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ORIGINAL ARTICLE

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Impact of Land Use Interventions on Soil Organic Carbon Stocks: A Case Study from Antisar Watershed, Western India

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ABSTRACT

A study conducted during 2021–2022 at the Antisar watershed in Kapadvanj Taluka, Kheda District, Gujarat, evaluated soil organic carbon (SOC) and nitrogen (N) stocks across four land use systems: silvi-pasture (SLS), grazing (GLS), agriculture (ALS), and fallow (FLS). Forty soil samples were collected at three depths (0–10, 10–20, and 20–30) cm from treated (Antisar) and control (Malkahana) watersheds. Results revealed significant variations ($p < 0.05$) in soil pH, SOC, and total N across land uses, with ALS showing the highest pH, SOC, and N content, followed by SLS and FLS. SOC and N declined with depth across all systems. Compared to the control, SOC stocks in Antisar increased across all land uses (21–119) %, highest in fallow lands due to field bunding and leveling. Similarly, total soil carbon stock (TSCS) increased by (-2–315) %, with the highest gain in fallow lands and the lowest in SLS due to inadequate grazing control. The deterioration index indicated net losses of SOC and N with conversion from natural to managed systems, especially in continuously cultivated areas. These findings highlight the vulnerability of agricultural soils to degradation and stress the need for climate-smart, adaptive land use and management practices to enhance carbon sequestration and improve soil health in western India.

1 | INTRODUCTION

Soil is the largest land-based carbon reservoir on Earth, containing nearly three times the carbon found in the atmosphere (Jobbagy & Jackson, 2000). With an average carbon retention period of about 1,200 years, it plays a crucial role in sequestering atmospheric carbon (Post *et al.,* 1982). However, this capacity is significantly compromised by unsustainable land use, inadequate land management, and land degradation (Mchunu & Chaplot, 2012). Erosion processes caused by wind and water affect soil organic carbon (SOC) levels, which vary across landscapes. Furthermore, soil erosion diminishes soil fertility (Lal, 2003) and increases greenhouse gas emissions, raising environmental concerns. Land use changes and the burning of fossil fuels are the primary causes of disruption to the carbon cycle. Fossil fuel consumption in industries such as manufacturing, transportation, and air conditioning accounts for over 75% of global CO_2 emissions (Steen, 2000). Intensive agricultural techniques deplete carbon stocks through methods such as soil ploughing, biomass clearance, and erosion (Mandal *et al.,* 2013), and the conversion of natural ecosystems into cultivated land also disrupts the carbon balance (Selassie & Ayanna, 2013). However, agriculture can serve as a carbon sink due to its ability to sequester carbon through sustainable farming practices. The conversion of forest land to agricultural use accelerates carbon loss through decomposition and harvesting. In contrast, converting cropland to forests can increase soil carbon levels by up to 50% (Dawson & Smith, 2007). Agroforestry systems also support carbon balance, particularly by restoring soil carbon in previously managed areas. Understanding how different types of land use affect carbon stocks is essential, as each influences the carbon balance positively or negatively. Additionally, assessing a watershed's carbon storage capacity (Mandal *et al.,* 2013) is critical for developing effective strategies to conserve and enhance carbon stocks. There is a lack of research on organic carbon stocks and storage in western India; most studies focus on soil carbon and do not examine different carbon stores at the watershed scale. Under population pressure, the effects of small-scale subsistence farming, characterized by poor management and low input resources, have not been sufficiently investigated. Strategies to increase productivity, improve carbon stocks, and reduce greenhouse gas emissions require comprehensive data on carbon emissions and storage, particularly as climate change intensifies. Therefore, the objective of this study was to evaluate the various soil properties at different soil depths and assess the carbon and nitrogen stocks in the Antisar (Treated) and Malkahana (Control) watersheds of western India across a range of land uses.

