The Academic
International Journal of Multidisciplinary Research

An Online Peer Reviewed / Refereed Journal
Volume 4 | Issue 3 | March 2026
ISSN: 2583-973X (Online), SJIF IF: 5.6
Website: www.theacademic.in

Role of Soil Erosion on Carbon Cycling in Tropical Watersheds

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DOI : https://doi.org/10.5281/zenodo.19541896

ARTICLE DETAILS

Research Paper

Accepted: 24-03-2026

Published: 10-04-2026

Keywords:

Tropical watersheds, soil organic carbon (SOC), soil and water conservation (SWC)

ABSTRACT

Tropical watersheds are critical hotspots for the global carbon cycle, characterized by high primary productivity and rapid decomposition. In India, where approximately 94.87 million hectares of land are affected by water and wind erosion, soil erosion acts as a powerful, yet poorly constrained, modulator of this cycle. This paper critically examines the dual role of soil erosion as both a net source and sink of atmospheric carbon within the Indian context. Through a comprehensive review of recent studies from Maharashtra, the Western Ghats, and the Indian Himalayan region, we demonstrate that erosion's impact is a complex process of carbon displacement, transformation, and burial. Our synthesis integrates findings from RUSLE-based modeling, field sampling of soil organic carbon (SOC) in erosional and depositional zones, and analysis of soil and water conservation (SWC) interventions. Results from the Central MPKV Campus Watershed in Maharashtra indicate that SWC measures reduced average annual soil loss from 18.68 to 9.41 t ha^{-1} yr^{-1}, with corresponding carbon loss reduction from 348.71 to 205.52 kgC ha^{-1} yr^{-1}. In the Western Ghats, nature-positive interventions reduced carbon loss by over 21% within a single year. Studies from the Indian Himalayas further reveal that high erosion rates do not necessarily promote net carbon loss to the atmosphere, as burial and separation from fresh carbon inputs reduce decomposition rates. We conclude that Indian tropical watersheds are dynamic reactors where geomorphic and biogeochemical processes are tightly coupled. Effective land management, particularly the strategic implementation of deep continuous contour trenches (DCCT) and compartment bunds, is crucial for optimizing carbon sequestration potential, with rates reaching 0.723 t C ha^{-1} yr^{-1} in forest lands.

1. Introduction

The global carbon cycle is a complex web of fluxes, with terrestrial ecosystems playing a pivotal role as both major sinks and sources of atmospheric CO_2. Tropical regions, which account for approximately 50% of global terrestrial gross primary productivity, are central to this balance (Beer et al., 2010). India, with its diverse tropical ecosystems ranging from the Western Ghats to the Eastern Himalayas, represents a critical component of this balance. However, the integrity of this carbon sink is increasingly threatened by anthropogenic pressures, most notably land-use change and accelerated soil erosion.

Soil erosion, the detachment and transport of soil particles by water, wind, or gravity, has long been recognized as a major threat to soil fertility and agricultural productivity in India. The Indian Council of Agricultural Research (ICAR) estimates that water and wind erosion affect 94.87 million hectares of land in the country, leading to severe on-site and off-site impacts. However, the role of erosion in the carbon cycle is only beginning to be fully appreciated in the Indian context. For decades, erosion was simplistically considered a net carbon source, as it leads to the loss of SOC from terrestrial landscapes, potentially increasing atmospheric CO_2 through the mineralization of displaced carbon during transport. This perspective, however, overlooks the nuanced fate of eroded carbon.

Indian tropical watersheds present a unique and critical environment for studying this phenomenon. They are characterized by:

1. High Erosion Rates: Intense monsoon rainfall, steep topography in the Western Ghats and Himalayas, and erodible soils create naturally high background erosion rates, which are dramatically accelerated by deforestation and agriculture.

2. Rapid Carbon Dynamics: High temperatures and humidity facilitate rapid decomposition, but also promote fast vegetation regrowth and dynamic carbon replacement.

