2.704	2.627	4.682	10.014	3.34 ± 1.18
	Agriculture	2.797	2.290	4.157	9.243	3.08 ± 1.04
	Forest	2.379	2.374	4.334	9.087	3.03 ± 1.13
	<b>Village Total</b>				<b>38.66</b>	

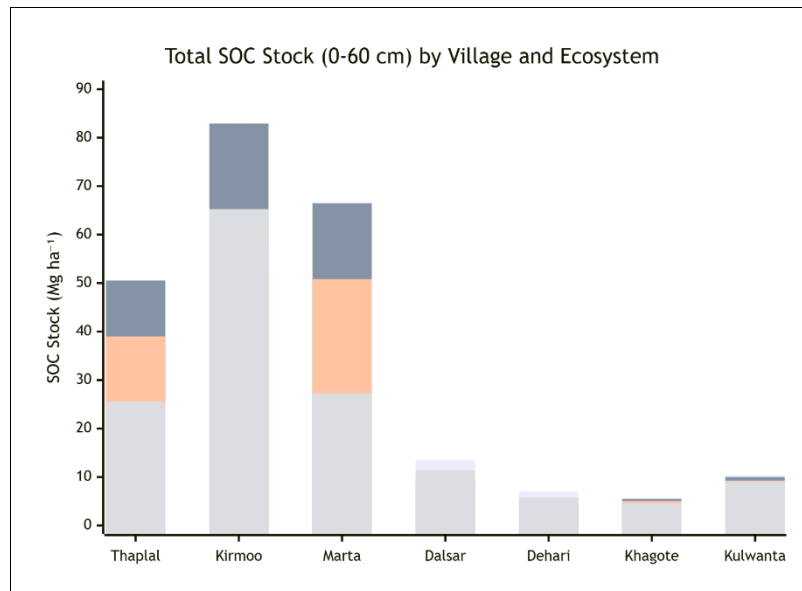


Figure 1: Total SOC Stock Variation Across Villages

### Depth Dependent Carbon Distribution Patterns

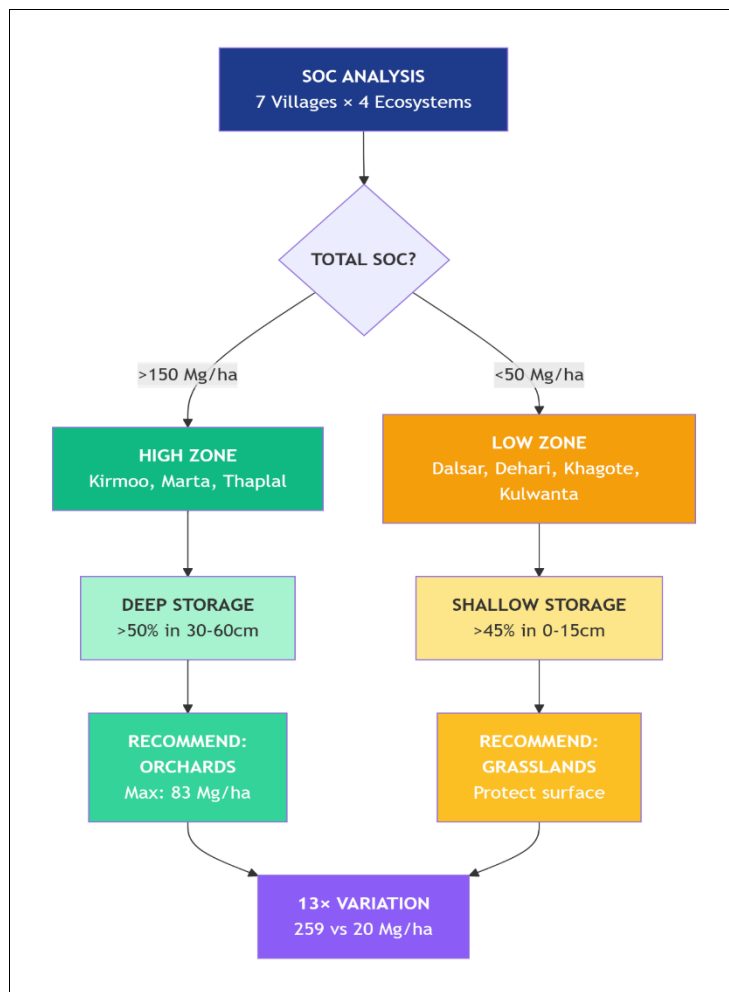
SOC stocks are vertically distributed in discrete patterns that consistently alter with land use type, giving evidence for variable carbon allocation and stabilisation processes across ecosystems. Surface enrichment (0 to 15 cm) is notably high in orchards in Thaplal (23.41 Mg/ha) where the amount of carbon in the topsoil is greater than in other settlements and land uses. This remarkable surface C buildup may be attributed to mulching procedures, continual integration of leaves, pruning residues and little mechanical disturbance associated with mature perennial tree systems. The addition of organic inputs at the soil surface, and low tillage, which would ordinarily transfer carbon vertically, lead to circumstances favouring topsoil carbon enrichment.

The orchard systems of Kirmoo show a distinct trend towards deeper carbon storage, where the subsurface layers (30 to 60 cm) store 59.05 Mg/ha, accounting for 71.2% of the total profile SOC stock. This impressive subsurface stock implies a large input of deep root biomass from mature fruit trees, whose large root systems extend well beyond the depths normally tilled in agriculture. This pattern shows that root-derived organic matter may be sustained for extended periods in subterranean strata due to little carbon mineralisation as a result of ploughing. Deep carbon storage in orchards is a very stable carbon pool that is safe from surface disturbances and has slower turnover rates than surface organic matter. Kirmoo's orchards may potentially be indicative of soil conditions beneficial for root penetration and subsurface organic matter stabilisation, with preferential allocation of carbon to lower layers.

The SOC distribution in agricultural areas of Marta over depths is reasonably balanced with stocks of 10.60, 16.22 and 24.01 Mg/ha for consecutive layers (0 to 15, 15 to 30 and 30 to 60 cm). Other land uses showed surface-enriched or subsurface dominated patterns. The very consistent vertical distribution indicates that tillage operations may mineralise some carbon via increased aeration and microbial activity, but may also incorporate organic matter into deeper soil layers. Frequent ploughing breaks up the soil structure and spreads organic wastes across the tilled layer, resulting in a more uniform carbon profile. The accumulation of organic matter in the subsurface layers of Marta's agricultural fields may be due to the successful

integration of organic amendments or to the persistence of stable mineral associated organic matter throughout time despite farming.