2 | MATERIALS AND METHODS

The Government of India initiated model watershed projects aimed at rainfed areas as part of its five-year plans. In March 1997, the ministry of rural development kicked off the integrated wasteland development program (IWDP) at the ICAR-Indian Institute of Soil and Water Conservation, formerly known as CSWCR&TI, in Vasad. This initiative aimed to create a model watershed for researching and showcasing soil and water conservation practices through effective watershed management, focusing on the conservation of natural resources and improving rainfed land productivity. The 812 ha Antisar watershed, located in Kapadvanj Taluka of Kheda District, Gujarat, comprises 736 ha of agricultural land and 76 ha of community land. The watershed experiences an average annual rainfall of 830 mm, with temperatures ranging from 18.9 ° C to 33. 7 ° C. Agricultural practices in the area include mixed cropping of pearl millet, cotton, castor, groundnut, and tobacco alongside livestock management, according to Bagdi and Kurothe (2013). The primary soil and water conservation measure implemented across 142 ha of agricultural land involved field bunding with minor leveling, while trenching was utilized in silvi-pasture systems. Within the watershed, 16 new check dams, 28 gully plugs, renovating four existing ponds, and constructing 23 groundwater recharge filters were completed. To control erosion, a vegetative barrier was established in a strip at the lower end of the study area. On the upstream side, several interventions took place, including crop demonstrations on 136 ha of arable land, afforesting 37 ha of pasture, and establishing horticulture plantations on 11 ha. The main land use and land cover (LULC) categories identified in the watershed were mapped using a 1: 50, 000 topographic map from the survey of India, along with cadastral maps of the local villages. Field observations confirmed the LULC types, while the survey of india map and GDPS data helped delineate the watershed boundary. The LULC map, created with surfer software, highlighted three main land use types: silvi-pasture land use (SLU), grazing land system (GLS), and agricultural land system (ALS). The details and characteristics of the major land use types identified in the watershed are outlined in Table 1.

HIGHLIGHTS

- Agricultural land uses showed highest soil organic carbon recovery in response to conservation measures.
- Fallow lands achieved the greatest improvement in total soil carbon stocks in response to bunding and leveling, and natural accumulation of inorganic carbon.
- The deterioration index revealed that converting natural ecosystems into managed lands leads to significant losses in organic carbon.

2.1 | Sampling techniques

The sampling sites were selected to assess the soil carbon and nitrogen stocks from different land uses within the implemented watershed, with their characteristics provided in Table 1. Soil sampling was conducted during April and May of 2021-22 at various soil depths, namely 0-10 cm, 10-20 cm, and 20-30 cm across the different land uses of the watershed. The Antisar watershed project concluded in 2008-2009, and a control watershed was selected in proximity to the implemented watershed, as illustrated in *Fig. 1*. The Malkhana watershed (Control) served as a reference for studying the impact of soil and water conservation measures on the major land uses of the Antisar watershed (Treated). Two transects, spaced 1,000 m apart, were established in the agricultural land use system, grazing land use system, and silvi-pasture land use system in both watersheds. Additionally, random soil sampling points were

TABLE 1 Description of major land uses in Antisar (Treated) and Malkhana watershed (Control) for assessing the soil carbon and nitrogen stock

Land use	Description
Silvi-pasture land use (SLS)	Sparse vegetation mixed with woodland and grassland ecosystems characterized by widely spaced trees and native species of grasses for more than 10 years.
Grazing land use system (GLS)	Abandoned community-owned lands left for more than 10 years to recover their fertility and for grazing of stray animals in the villages.
Agricultural land use system (ALS)	The continuously cropped land with Maize, Cotton, Pearl millet, Castor, Fennel, Chickpea, Cumin, Sorghum, characterized by continuous clearing, tilling with farm machinery, removal of above-ground biomass (crop residue), and leveling of farm fields for more than 10 years.
Fallow land use system (FLS)	The agricultural land is suitable for cultivation, but has been kept fallow continuously for more than 5 years.