3. Efficient Burial Potential: The presence of extensive floodplains (e.g., Ganga and Brahmaputra basins), alluvial fans, and thousands of reservoirs provides ideal environments for the rapid burial of eroded carbon, which can effectively lock it away from atmospheric exchange.

This creates a critical scientific paradox: does soil erosion in Indian tropical watersheds act as a net source of CO_2 to the atmosphere, or can it, under certain conditions, constitute a significant geological carbon sink? This paper aims to resolve this paradox by moving beyond a simple mass-balance approach to a process-based understanding, drawing exclusively on studies conducted in India.

The central hypothesis of this research is that the net effect of soil erosion on carbon cycling in Indian tropical watersheds is not inherently a source or a sink, but is a dynamic equilibrium controlled by the balance between carbon mobilization, replacement by regrowing vegetation, and the efficiency of stabilization and burial in depositional environments.

Objectives of the study

This paper will test this hypothesis through a synthesis of Indian studies, with the following objectives:

1. To quantify the magnitude and spatial pattern of SOC mobilization by water erosion across different Indian forest types and watersheds.

2. To assess the mechanisms and rates of carbon replacement and the effectiveness of soil and water conservation measures.

3. To determine the fate of mobilized carbon, focusing on stabilization and burial in depositional sinks.

4. To synthesize these components into a comprehensive understanding of the net carbon budget for Indian tropical watersheds.

3. Literature Review

The understanding of soil erosion's role in the carbon cycle has evolved through three distinct phases: the "source" paradigm, the "sink" paradigm, and the current "dynamic replacement" framework. Indian research has contributed significantly to this evolving understanding.

2.1. The Erosion as a Source Paradigm

Early research, rooted in agricultural science, focused on the "on-site" effects of erosion: the loss of fertile topsoil and the decline in crop yields. From a carbon perspective, erosion was seen as a net source of CO_2. Lal (1995) estimated that erosion-induced SOC mineralization could account for a significant portion of the global carbon debt. In India, this perspective was dominant for many years, with studies documenting severe SOC loss from degraded agricultural lands. Recent research from Maharashtra has quantified this loss, showing that before the implementation of conservation measures, the Central MPKV Campus Watershed experienced an average annual soil loss of 18.68 t ha^{-1} yr^{-1}, with associated carbon loss of 348.71 kgC ha^{-1} yr^{-1}.

2.2. The Erosion as a Sink Paradigm

A paradigm shift began with research showing that erosion could act as a net sink if the primary fate of eroded carbon was rapid burial in alluvial or lacustrine environments. In India, the extensive river systems (Ganga, Brahmaputra, Godavari) and their deltas have long been recognized as major sediment sinks. A 2024 assessment of Indian forests using RUSLE-SDR and GIS techniques revealed that Indian forests provide significant SOC conservation services, with tropical dry deciduous forests alone contributing to an annual SOC conservation of 331,115.06 tonnes. This finding highlights that forests act as critical barriers against erosion-induced carbon loss.

2.3. The Dynamic Replacement and Net Balance Framework

The current consensus, supported by Indian research, is that the net effect is the sum of three key processes:

1. Mobilization: The detachment and transport of SOC. Studies from Maharashtra have precisely quantified this, showing that even in treated watersheds, carbon loss remains substantial at 205.52 kgC ha^{-1} yr^{-1}.

2. Mineralization: The decomposition of SOC during transport. Research from the Indian Himalayas has shown that while erosion rates are high, the burial of soil carbon and its separation from fresh carbon inputs leads to reduced rates of decomposition, offsetting potential carbon losses.

3. Dynamic Replacement: A critical mechanism involving deep-rooted plant growth and subsoil exposure. Studies in the Western Ghats have demonstrated that nature-positive interventions such as bunding, trenching, and terracing can enhance carbon sequestration by improving water retention and reducing run off.

The net carbon balance for Indian watersheds is therefore highly sensitive to land management practices. The implementation of scientifically planned SWC measures has been shown to reduce carbon loss by up to 41% in Maharashtra watersheds.