Under this concept, communities may be classified into two main categories according on their overall SOC stocks. Deep soil layers in high potential communities (>150 Mg/ha) retain the majority of carbon in orchards, the best land use. Villages with low potentials (<50 Mg/ha) are storing carbon on the surface for which grassland management is required to be preserved. The 13 fold variance in SOC emphasises the necessity for location-specific interventions (Fig 2)



**Fig 2: Soil Carbon Management Framework**

**Land Use-Specific Carbon Sequestration Efficiency**

Across all the villages, orchards show consistently better carbon storage ability in the whole research region with mean cumulative stocks of 39.46 Mg/ha, which are significantly higher than that of agricultural areas (28.75 Mg/ha), forests (27.75 Mg/ha) and grasslands (23.13 Mg/ha) (Fig. 3; Table 7). The perenniality of orchard systems, together with continuous root exudation, low soil disturbance and persistent organic residue inputs from

pruning and leaf fall, produces highly conducive circumstances for long term carbon stabilisation. Unlike annual cropping systems with periods of bare soil and extensive ploughing, orchards have year round vegetative cover and root activity, which supports carbon inputs and minimises losses due to erosion. The economic worth of fruit trees also provides an incentive to manage them judiciously with organic amendments and erosion control methods, which indirectly assist soil carbon sequestration.

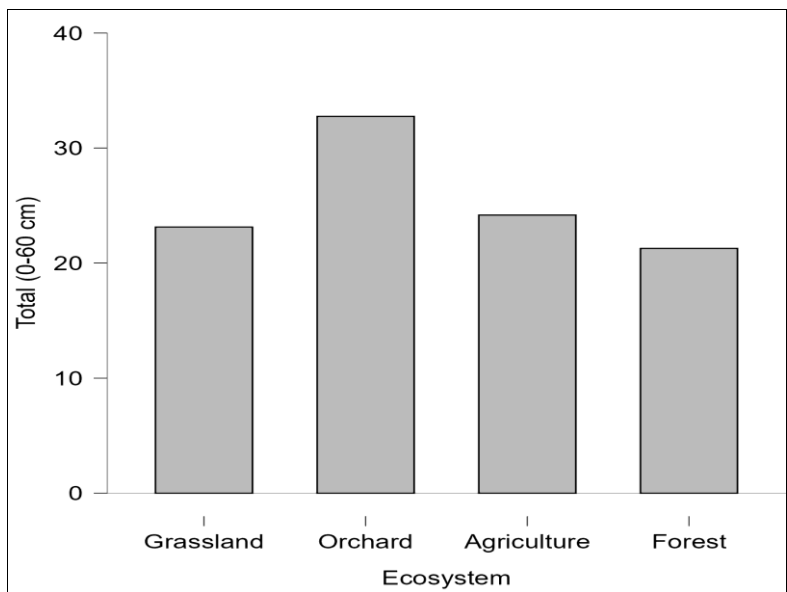


Figure 3: Contribution of different ecosystems to total soil carbon stocks (0-60 cm)

Table 7: Descriptive Statistics by ecosystems for total SOC stock (0-60cm)

	Grassland	Orchard	Agriculture	Forest
Valid	7	7	7	7
Missing	0	0	0	0
Mean	23.13	32.75	24.18	21.28
St, Deviation	19.81	33.11	22.31	21.42
Minimum	5.101	4.472	4.507	4.591
Maximum	58.15	82.94	52.74	65.27

Among the land use categories, the forest ecosystem showed the highest inter village variability in SOC stocks (4.59 to 65.27 Mg/ha, 14.2 fold difference). Specialized forests of Kirmoo have substantial carbon storage (65.27 Mg/ha) with SOC stocks equivalent or even better than managed agricultural systems in adjacent communities. This performance shows that well conserved forests with high canopy cover, substantial litter accumulation, diverse understory plant structure and little human disturbance may behave as important carbon sinks. Constant input of leaf litter, woody debris, and root turnover, together with a slower rate of decomposition in the forest canopy microclimate, leads to a huge accumulation of organic matter. However, the SOC reserves of degraded forest (5.79 Mg/ha in Dehari and 4.59 Mg/ha in Khagote) were lower than certain agricultural systems, indicating considerable human influence. These degraded forests are likely to suffer regular disturbance from fuelwood collection, livestock grazing or prior deforestation. These activities decrease biomass, compact soil, increase erosion and decrease litter inputs, creating conditions which are detrimental to carbon accumulation.

In top performing communities, agricultural lands prove that cultivated systems don't have to be carbon depleted. The agricultural SOC stocks in Kirmoo (52.74 Mg/ha) and

Marta (50.83 Mg/ha) are comparable to those of orchard systems suggesting that the adoption of conservation agriculture techniques may result in substantial benefits in terms of carbon sequestration even in intensively farmed areas. These are likely to include maintaining crop residue on the ground rather than burning or removing it, reduced or zero tillage to minimize soil disturbance, incorporation of organic amendments such as farm yard manure or compost and potentially crop diversification including legumes which enhance nitrogen availability and organic matter quality. The performance of these communities demonstrates the possibility of carbon sequestration in well managed agricultural systems. On the contrary, the carbon mining from extractive operations is evident in the degraded agricultural lands of Dehari (4.51 Mg/ha) and Khagote (5.00 Mg/ha). Intensive tillage improves soil aeration and microbial decomposition, crop residues are completely removed, which is the major source of carbon, and minimal organic amendments do not compensate for carbon loss. These activities lead to the deterioration of soil physical properties and decline in soil productivity over time and thus leads to a degradation cycle. Grasslands have low SOC stocks, but there are several interesting exceptions which highlight the importance of grazing management. The Kirmoo grasslands (58.15

Mg/ha) are greater than many agricultural and wooded areas in adjoining communities, illustrating the carbon sequestration potential of well managed grassland ecosystems. The better performance is probably due to the existence of deep rooted perennial grasses that store large amount of carbon underground, moderate grazing intensity that facilitate tillering and root growth without causing vegetation degradation and less mechanical disturbance that enable undisturbed carbon accumulation. The high subsurface carbon storage (33.26 Mg/ha at 30 to 60 cm) observed demonstrates an efficient belowground carbon allocation process in grassland ecosystems in which perennial root systems continuously contribute organic matter to the soil and turnover of fine roots provides labile carbon for microbial communities and soil aggregate formation. In Khagote (5.10 Mg/ha) and Dehari (6.97 Mg/ha) grassland degradation was due to overgrazing. Livestock exerts high pressure on vegetation cover, exposing the soil to erosion, compacting surface layers and reducing organic matter inputs from reduced plant output, leading to increased carbon losses.