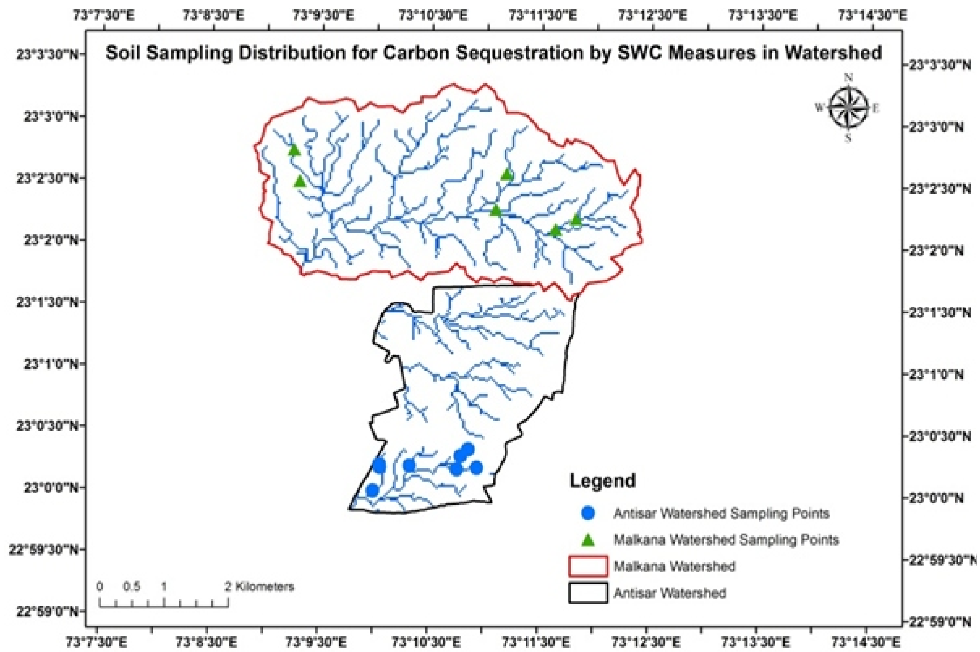


FIGURE 1 Soil sampling point under different land uses in Antisar (Treated) & Malkhana watershed (Control)

established outside these designated transects, as shown in *Fig. 1*. The soil sample plots of 10 m × 10 m were set at 500 m intervals for the agricultural and grazing land use systems, while 20 m × 20 m plots were utilized for the silvi-pasture land use system. A nested sampling approach (Iqbala & Tiwari, 2015) was applied, with plots starting 150 m into the different land uses to minimize edge effects. The GPS coordinates were recorded, and trees/shrubs with a DBH of 5 cm or greater were also measured. Leaf litter samples from 0.5 m × 0.5 m quadrats were combined, and above-ground carbon was estimated from tree diameter, while below-ground biomass was calculated using above-ground biomass values based on the methodology reported by Santantonio *et al.* (1977).

Soil samples were collected from the center and corners of 10 m × 10 m sub-plots from all land uses investigated. Samples were taken at depths of 0-10, 10-20, and 20-30 cm, as recommended for carbon accounting (Abera & Wolde-Meskel, 2013). Organic carbon, total nitrogen, soil texture, and pH were measured from three composite samples. The samples were air dried and ground to pass a 0.5 mm screen. Undisturbed samples for bulk density were obtained at the same depths using core samples.

2.2 | Laboratory analysis of soil samples

To evaluate the soil carbon stock, a 100 g soil sample from a composite was oven-dried at 105°C until constant weight, and a 4 g sample was fired at 500°C for 8 hours in a Muffle furnace, with all measurements done in triplicate (Campbell & Plank, 1977). The dry bulk density was determined using the core method (Blake, 1986), with core samples oven-dried to constant weight at 105°C, and calculated by dividing the oven-dry weight by core volume (Campbell & Plank, 1977). The soil texture was analysed using the Bouyoucos hydrometer method (Van reeuwijk, 2002), pH was measured in a 1:2.5 soil-water suspension (McLean, 1982), Total nitrogen by Micro-Kjeldahl method (Bremner & Mulvaney, 1982), and soil organic carbon via the Walkley-Black method (Walkley & Black, 1934).