3. Methodology

This study synthesizes findings from multiple Indian studies that employed a multi-faceted, integrated approach to quantify the net carbon budget for tropical watersheds. The methodology is derived from key studies conducted in Maharashtra, the Western Ghats, and the Indian Himalayan region.

3.1. Study Areas

The synthesis draws from three representative Indian tropical watershed contexts:

1. Central MPKV Campus Watershed, Rahuri, Maharashtra: Located in the rain shadow region, this watershed (approximately 500 ha) represents a rainfed agricultural landscape with steep slopes and limited vegetation cover. The watershed was treated with various scientifically planned SWC measures .

2. Chichundi Village Watersheds, Western Ghats, Maharashtra: Two micro-watersheds (136 ha and 63 ha) in the Akole taluka, characterized by rugged hilly terrain, annual rainfall of approximately 1,700 mm, and sandy loam to sandy clay soils. These watersheds received nature-positive interventions including drainage line treatment and land area treatment.

3. Indian Himalayan Region: Representing a global soil erosion hotspot with high-altitude, low-input agricultural systems, providing insights into erosion-induced changes in soil carbon storage.

3.2. Quantifying SOC Mobilization and Erosion Rates

Studies employed the Universal Soil Loss Equation (USLE) or Revised Universal Soil Loss Equation (RUSLE) integrated within GIS:

- Data: SRTM DEM for slope factors; rainfall erosivity (R) factor from long-term rainfall data; soil erodibility (K) factor from national soil databases; and land use/cover (C) and support practice (P) factors from satellite imagery.

- Calculation: Soil loss was calculated as $E = R * K * LS * C * P$, generating raster maps of gross soil loss (t ha^{-1} yr^{-1}).

- SOC Mobilization: Calculated by multiplying soil loss by spatially explicit SOC concentrations derived from field sampling, incorporating a carbon enrichment ratio to account for preferential erosion of light organic matter.

3.3. Field Sampling for Carbon Pools and Fluxes

Studies captured carbon dynamics across different landscape positions:

1. Erosional Uplands: Paired sites were established on eroding slopes under different land uses (forest, barren, horticultural, agricultural). Soil cores were taken to 30 cm depth to assess SOC stocks and the impact of SWC measures.

2. Depositional Zones: In the Himalayan study, depositional areas within cultivated fields were sampled to assess subsoil carbon dynamics and decomposition rates using long-term incubations.

3.4. Assessment of Soil and Water Conservation Measures

The impact of SWC measures was evaluated by comparing pre- and post-intervention scenarios:

- Deep Continuous Contour Trenches (DCCT): Assessed on barren, forest, and horticultural land.

- Compartment Bunds: Assessed on agricultural land.

- Nature-Positive Interventions: Included drainage line treatments (check dams, gabion structures, percolation tanks) and land area treatments (bunding, trenching, terracing).

Carbon sequestration rates were calculated using the formula: Carbon Sequestration Rate (t C ha^{-1} yr^{-1}) = (SOC_post - SOC_pre) / Time Interval.

3.5. Net Carbon Budget Calculation

For the Himalayan study, a field-scale soil budget approach was employed, combining:

- Measurement of erosion-induced changes in soil carbon storage.

- Long-term (1-year) incubations of separate and mixed soil horizons to understand decomposition mechanisms.

4. Analysis and Results

4.1. SOC Mobilization Across Indian Landscapes

The RUSLE-based assessment of Indian forests revealed significant spatial heterogeneity in soil loss rates:

- Maximum soil loss rates were observed in Tropical Thorn Forest and the Ganga River basin .

- For the Central MPKV Campus Watershed in Maharashtra, mean gross soil erosion was 18.68 t ha^{-1} yr^{-1} before conservation measures, translating to a carbon loss of 348.71 kgC ha^{-1} yr^{-1}.

- In the Western Ghats watersheds, more than 40% of the area was affected by moderate to extremely severe soil loss, causing loss of associated carbon and nutrients.

- SOC conservation service by Indian forests was estimated at 331,115.06 tonnes annually, with tropical dry deciduous forests providing the maximum contribution.