#### **Mechanistic Interpretation of SOC Depletion Hotspots**

The consistently low SOC stocks in Dehari and Khagote across all land uses and depths of soil are reflective of systemically driven carbon depletion, rather than of individual management failures. The observed patterns are most likely the consequence of the interaction of multiple factors. (a) shallow soil profiles that limit root development and the volume of soil available for carbon storage and (b) coarse texture with high sand content that provides limited physical protection for organic matter and reduces water retention capacity and consequently limited primary productivity due to moisture stress and nutrient limitations. Edaphic constraints may include Natural soil properties provide a poor basis for carbon sequestration independent of management practices.

Topographic characteristics may enhance further carbon losses in these communities. steeper slopes mean higher water flow and more soil erosion, which tends to wash away the more organic topsoil where most of the organic matter resides. Not only does erosion remove existing carbon storage, but it impairs soil structure and fertility, thereby restricting future carbon inputs in the form of lower plant output. Convex portions of the slope experience net loss of soil, while depositional sections, often small, receive sediment. Erosion is caused by the interaction of topography and land use intensity. Erosion may be particularly intense in cultivated fields on slopes when tillage breaks down soil aggregates and plant cover.

Management intensity seems to be an important driver of SOC stocks in these degraded areas. There is evidence that unsustainable practices are common, including: excessive tillage, which speeds up carbon mineralization through repeated soil disturbance; removal of all crop residues for fodder or fuel, thus removing primary carbon inputs;

overgrazing of grasslands and forests, which reduces vegetation cover and prevents litter accumulation; and a lack of organic amendments, such as manure or compost, that might offset carbon losses. These practices, often determined by the need for immediate livelihoods and resource constraints, are conducive to the quick extraction of biomass at the expense of the health of the soils over the long term.

These pathways lead to a cascade of degradation with positive feedback loops. Low SOC levels influence soil fertility, water holding capacity and structural stability, which in turn reduces plant productivity and further limits organic matter inputs. Reduced productivity may result in more extractive activities by farmers seeking to preserve yields, thereby increasing degradation. This self reinforcing cycle is difficult to halt without external interventions that break the feedback loop via large inputs of organic matter, soil conservation structures and modifying management strategies.

#### **Implications for Carbon Management and Soil Health**

The ANOVA analysis (Table 2) indicated significant variation in SOC stocks at village level ( $F = 24.43$ ,  $p < 0.001$ ) suggesting that targeted location-specific interventions might provide major carbon sequestration benefits and improve soil health outcomes. The existence of high performing villages within the same district illustrates that environmental restrictions are not insurmountable and that, with careful management, carbon storage may be greatly improved even under adverse conditions. The finding provides a road forward for designing interventions and evidence that restoration is achievable.

The carbon restoration zones, especially Dehari and Khagote need to undertake extensive soil conservation measures immediately. Agroforestry systems, in which trees are grown together with crops or pastures, can provide several benefits, including a continuous supply of organic matter from leaf litter and root turnover, control of erosion through permanent vegetative cover, multiple sources of income reducing the pressure on any one land use, and modification of the microclimate which may increase productivity. To build up the organic matter of the soil and restore its fertility, regular application of organic amendments like compost, farmyard manure or vermicompost is required. Legumes or other cover crops used in fallow periods may generate biomass, fix nitrogen, protect the soil from erosion, and break insect cycles. On sloping regions, physical erosion control structures such as contour bunds, check dams or vegetative barriers may be required to reduce soil erosion and produce conditions suitable for carbon sequestration. Such interventions should be implemented as integrated packages and not as standalone practices since the synergies between the practices are usually greater than the sum of the individual benefits.

**Table 2. ANOVA Results for SOC Stock Variation across Villages**

Source of Variation	Sum of Squares	df	Mean Square	F-Statistic	p-value	Significance
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Between Groups	3492.13	6	582.02	24.43	$1.91 \times 10^{-8}$	***
Within Groups	494.25	42	11.77			
Total	3986.38	48				

Significance codes: \*\*\*  $p < 0.001$ ; \*\*  $p < 0.01$ ; \*  $p < 0.05$

Carbon maintenance zones, including Kirmoo, Marta, and Thaplal, should focus on sustaining current practices while optimizing for long term sustainability and climate resilience. These villages have demonstrated effective soil management and provide models for other areas. However, maintaining high SOC stocks requires ongoing attention to organic matter inputs, minimizing disturbance, and adapting to changing environmental conditions. Diversified cropping systems that include deep rooted perennials, nitrogen fixing legumes, and crops with varied residue quality can enhance ecosystem resilience and provide stable carbon inputs. Enhanced residue management through retention rather than burning or removal, strategic incorporation to balance surface cover with subsurface organic matter, and possibly composting of residues with other organic materials can optimize carbon sequestration. Climate adaptation strategies including drought tolerant varieties, water harvesting structures, and modified planting schedules may be necessary to maintain productivity and carbon inputs under changing climate conditions. Knowledge transfer represents a critical but often neglected component of soil carbon management. The successful practices evident in high SOC villages should be systematically documented through participatory research that engages farmers in identifying and explaining effective techniques, field demonstrations that allow farmers from degraded areas to observe results first hand, and farmer to farmer extension programs that leverage social networks and build trust. Documentation should capture not only technical practices but also the socioeconomic context,

resource requirements, and adaptations that may be necessary in different settings. Extension programs should emphasize practical, low cost interventions that can be implemented with locally available resources, as capital intensive approaches may be infeasible for resource constrained farmers.