2.3 | Estimation of soil carbon stock

The soil carbon stock per hectare was determined using the organic carbon content from soil samples analysed in the soil laboratory. The Zhang *et al*. (2008) technique was used to calculate the carbon stock for each soil layer.

$$C_i = BD_i \times (1 - CF_i) \times d_i \times OC_i \quad \ldots(1)$$

The carbon stock of the ith layer, C_i (t/ha), is calculated using bulk density Bd_i (kg/m^3), coarse fragment content CF_i, organic carbon content OC_i (%), and layer thickness d_i (m), with a conversion factor of 10 from kg/m² to t/ha. The coarse fraction was identified by breaking up clods, mechanically grinding, drying, and sifting material through a 2 mm sieve, and its proportion was determined using the Zhang *et al*. (2008) method.

$$CF_i = (\text{Total weight} - \text{fractional weight} < 2\text{ mm of total weight}) \times 100 \quad \ldots(2)$$

For the depth of 0 to 30 cm, the total carbon stock was computed as follows:

$$C = \sum C_i \qquad ...(3)$$

The following formula was used to determine the dry bulk density.

$$BD = 1000 \times MODS \times V_t \qquad ...(4)$$

Where, V_t is the total volume of the soil core determined using the formula $V_t = \pi r^2 h$ and MODS is the mass of the oven-dry soil (g). Within this formula, r represents the cores' internal radius in cm, h represents their height as measured by a hand tape, 1000 represents the conversion ratio from g cm^{-3} to kg m^{-3}, and π\pi is a constant roughly equivalent to 22/7.

2.4 | Calculation of Deterioration Index (D_i)

To construct the deterioration index (D_i), it was assumed that organic carbon and total nitrogen levels in soils under silvi-pasture land use system, grazing land use system, and agricultural land use system were compared with silvi-pasture land use soils for relative index formulation for deterioration of soil quality for different land use systems. Based on Adejuwon and Ekanade's (1988) method, an overall soil deterioration index was created by averaging changes across these properties, with individual degradation indices calculated as given in equation (5).

$$D_i = \left(\frac{PSL - PRL}{PRL}\right) \times 100 \qquad ...(5)$$

Where, D_i is the deterioration index of specific land use system in the watershed, PRL is the mean value of the total soil carbon stock under selected land use in treated watershed, PSL is the mean value of the total soil carbon under selected land use in control watershed.

2.5 | Statistical analysis

The data was organized by land use and soil depth, with standard errors calculated for all the determined soil parameters. A Least Significant Difference (LSD) test with ANOVA ($p < 0.05$) was applied to assess significant differences across different depths of soil in different land uses. A two-way ANOVA was also performed in Microsoft Excel 2013 to evaluate the significant difference between the soil properties across different land uses in the watershed.

3 | RESULTS AND DISCUSSION

3.1 | Soil properties

The soil pH varied significantly ($p < 0.05$) among the four land use types; however, no significant variation was found within soil depths across these uses, as shown in Table 2. The agricultural land use system exhibited higher pH values at the surface, while the fallow land use system displayed lower pH values. The soil organic carbon content significantly differed by land use and soil depth, with the agricultural land use system showing the highest organic carbon content, followed by the silvi-pasture system and the fallow land use system. The organic carbon content significantly decreased with increasing soil depth across all land uses, as detailed in Table 2. Additionally, the total nitrogen content was highest in the agricultural land use system, followed by the silvi-pasture land use system, as indicated in Table 2, which may be attributed to fertilizer application in the agricultural land use system by farmers for crop production.

The depletion of basic cations from top soil layers may leach and deposit at lower depths, resulting in higher pH values in deeper strata (> 30 cm). Tadesse *et al*. (1991) found that the soils under study ranged from neutral in other land

TABLE 2 Soil physical properties in relation to different land uses and soil depths (mean ± SD) in Antisar watershed