4.2. Impact of Soil and Water Conservation Measures

The implementation of SWC measures demonstrated significant reductions in erosion and carbon loss:

Central MPKV Campus Watershed, Maharashtra:

Parameter	Pre-Conservation	Post-Conservation	Reduction
Average Annual Soil Loss	18.68 t ha^{-1} yr^{-1}	9.41 t ha^{-1} yr^{-1}	49.6%
Carbon Loss	348.71 kgC ha^{-1} yr^{-1}	205.52 kgC ha^{-1} yr^{-1}	41.1%

Source: Shelar et al., 2023

Carbon Sequestration Rates by SWC Measure (0-30 cm depth):

Land Type	SWC Measure	Carbon Sequestration Rate (t C ha^{-1} yr^{-1})
Barren Land	Deep Continuous Contour Trenches (DCCT)	0.237
Forest Land	Deep Continuous Contour Trenches (DCCT)	0.723
Horticultural Land	Deep Continuous Contour Trenches (DCCT)	0.594

| Agricultural Land | Compartment Bunds | 0.612 |

Source: Shelar et al., 2022

4.3. Nature-Positive Interventions in the Western Ghats

A one-year study (2023-2024) in the Chichundi watersheds revealed immediate positive impacts:

- Overall soil loss was reduced by approximately 18% in both watersheds.

- Carbon loss rate decreased by more than 21% in each watershed.

- Runoff coefficient decreased from 0.42 to 0.32 in watershed 1 and to 0.28 in watershed 2, indicating improved water retention.

These findings demonstrate that even short-term interventions can yield significant carbon benefits, with enhanced carbon sequestration capacity across the landscape.

4.4. Carbon Dynamics in Erosional and Depositional Landscapes: Himalayan Evidence

Research from the Indian Himalayas provided critical insights into the net carbon balance:

- High rates of soil erosion did not promote a net carbon loss to the atmosphere at the field scale.

- Decomposition rates in organic matter-rich subsoil layers in depositional areas were lower per unit of soil carbon than from other landscape positions.

- Mixing of subsoils with topsoils increased decomposition rates, highlighting the importance of burial and separation from fresh carbon inputs.

- The burial of soil carbon, and separation from fresh carbon inputs, led to reduced decomposition rates, offsetting potential carbon losses during erosion and transport.

This finding is crucial: it suggests that in rapidly eroding landscapes like the Himalayas, depositional zones act as carbon sinks rather than sources, provided the buried carbon remains undisturbed.

4.5. Synthesis: Net Carbon Balance for Indian Tropical Watersheds

Synthesizing the evidence from Indian studies:

Upland Dynamics:

- Gross carbon mobilization ranges from 205 to 348 kgC ha^{-1} yr^{-1} in agricultural watersheds.

- SWC measures can reduce this loss by 41-50%.

- Carbon sequestration through DCCT and bunds adds 0.237-0.723 t C ha^{-1} yr^{-1}.

Downstream Dynamics (Himalayan Evidence):

- Eroded carbon that is rapidly buried in depositional zones experiences reduced decomposition rates.

- This burial effect can offset carbon losses during transport, potentially making erosion a net sink over appropriate timescales.

Forest Conservation Service:

- Indian forests conserve 331,115.06 tonnes of SOC annually, with an economic value estimated at US$ 535.6 million.

Net Balance: The net carbon balance for Indian tropical watersheds is positive (net sink) when:

1. Effective SWC measures are implemented.

2. Depositional zones allow rapid burial and separation from fresh carbon inputs.

3. Forest cover is maintained or restored.

The balance is negative (net source) when:

1. Steep slopes are deforested without conservation measures.

2. Eroded carbon is continuously remobilized rather than buried.

3. Subsoils are mixed with topsoils, enhancing decomposition.

5. Discussion

5.1. The Indian Context: A Dual Narrative

The findings from Indian tropical watersheds reveal a dual narrative. On one hand, erosion in unprotected, steep landscapes with limited vegetation cover leads to severe carbon loss, as documented in Maharashtra before SWC interventions. On the other hand, strategic interventions—both structural

(DCCT, bunds) and nature-positive (trenching, terracing, afforestation)—can transform these landscapes into net carbon sinks.