**Statistical Robustness**

The highly significant ANOVA result ( $p = 1.91 \times 10^{-8}$ ) provides robust statistical evidence for inter village SOC differences, with the probability of observing such large differences by chance alone being essentially zero (Table 3). However, the within group variance (Mean Square = 11.77) indicates considerable heterogeneity within villages, suggesting that village level classification, while explaining the majority of variance, does not capture all relevant sources of variation (Table 3). This within village heterogeneity is likely attributable to micro site variations in topography such as slope position and aspect, management history including differences in cropping patterns, organic input levels, and land tenure, and soil properties that vary at scales finer than village boundaries. The findings from the two way ANOVA (Table 4) indicate that ecosystem type had a statistically significant impact on total soil carbon stocks (0 to 60 cm) ( $F = 5.12, p = 0.012$ ), suggesting notable variations in carbon storage across the examined ecosystems. The effects of replication were notably significant ( $F = 9.37, p < 0.001$ ), indicating considerable spatial variability within the sampling structure.

**Table 3. Descriptive Statistics of SOC Stocks by Village (Mg/ha)**

Village	Mean SOC	Standard Deviation	Coefficient of Variation (%)	Min	Max	Range
Kirmoo	64.77	13.72	21.18	52.74	82.94	30.20
Marta	43.42	18.24	42.01	27.25	66.49	39.24
Thaplal	38.48	10.14	26.35	25.58	50.52	24.94
Dalsar	10.54	2.61	24.76	7.96	13.43	5.47
Kulwanta	9.67	0.57	5.89	9.09	10.32	1.23
Dehari	5.43	1.05	19.34	4.47	6.97	2.50
Khagote	5.05	0.36	7.13	4.59	5.50	0.91

**Table 4: Two-way ANNOVA summary for total soil carbon stock (0-60cm) across ecosystems and zones.**

Cases	Sum of squares	df	Mean square	F	P
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Ecosystem	543.7	3	181.24	5.120	0.012
zone		0			
Replication	1659.0	5	331.81	9.373	<0.001
Ecosystem X zones	832.2	3	277.39	7.836	0.002
Residuals	531.0	15	35.40		

Notably, the interaction between the ecosystem and zone was significant ( $F = 7.84, p = 0.002$ ), indicating that the effect of ecosystems on soil carbon stocks differed among zones. In comparison, the primary impact of the zone by itself was not significant.

Post HOC pairwise comparisons using Tukey's Honestly Significant Difference (HSD) or Bonferroni corrected t-tests to identify which specific village pairs differ significantly in SOC stocks is also incorporated (Table 5). The studies show orchards ecosystem shows significantly higher values as compared other three ecosystems (grassland  $p=0.013$ , agriculture  $p=0.034$  and forest ecosystem  $p=0.004$ ). On the contrary no statistically significant difference observed for grassland, agriculture and forest ecosystem ( $p>0.005$ ). The letter based grouping reinforces these results, as orchard ecosystems represented a separate group (b), while grassland, agriculture, and forest ecosystems grouped together in a unified category (a), validating the major role of orchard land use in overall variability. However, Tukey's post HOC test indicated a

highly significant variance among zones (Table 6). There was a significant difference in the results between the high zone and the lower zone (mean difference = 41.22;  $p < 0.001$ ) indicating a strong zonal influence on the parameter studied. The alphabetic categorization clearly divided the zones with (b) being the high zone and (a) the low zone indicating the strength of the zonal difference. The zones and interaction with the ecology displayed distinct layering in the zones. (c) Under high-zone situations, orchard ecosystems were grouped separately, whereas grassland, agricultural and forest ecosystems were grouped together (b). This shows that the orchard ecosystems are more impacted by the zonal circumstances than the other land use systems. Conversely, low-zone conditions clustered all habitats (grassland, orchard, farm and woodland) together (a). No substantial differences across ecosystems in the low zone. The trend suggests that zonal impacts are dominant over ecosystem-specific effects under low zone circumstances.

**Table 5: Post HOC comparisons- Ecosystem**

		Mean Difference	SE	df	t	ptukey
Grassland	Orchard	-11.496	3.213	15	-3.578	.013
	Agriculture	-1.600	3.213	15	-0.498	.958
	Forest	1.954	3.213	15	0.608	.928
Orchard	Agriculture	9.896	3.213	15	3.080	.034
	Forest	13.450	3.213	15	4.186	.004
Agriculture	Forest	3.554	3.213	15	1.106	.691
<b>Ecosystem</b>					<b>Different Letters show significant differences in the Land Uses</b>	
Grassland					a	
Orchard					b	
Agriculture					a	
Forest					a	

**Table 6: Post HOC comparisons- Zones**

Zones		Mean Difference	SE	df	t	Ptukey
High	Low	41.22	2.272	15	18.14	<.001
Zone			Letter			
High			b			
Low			a			

The present study revealed the wide variation of SOC stocks from severely deficient areas (20.19 Mg/ha in Khagote) to relatively carbon rich systems (259.10 Mg/ha in Kirmoo) in the 0 to 60 cm soil profile of Udhampur district. The ANOVA results show that geographical location, which is impacted by environmental conditions and land management practices, is a significant determinant in the soil carbon sequestration capacity. Reduced disturbance, perennial flora and continued organic inputs are important. Orchard and well managed forests are good land uses for carbon storage. At the same time, degraded sites across a range of land uses point to the urgent need for integrated soil health restoration efforts that address the many, inter related drivers of carbon loss. The existence of high performing communities within the study area suggests that restoration is possible, and provides models for intervention design. The best chance of reversing carbon depletion, enhancing ecosystem services and establishing resilient agricultural landscapes in the region lies in location specific solutions which mix technical practices with knowledge distribution and community engagement.

**DISCUSSION**

The findings of the research showed high spatial variation in soil organic carbon (SOC) stocks in various land uses and villages of Udhampur region of Jammu and Kashmir. Soil organic carbon (SOC) is an important component of soil fertility and health because of its essential role in carbon sequestration, and soil structure and nutrient cycling. This study investigated the soil organic carbon stocks in four major land use types, namely grassland, orchard, agricultural land and forest at three different soil levels (0 to 15 cm, 15 to 30 cm and 30 to 60 cm). The results suggest anticipated trends and some surprises, especially in view of the unique environmental circumstances in Udhampur, influenced by the way the land is managed.