Variable	Depth (m)	Land Uses				
		ALS#	SLS	GLS	FLS	Overall
pH (H_2O)	0-0.1	8.23 (±0.16)	7.94 (±0.04)	7.8 (±0.49)	7.3 (±0.04)	7.91 (±0.41)
	0.1-0.2	8.34 (±0.16)	7.89 (±0.1)	7.73 (±0.64)	7.11 (±0.05)	7.89 (±0.55)
	0.2-0.3	8.35 (±0.08)	7.89 (±0.09)	7.85 (±0.52)	7.33 (±0.09)	7.94 (±0.46)
	Overall	8.31 (±0.15)c	7.91 (±0.07)b	7.80 (±0.48)b	7.23 (±0.12)a	
OC (%)	0-0.1	0.64 (±0.05)	0.34 (±0.05)	0.27 (±0.029)	0.18 (±0.01)	0.36 (0.02)b
	0.1-0.2	0.42 (±0.03)	0.30 (±0.01)	0.23 (±0.02)	0.16 (±0.01)	0.28 (0.01)a
	0.2-0.3	0.29 (±0.08)	0.20 (±0.01)	0.17 (±0.01)	0.16(±0.02)	0.21(0.01)a
	Overall	0.48 (±0.15)c	0.27 (±0.06)b	0.22 (±0.04)ab	0.16 (±0.03)a	
TN# (%)	0-0.1	0.12 (±0.01)	0.07 (±0.07)	0.04 (±0.01)	0.03 (±0.01)	0.07 (±0.02)b
	0.1-0.2	0.09 (±0.03)	0.05 (±0.03)	0.04 (±0.03)	0.01 (±0.02)	0.05 (±0.01)a
	0.2-0.3	0.07 (±0.04)	0.03 (±0.04)	0.03 (±0.01)	0.02 (±0.02)	0.03 (±0.09)a
	Overall	0.09 (±0.02)b	0.05 (±0.07)a	0.03 (±0.03)a	0.02 (±0.02)a	

#TN total nitrogen, ALS Agricultural Land use system, SLS Silvi-paturse land use systems, GLS Grazing land use System, FLS fallow land use system. For each parameter, different letters indicate significant differences ($p < 0.5$) with respect to land uses, respectively at each depth ($p < 0.05$).

TABLE 3 The changes in SOCS, SICS and total soil carbon stock in different land uses of Antisar and Malkhana watershed

	Soil organic carbon stock (SOCS) t ha^{-1}			Soil inorganic carbon stock (SICS) t ha^{-1}			Total soil carbon stock (TSCS) t ha^{-1}		
Land use system	Antisar WS	Malkhana WS	% change	Antisar WS	Malkhana WS	% change	Antisar WS	Malkhana WS	% change
SLS	72	54	32	44	45	-2	116	99	17
FLS	46	21	119	62	15	315	108	36	201
GLS	22	19	21	50	12	305	72	31	135
ALS	115	65	79	86	52	65	201	117	72

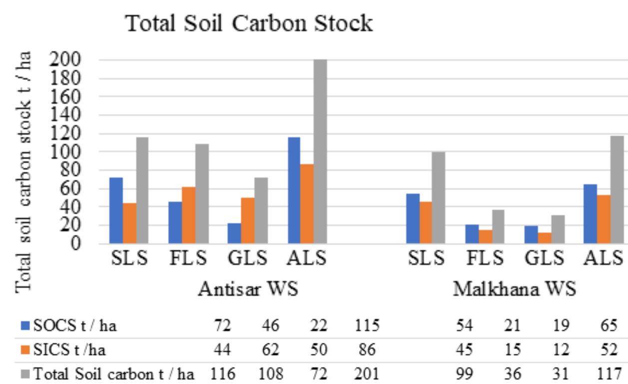
SLS: Silvi-pasture land use system, FLS: Fallow land use system, GLS: Grazing land use system, ALS: Agriculture land use system

uses to slightly alkaline in cultivated areas, which encourages microbial activity, plant development, and nutrient availability (Landon, 2014). The increased organic carbon content, which is a major source of total nitrogen (mostly organic nitrogen), is associated with a highly significant correlation ($p < 0.01$) of total nitrogen in the forest land use system.

3.2 | Soil carbon stock

The agricultural land use system had the highest total soil carbon stock among all depths, followed by the silvi-pasture system. The grazing land use system had the lowest carbon levels at all depths. In the Antisar watershed, all land use systems showed an increase in soil organic carbon stock (SOCS) compared to control (*Fig. 2*), with percent changes ranging from 21 to 119%, highest in fallow land (119%) likely due to field bunding and minor leveling. All land use systems also exhibited variations in soil inorganic carbon stock (SICS) compared to control, with changes ranging from -2 to 315%, the highest in fallow land (315%) connected to soil parent material characteristics. Additionally, total carbon stock (TSCS) increases (Table 3) were observed across all systems, ranging from 2% to 315%. The silvi-pasture system showed the lowest TSCS increase (Table 3) (17%) due to inadequate protection from uncontrolled grazing, while fallow land saw the highest change (201%), potentially due to higher inorganic carbon contributions. The agriculture land system showed the least TSCS variation, likely due to changes in cropping patterns by farmers.