The Himalayan evidence adds a crucial dimension: even without structural interventions, the geomorphic setting itself can promote carbon stabilization through rapid burial. This suggests that the net carbon outcome is as much a function of landscape connectivity and depositional efficiency as it is of erosion rates.

5.2. Policy and Management Implications

India's commitment to the Paris Climate Agreement includes a target of sequestering 2.5–3 billion tonnes of CO_2 equivalent by 2030. Soil and water conservation measures in tropical watersheds represent a viable pathway toward this goal. The findings indicate that:

1. Watershed-level planning is essential. The success of SWC measures in Maharashtra and the Western Ghats demonstrates that integrated approaches yield better outcomes than piecemeal interventions.

2. Forest conservation provides significant SOC conservation services, with tropical dry deciduous forests playing a particularly important role.

3. Targeted interventions on different land uses yield varying carbon sequestration rates. Forest lands treated with DCCT show the highest rates (0.723 t C ha^{-1} yr^{-1}), followed by agricultural lands with compartment bunds (0.612 t C ha^{-1} yr^{-1}).

4. Monitoring and evaluation over longer timescales is needed. The Western Ghats study, while promising, only captured one year of post-intervention data. Long-term monitoring would capture seasonal and interannual variations more robustly.

5.3. Limitations and Future Research Directions

Several limitations emerge from the synthesis:

- Geographic concentration: Most studies are concentrated in Maharashtra and the Western Ghats. India's northeastern region, Eastern Ghats, and central Indian forests remain understudied.

- Timescale: Most assessments are short-term (<5 years). Carbon dynamics, particularly burial and stabilization, require decadal-scale observations.

- Methodological heterogeneity: While RUSLE is widely used, variations in input parameters and SOC sampling methods limit direct comparability across studies.

- Lack of reservoir and floodplain studies: Unlike the international literature that emphasizes reservoir carbon burial, Indian studies have not yet quantified carbon trapping in the country's extensive reservoir network.

Future research should prioritize:

1. Long-term monitoring of existing SWC interventions.

2. Quantification of carbon burial in India's reservoirs and major floodplains.

3. Integration of soil carbon dynamics with aquatic carbon export (DOC, DIC, POC) at watershed scales.

4. Assessment of climate change impacts on erosion-carbon dynamics under changing monsoon regimes.

6. Conclusions

This paper has examined the role of soil erosion on carbon cycling in tropical watersheds with specific reference to India. The evidence synthesized from recent Indian studies supports the hypothesis that the net effect of erosion is not inherently a source or a sink, but is determined by the balance between carbon mobilization, replacement, and stabilization.

Key conclusions include:

1. Erosion rates and carbon loss in Indian tropical watersheds are substantial but highly responsive to land management. Before conservation, carbon loss in Maharashtra watersheds reached 348.71 kgC ha^{-1} yr^{-1}, which was reduced by 41% through SWC measures.

2. Soil and water conservation measures provide dual benefits: they reduce erosion and associated carbon loss while actively sequestering carbon at rates of 0.237–0.723 t C ha^{-1} yr^{-1} depending on land use and intervention type.

3. Nature-positive interventions in the Western Ghats demonstrated rapid impacts, reducing carbon loss by over 21% within a single year while improving water retention.

4. Indian forests provide critical SOC conservation services, conserving 331,115.06 tonnes of SOC annually, with significant economic value.

5. The Himalayan evidence challenges the simple "erosion-as-source" paradigm, showing that rapid burial in depositional zones can reduce decomposition rates and offset carbon losses.

Indian tropical watersheds are dynamic reactors where geomorphic and biogeochemical processes are tightly coupled. Effective land management, particularly the strategic implementation of deep continuous contour trenches and compartment bunds, can optimize carbon sequestration potential. As India works toward its climate mitigation targets under the Paris Agreement, investment in scientifically planned watershed management represents a nature-positive solution with measurable carbon benefits, enhanced water security, and improved livelihoods for vulnerable rural communities.

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