*Spatial Variation in SOC Stocks*

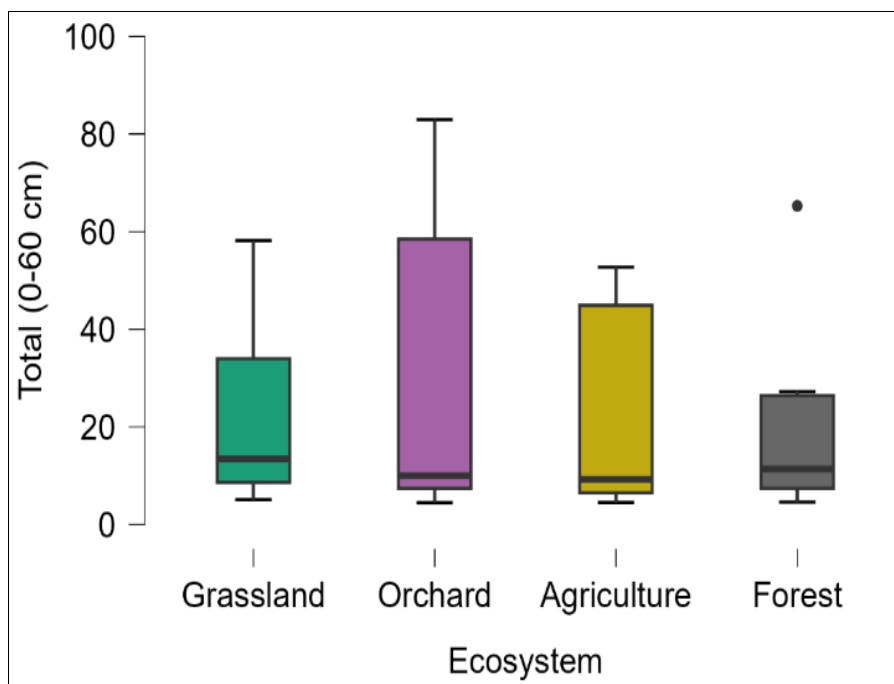
Kirmoo was the most carbon dense area with the highest total soil organic carbon storage (259.098 Mg/ha)

irrespective of land use and soil depth. Favourable climatic conditions including uniformly spaced vegetation, moderate precipitation and good land management practices can be the reason for Kirmoo’s greater SOC stocks. The region may also have been largely free of human activity such as heavy farming or overgrazing, which may have helped preserve the organic materials. Marta had relatively large stocks of SOC, notably in agricultural and orchard areas, suggesting that the use of managed land might boost SOC storage if sustainable methods are used.

Dehari and Khagote, on the other hand, always had the least soil organic carbon storage particularly in the deeper soil profiles (15 to 30 cm and 30 to 60 cm). Increased agricultural overgrazing and deforestation probably contributed to the decline in several areas. The decline in SOC stocks in these areas indicates a disturbing loss of soil organic matter. Such loss may result in a reduction in soil fertility, erosion and soil biodiversity. The lower organic carbon in the deeper layers of these settlements indicates that, particularly in areas of high soil disturbance, organic carbon imports do not compensate for losses via oxidation, erosion and microbial decomposition.

*Land Use Impact on SOC Storage*

Figure 4. Among the land use types, the highest SOC stocks were found in orchards, consistently in Kirmoo (82.9365 Mg/ha) and Marta (66.492 Mg/ha). Sustainable management practices in orchards such as limited tillage, mulching and organic fertilisation are key contributors to SOC storage. Orchard perennial vegetation stabilises the soil, improves soil structure and enhances organic matter input which leads to increased rates of carbon absorption. High SOC stocks in orchards at Kirmoo and Marta showed that there are deep rooted plants in these areas which are responsible for accumulation of organic matter deeper in the profile notably at 30 to 60 cm depth.



**Figure 4: The average effect of ecosystems on total soil carbon stock.**

Nonetheless, agriculture was associated with moderate SOC reserves; Kirmoo (52.74 Mg/ha) and Marta (50.83 Mg/ha) had greater values than Dehari (4.51 Mg/ha) and Khagote (5.00 Mg/ha). This discrepancy is most likely caused by variations in agricultural practices such as tillage, crop residue management, and fertilisation. Reduced SOC stocks are often associated with intensive tillage and monocropping, which may cause organic matter breakdown and soil particle erosion. Rather, areas that use crop rotation, conservation tillage, and cover crops often have larger soil organic carbon (SOC) stocks. The declining SOC stocks in the agricultural districts of Dehari and Khagote show that organic matter is being depleted due to a lack of organic inputs or management strategies that prevent carbon retention.

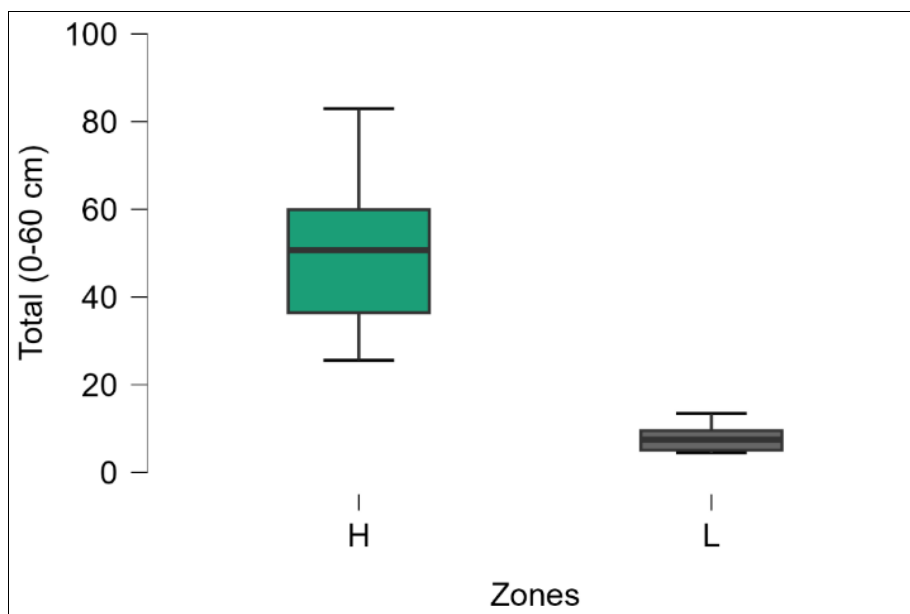
Grasslands exhibited intermediate SOC stocks, with minimal values of 5.10 Mg/ha in Khagote and 6.97 Mg/ha in Dehari and high values of 58.15 Mg/ha in Kirmoo and 38.845 Mg/ha in Thaplal. Because their deeply ingrained vegetation adds organic matter to the soil profile, grasslands are crucial for sequestering carbon. Overgrazing, however, may have an impact on grasslands' capacity to store carbon. Grazing lowers biomass and plant density, which in turn lowers organic matter inputs and root biomass. Additionally, grazing may worsen soil erosion and compaction, which would lower SOC retention.