Research indicates that upper layers typically have higher organic carbon levels than deeper ones (Ehrenbergerova, 2016). The intensive farming practices in the region lead to greater SOC depletion compared to grazing land use systems, potentially increasing soil emissions. To mitigate climate change, it is vital to adopt land use strategies that enhance organic carbon content while reducing emissions. Effective management practices significantly influence the balance between carbon inputs and outputs and organic matter decomposition rates (Melero *et al*., 2011). The techniques such as fertilization, agroforestry, conservation tillage, and no tillage should be implemented in low-input subsistence farming to improve carbon sequestration. Additionally, excessive grazing pressure and the cut-and-



SLS: Silvi-pasture land use system, FLS: Fallow land use system, GLS: Grazing land use system, ALS: Agriculture land use system

FIGURE 2 Total soil carbon stock in different land uses of Antisar watershed (Treated) & Malkhana watershed (Control)

carry system have diminished organic matter inputs (Riedo *et al*., 2000), supporting Guo and Gifford's (2002) findings that grazing negatively affects plant biomass by removing essential high-energy, palatable plants.

Population optimization can increase the carbon stock in grazing fields (Guo & Gifford, 2002). However, because of the high demand for agricultural land and population pressure, rotational grazing is not feasible in the study region. Alternative tactics, such as planting fodder grasses on bunds and introducing fodder species on marginal lands, are crucial to lessen grazing pressure and improve carbon sequestration in these places.

3.3 | Deterioration index

According to the deterioration index calculated for different land use systems in the watershed, there has been a net loss of organic carbon and total nitrogen as a result of the conversion of natural ecosystems like grasslands into managed systems like grazing land, silvi-pasture, and farmland. The areas with continuous crop cultivation observed the highest decline in soil quality, followed by Silvi-pasture, as shown in *Fig. 3*.

More successful soil management techniques are associated with a lower deterioration index in perennial

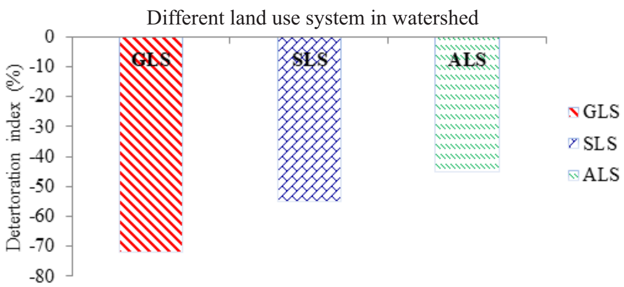


FIGURE 3 Deterioration index of major land uses in Malkhana watershed (Control)

vegetation systems (such as grassland and silvi-pasture system). In western India, research shows that cultivated and agricultural soils degrade more quickly than other land uses. This suggests that smallholder subsistence farming is frequently exploitative, which limits the sector's capacity to retain carbon and fight against climate change. In order to increase carbon stocks and lower emissions, this emphasizes the necessity of alternative land uses and management techniques, such as climate-smart agriculture. These tactics must be implemented to increase subsistence farmers' ability to adapt to climate change.

4 | CONCLUSIONS

The exploitative subsistence farming by smallholder farmers has depleted soil organic carbon, especially in agricultural land use systems, potentially increasing emissions. The findings of this study imply that the fallow and grazing land use systems showed the greatest variation in the total soil carbon stock. The total soil carbon stock under the Silvi pasture land use system varied the least, followed by the Agriculture land use system. Therefore, adopting conservation-based practices that include perennial grasses and tree crops is essential for increasing total soil carbon stock. However, comprehensive knowledge of carbon stocks across various land uses in Western India is lacking. This study emphasizes the need for watershed-level assessments of carbon stocks to guide sustainable land use decisions, while also highlighting the necessity for further research on carbon acquisition and loss specific to each land use.

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CONFLICT OF INTEREST

There is no conflict interest in the study .

AUTHOR'S CONTRIBUTION

DD: Concept planning and drafting manuscript; GS: field survey and map preparation; DJ: Methodology and drafting manuscripts; NKN: Reviewing and drafting manuscripts preparations, AKS: Methodology and data preparing MJK: Data processing and analysis

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