Soil organic carbon (SOC) storage is moderate to high in forests, particularly in Kirmoo (65.27 Mg/ha). This implies

that the woodlands might be useful carbon sinks. Through microbial activity, root exudates, and litterfall, forests provide organic carbon to the soil. However, the forested areas of Dehari (5.7885 mg/ha) and Khagote (4.5913 mg/ha) have far lower soil organic carbon (SOC) stocks, suggesting potential issues such as deforestation, degradation, or inadequate management. Reduced root biomass and forest floor litter, as well as lower absorption of organic matter, are associated with forest decline. These factors together diminish soil organic carbon stocks. Our results highlight the need of appropriate forest management techniques to protect and encourage carbon storage in forest soils.

Our findings demonstrate how crucial land use patterns are to the development of soil organic carbon stocks. In order to increase soil organic carbon sequestration, conservation, orchard management, and sustainable farming practices are crucial, as shown by the greater SOC stocks in Kirmoo and Marta. It is commonly recognised that conservation tillage, agroforestry, and organic farming may enhance soil health and encourage soil organic carbon retention.

Dehari and Khagote's lower SOC levels point to the need for soil conservation techniques in areas where soil degradation is occurring. In contrast to a continuously low SOC stock with less variance for the low potential zone (Dalsar, Dehari, Khagote, and Kulwanta) (Table 8), Figure 5 shows a significantly high mean SOC stock with a broad range of values for the high-potential zone (Kirmoo, Thaplal, and Marta).



**Figure 5: The average effect of zones [High potential zones (Kirmoo, Marta and Thaplal) and Low potential zones (Dalsar, Dehari, Khagote and Kulwanta)] on total soil carbon stocks.**

**Table 8: Descriptive Statistics by zones (high zone and low zone) for total SOC stock (0-60cm)**

	High	Low
Valid	12	16
Missing	0	0
Mean	48.89	7.671
St, Deviation	17.70	2.820
Minimum	25.58	4.472
Maximum	82.94	13.43

Strategies for reforestation, rewilding, or grassland restoration might assist restore organic matter levels in these places. Farmer and landowner education on sustainable land management practices including management of agricultural wastes and application of organic amendments might be an important aspect in reversing the decline of SOC stocks at these sites. The results of the research are also important for higher efforts in sequestration of carbon in the face of the climate change mitigation. Soil organic carbon (SOC) storage in soils is important in the global carbon cycle and its mitigation in the atmosphere. Effective land management practices that increase SOC supplies may, therefore, be vital to the regional approach to climate change mitigation and adaptation.

**Agricultural Management Policies for Improving SOC**  
 The most immediate approach for humans to alter SOC stocks is via agriculture management. Examples of conservation agriculture strategies that have repeatedly demonstrated potential to increase soil carbon sequestration rates include reduced tillage, cover crops, improved crop

rotations and integrated nutrient management. Conservation tillage may sequester between 0.1 and 0.5 metric tonnes of carbon per hectare per year across a range of agroecosystems (Paustian et al., 2016). However, adoption of such solutions is still limited in many locations due to social, technical and economic barriers. These hurdles might be addressed by coordinated policies that successfully promote agricultural methods that improve SOC. They have been particularly effective when financial incentives are tailored to lower farmers' upfront costs and risks. A case in point of the kind of effect that targeted subsidies may have in speeding up the adoption of conservation practices is the United States' Environmental Quality Incentives Program (EQIP). Similarly, the European Union's Common Agricultural Policy has slowly included "greening" laws that boost soil carbon. Well designed incentive schemes may increase adoption rates of conservation practices by 30 to 45% above information only approaches (Richards et al., 2019). Agricultural extension services are critical for the transfer of information and capacity building for soil carbon management, even without financial incentives. In several agricultural settings

measures to strengthen extension systems focusing on soil health have demonstrated promising results. The Carbon Farming Initiative in Australia has successfully combined financial incentives and technical assistance and has resulted in increased uptake of carbon sequestration methods by the participating farms. Sanderman et al. (2017) found that farmers that received financial help and technical support were 60% more likely to adopt and persist with activities that enhance SOC than farmers who just received financial incentives. Market based incentives for soil carbon management might also be introduced via certification systems that recognise carbon smart farming. Such solutions might enable farmers to benefit from increased pricing for items produced using carbon-sequestering processes. A good example is the “4 per 1000” initiative in France, where national commitments have mobilised numerous stakeholders around soil carbon targets and developed legal frameworks that facilitate innovation throughout agricultural value chains. However, Thamo and Pannell (2016) advise that certification approaches need to be carefully constructed to ensure they effectively reflect carbon benefits and are accessible to a range of agricultural operations, including smallholders.

#### *Land use policies and SOC preservation*

Land use change is the largest threat to soil carbon stocks, but there is also a significant opportunity to recover depleted soil and retain carbon. Land use change from grasslands and forests to farms has been a major contributor to long term soil carbon loss. SOC in the top soil layers may be decreased by 20-50% notably in Indian Himalayan Region (Rawat et.al., 2016). Holistic climate solutions must thus include policies that regulate land use change in a soil carbon accounting method.

One of the greatest methods to guarantee carbon-rich ecosystems are conserved is via protected area laws. A direct climate benefit would be the avoidance of carbon emissions, which might be accomplished by strengthening protection for carbon rich soils, such as peatlands, old-growth forests and permafrost zones. Griscom et al. (2017) noted that protection of carbon rich ecosystems is the best means of reducing greenhouse gases. Including all the services ecosystems give, the benefits might be more than \$100 per tonne of CO<sub>2</sub> equivalent.

There is significant potential for policies to sequester carbon in degraded soils as well as other environmental benefits. Restoring agricultural fields that have been harmed by erosion, salinisation or pollution may restore ecological function and store 0.3 to 0.7 metric tonnes of carbon per hectare each year. Lal (2016) estimates that the restoration of degraded soils may sequester 0.9 to 1.9 gigatonnes of carbon per year globally, which is a significant fraction of the emissions reductions needed to meet the targets of the Paris Agreement. Payment for ecosystem services (PES) systems are beginning to recognise soil carbon as a valued service, and new financial methods for executing restoration at a broad scale are emerging.

Soil carbon is also impacted by development laws, green space requirements and urban forestry initiatives, all of

which are components of urban planning policy (Wiesmeier, 2019). Urban soil management is a new and fascinating field for carbon policy that is becoming more significant as cities develop throughout the globe. since Lorenz and Lal (2012) point out, there are possibilities to integrate climate concerns in city land use planning, since well managed urban soils may sequester 0.15 to 0.3 metric tonnes of carbon per hectare each year.

#### **CONCLUSION**

The study emphasises the role of land use patterns, soil management techniques and environmental variables controlling SOC stocks in different villages of Udhampur. The results suggest that well managed woods and orchards are the best sites for SOC sequestration, whereas intensive farms and degraded grasslands likely to have smaller SOC reserves. The variation in SOC stocks across communities reveals the importance of village specific soil management practices and insights for improved land use in the area. Future conservation actions and sustainable land management methods should enhance soil health, boost carbon sequestration and contribute to broader climate change mitigation goals.

Soil carbon programs, especially in poor countries, have strong international channels of assistance, notably the Clean Development Mechanism and the emerging architecture of the Paris Agreement. But for these frameworks to perform as they are supposed to, we need new ways of doing things, easier ways of keeping track of things and ways of implementing programmes that cut transaction costs without jeopardising environmental protection. Integrating soil carbon objectives into larger sustainable development goals such as food security, water quality, protection of biodiversity and rural livelihoods may result in important policy synergies and be supported by a variety of stakeholders and funding approaches. Such integrated methods provide the economic case for sustainable soil management, understanding the many ecological advantages delivered by healthy soil in addition to carbon sequestration. We need to tackle implementation issues via capacity building, risk management mechanisms, improvements in tenure security and creative monitoring techniques if we are to achieve actual results from policy potential. These enabling circumstances may increase acceptance by farmers of techniques that improve SOC and enable reliable measurement, reporting and verification of carbon benefits. Soil carbon management is one of the oldest, most widely available nature based solutions, offers several co-benefits and should get greater attention as climate policy develops. Through developing holistic policy frameworks that consider the specificities of soil carbon its distribution across millions of land managers, its sensitivity to local conditions and its relation to food production systems policymakers can unleash a critical weapon in the fight against climate change.

#### **Availability of Data and Material**

Yes.

#### **Competing Interests**

The authors declare that they have no competing interests.

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**Clinical Trial Information**

‘Clinical trial number: not applicable.’

**Authors' Contributions**

**Ritika Mahajan** contributed to the conceptualization and writing of the manuscript, with a focus on soil carbon chemistry and mitigation pathways.

**Tanmoy Roy** was involved in the chemical assessment of soil carbon stocks and contributed to drafting the methodology.

**Vikas Sharma** provided expertise in soil management practices, field data interpretation, and contributed to the review of agricultural aspects.

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**REFERENCE**

1. Batjes, N.H., 2014. Total carbon and nitrogen in the soils of the world. *European Journal of Soil Science* 65, 10–21. <https://doi.org/10.1111/ejss.12114>
2. Bhattacharyya, R., Chatterjee, S., Tiwary, P., 2013. Soil organic carbon stocks in India: Spatial variation and potential sequestration. *Environmental Earth Sciences* 70, 2923–2932. <https://doi.org/10.1007/s12665-013-2563-9>
3. Bhattacharyya, T., Pal, D.K., Mandal, C., Velayutham, M., 2008. Organic carbon stock in Indian soils and their geographical distribution. *Current Science* 95, 482–489.
4. Bossio, D.A., Cook-Patton, S.C., Ellis, P.W., Fargione, J., Sanderman, J., Smith, P., Wood, S., et al., 2020. The role of soil carbon in natural climate solutions. *Nature Sustainability* 3, 391–398. <https://doi.org/10.1038/s41893-020-0491-z>
5. Campbell, E.E., Bailey, J.P., 2015. Soil organic carbon sequestration and its impact on soil health in agricultural systems. *Journal of Soil and Water Conservation* 70, 111A–116A. <https://doi.org/10.2489/jswc.70.5.111A>
6. Dar, M.A., Reshi, Z.A., 2020. Influence of slope gradient on soil carbon and nutrient stocks in mountain ecosystems of Kashmir Himalaya. *Environmental Monitoring and Assessment* 192, 225. <https://doi.org/10.1007/s10661-020-8131-0>
7. Griscom, B.W., Adams, J., Ellis, P.W., Houghton, R.A., Lomax, G., Miteva, D.A., Schlesinger, W.H., et al., 2017. Natural climate solutions. *Proceedings of the National Academy of Sciences of the United States of America* 114, 11645–11650. <https://doi.org/10.1073/pnas.1710465114>
8. Guo, L.B., Gifford, R.M., 2002. Soil carbon stocks and

- land use change: A meta-analysis. *Global Change Biology* 8, 345–360. <https://doi.org/10.1046/j.1354-1013.2002.00486.x>
9. Gupta, R.K., Singh, R., 2010. Soil organic carbon in agricultural soils: Quantification, role, and management strategies. *Journal of Agricultural and Food Chemistry* 58, 27–41. <https://doi.org/10.1021/jf9036064>
10. Jobbágy, E.G., Jackson, R.B., 2000. The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecological Applications* 10, 423–436. <https://doi.org/10.1890/1051-0761>
11. Hussain, S., Sharma, V., Arya, V.M., Sharma, K.R. & Rao, Ch.S. 2019. Total organic and inorganic carbon in soils under different land use/land cover systems in the foothill Himalayas. *CATENA*, 182, 104104.
12. Kour, G., Sharma, M.K., Sharma, P., 2018. Assessment of soil organic carbon pools under different land uses in Rajouri district of Jammu and Kashmir. *Indian Journal of Soil Conservation* 46, 178–183.
13. Lal, R., 2004a. Soil carbon sequestration impacts on global climate change and food security. *Science* 304, 1623–1627. <https://doi.org/10.1126/science.1097396>
14. Lal, R., 2016. Beyond COP21: Potential and challenges of the “4 per thousand” initiative. *Journal of Soil and Water Conservation* 71, 20A–25A.
15. Lorenz, K., Lal, R., 2005. The depth distribution of soil organic carbon in relation to land use and management and the potential of carbon sequestration in subsoil horizons. *Advances in Agronomy* 88, 35–66.
16. Lorenz, K., Lal, R., 2012. Carbon sequestration in urban ecosystems. Springer, Dordrecht. <https://doi.org/10.1007/978-94-007-2366-5>
17. Malik, R.S., Sinha, S.K., 2014. Soil organic carbon pools in different land uses and management practices in North India. *Journal of the Indian Society of Soil Science* 62, 26–32.
18. Mandal, B., Mandal, M.A.S., Majumder, B., 2020. Soil organic carbon dynamics and its relationship with climatic variables in Indian agroecological zones. *Geoderma Regional* 21, e00271. <https://doi.org/10.1016/j.geodrs.2020.e00271>
19. Nand, N., Kumar, A., 2020. Carbon sequestration and soil quality enhancement through conservation agriculture in Indo-Gangetic Plains. *Environmental Sustainability* 3, 233–242. <https://doi.org/10.1007/s42398-020-00119-0>
20. Nelson, D.W., Sommers, L.E., 1996. Total carbon, organic carbon, and organic matter. In: Sparks, D.L. (Ed.), *Methods of Soil Analysis. Part 3: Chemical Methods*. Soil Science Society of America, Madison, 961–1010.

21. Pan, Y., Birdsey, R.A., Fang, J., Houghton, R., Kauppi, P.E., Kurz, W.A., Hayes, D., et al., 2011. A large and persistent carbon sink in the world's forests. *Science* 333, 988–993. <https://doi.org/10.1126/science.1201609>
  22. Paustian, K., Lehmann, J., Ogle, S., Reay, D., Roberston, G. P., 2016. Climate-smart soils. *Nature* 532, 49-57.
  23. Post, W.M., Kwon, K.C., 2000. Soil carbon sequestration and land-use change: Processes and potential. *Global Change Biology* 6, 317–327.
  24. Powlson, D. S., Whitmore, A. P., 2011. Soil carbon sequestration to mitigate climate change: a critical re-examination to identify the true and the false. *European Journal of Soil Sciences* 62, 1-4. <https://doi.org/10.1111/j.1365-2389.2010.01342.x>
  25. Rawat, J.S., Sharma, S., 2016. Spatio-temporal dynamics of land use/cover change and carbon storage in the Indian Himalayan region. *Applied Geography* 76, 163–175. <https://doi.org/10.1016/j.apgeog.2016.09.015>
  26. Rather, M.A., Dar, J.A., Wani, M.H., Reshi, Z.A., 2020. Soil organic carbon stocks under different land use systems in Kashmir Valley, India. *Environmental Monitoring and Assessment* 192, 513. <https://doi.org/10.1007/s10661-020-08440-1>
  27. Richard, B. A., Lillicrap, T. P., Beaudoin, B., Bengio, Y., 2019. A deep learning framework of neuroscience. *Nature* 22, 1761-1770.
  28. Rumpel, C., Kogel- Knabner, I., 2011. Deep soil organic matter- a key but poorly understood component of terrestrial C cycle. *Plant and Soil* 338, 143-158.
  29. Sanderman, J., Hengl, T., Fiske, G.J., 2017. Soil carbon debt of 12,000 years of human land use. *Proceedings of the National Academy of Sciences of the United States of America* 114, 9575–9580.
  30. Schmidt, M.W.I., Torn, M.S., Abiven, S., Dittmar, T., Guggenberger, G., Janssens, I.A., Kleber, M., et al., 2011. Persistence of soil organic matter as an ecosystem property. *Nature* 478, 49–56. <https://doi.org/10.1038/nature10386>
  31. Sharma, V. & Arora, S. 2015. Land degradation processes and factors affecting crop production in foothills of Jammu Shivaliks. *Journal of Soil and Water Conservation*, 14, 295–300.
  32. Sharma, D., Sharma, V., Buttar, T.S., Sharma, A. & Arya, V.M. 2023b. Edge-of-field monitoring to assess the effectiveness of conservation practices in the reduction of carbon losses from the foothills of the Himalayas. *CATENA*, 225, 107030.
  33. Sharma, P., Sharma, M.K., 2018. Soil organic carbon fractions and carbon management index under different forest types in the western Himalayas. *Ecological Indicators* 85, 198–206. <https://doi.org/10.1016/j.ecolind.2017.10.049>
  34. Sharma, U.C., Datta, M. & Sharma, V. 2023a. Land Use and Management. In: *Soils in the Hindu Kush Himalayas: Management for Agricultural Land Use* (eds. Sharma, U.C., Datta, M. & Sharma, V.), pp. 295–462. Springer International Publishing, Cham.
  35. Sharma, V., Hussain, S., Sharma, K.R. & Arya, V.M. 2014. Labile carbon pools and soil organic carbon stocks in the foothill Himalayas under different land use systems. *Geoderma*, 232–234, 81–87.
  36. Singh, R., Ahmed, N., 2019. Land use change and soil degradation in Himalayan foothills of Jammu region. *Journal of Mountain Science* 16, 2103–2116.
  37. Smith, P., Rounsevell, M.D.A., Smith, J., 2005. Projected changes in mineral soil carbon of European croplands and grasslands, 1990–2080. *Global Change Biology* 11, 2141–2152.
  38. Thamo, T., Panell, D. J., 2016. Challenges in developing effective policy for soil carbon sequestration: perspectives on additionality, leakage and permanence. *Climate Policy* 16, 973-992. <https://doi.org/10.1080/14693062.2015.1075372>
  39. Trumbore, S.E., 2011. Soil organic matter dynamics in the subsoil. *Nature* 478, 205–206. <https://doi.org/10.1038/478205a>
  40. Walkley, A. & Black, I.A. 1934. An examination of the Degtjareff method for determining soil organic matter, and proposed modification of the chromic acid titration method. *Soil Science*, 37, 29–38.
- Wiesmeier, M., Urbanski, S., Hübner, R., et al., 2019. Soil organic carbon storage as a key function of soils A review of drivers and indicators at various scales. *Geoderma* 333, 149–162. <https://doi.org/10.1016/j.geoderma.2018.07.026>.