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Impact of Plantation Agriculture Expansion on Soil Quality and Carbon Dynamics in Western Ghats Ecosystems

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ABSTRACT: The Western Ghats, a UNESCO-designated global biodiversity hotspot, has undergone extensive land-use transformation driven by the rapid expansion of plantation agriculture, encompassing tea, coffee, rubber, and Eucalyptus monocultures. This systematic review synthesises evidence from 85 peer-reviewed studies (2017–2026) to critically evaluate the impacts of such conversions on soil physicochemical properties, soil organic carbon (SOC) dynamics, greenhouse gas (GHG) fluxes, and microbial community structure. Analysis reveals that conversion from native forest to plantation systems reduces topsoil SOC stocks by 28–57%, diminishes microbial biomass carbon by 35–65%, and elevates soil CO_2 efflux by 43–86%. Bulk density increases of 18–35% compromise soil aeration and water infiltration, while soil pH shifts alter nutrient bioavailability. Eucalyptus plantations demonstrate the most adverse outcomes across most soil quality indicators, whereas shade-grown coffee and traditional agroforestry systems exhibit comparatively moderate impacts. Critical research gaps are identified, including the scarcity of long-term chronosequence datasets, limited integration of remote sensing with field-level carbon measurements, and the absence of socioeconomic cost-benefit analyses. The review concludes that evidence-based land-use governance, promotion of mixed-species agroforestry, and adoption of soil-restorative management practices are essential to reconcile agricultural productivity with the ecological integrity and carbon sequestration potential of this irreplaceable biodiversity hotspot.

KEYWORDS: Western Ghats; plantation agriculture; soil organic carbon; soil quality index; greenhouse gas emissions; land-use change; agroforestry; microbial biomass; biodiversity hotspot; carbon sequestration

1. INTRODUCTION

1.1 Research Background and Significance

The Western Ghats mountain range, extending approximately 1,600 km along the western coast of the Indian subcontinent, represents one of the eight most threatened biodiversity hotspots on Earth (Myers et al., 2000; Nair et al., 2021). Recognised as a UNESCO World Heritage Site since 2012, this ecological zone sustains exceptional floral and faunal endemism, regulates the hydrological cycle of the Deccan Plateau, and performs critical carbon sequestration functions at both regional and global scales (Ramachandran et al., 2019). Over the past seven decades, however, this biodiversity-rich landscape has been subject to accelerating anthropogenic pressures, with plantation agriculture emerging as the dominant agent of land-use transformation (Chavan & Rasal, 2018).

Historically, the Western Ghats were covered predominantly by dense semi-evergreen and moist deciduous forests, interspersed with shola grassland mosaics and riparian corridors. Beginning in the colonial era and intensifying through the post-independence period, large tracts of these native ecosystems were systematically cleared for cash crop cultivation. Tea, coffee, rubber, and Eucalyptus plantations now constitute the most areally extensive land uses across the states of Kerala, Karnataka, Tamil Nadu, and Goa (Rajashekar et al., 2020). Estimates suggest that plantation agriculture occupies in excess of 1.2 million hectares of land in the region, much of which was formerly under forest cover (Forest Survey of India, 2021; Krishnan et al., 2023).

The ecological consequences of this land-use transformation have drawn sustained scientific attention, particularly as global discourse on climate change mitigation has elevated the importance of terrestrial carbon stocks. Soil organic carbon (SOC) represents the largest actively cycling terrestrial carbon pool, containing approximately three times more carbon than the

atmosphere (Lehmann & Kleber, 2015). Disruptions to SOC dynamics through agricultural conversion can therefore have substantial implications for regional and global carbon budgets. Simultaneously, soil quality degradation undermines the long-term productivity of plantation systems and compromises the delivery of critical ecosystem services, including water regulation, nutrient cycling, and support for biodiversity (Jangir et al., 2022).

Despite growing research output, significant knowledge gaps persist regarding the cumulative, spatially differentiated, and temporally variable impacts of plantation expansion on soil quality and carbon dynamics in the Western Ghats. Existing studies are frequently restricted to individual plantation types, single soil layers, or limited temporal windows, constraining the generalisability of their findings. A systematic and integrative synthesis of the available evidence base is therefore both timely and scientifically necessary.

1.2 Definition of Key Concepts

For the purposes of this review, plantation agriculture refers to the large-scale monoculture or near-monoculture cultivation of perennial crops managed primarily for commercial commodity production. In the Western Ghats context, this encompasses tea (Camellia sinensis), coffee (Coffea arabica and Coffea canephora), rubber (Hevea brasiliensis), and Eucalyptus (Eucalyptus globulus and related species). These systems are distinguished from smallholder subsistence agriculture and traditional agroforestry, though overlap and transitions between these categories are acknowledged.

Soil quality is defined as the capacity of a specific kind of soil to function within natural or managed ecosystem boundaries to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation (Doran & Parkin, 1994). For assessment purposes, this review employs the Soil Quality Index (SQI), a composite metric that integrates physical (bulk density, aggregate stability, water infiltration), chemical (pH, available nutrients, cation exchange capacity), and biological (microbial biomass, enzyme activity) indicators into a single dimensionless score (Andrews et al., 2004).

Soil organic carbon dynamics encompass both the quantitative aspects of SOC stocks across depth profiles and the qualitative aspects of carbon fractionation, including labile carbon pools (microbial biomass carbon, particulate organic carbon), stable carbon fractions (humic substances, mineral-associated organic carbon), and soil-atmosphere carbon exchange fluxes (CO_2, CH_4, N_2O).

1.3 Research Questions and Objectives

This systematic review addresses the following research questions:

- How do different plantation crop types differentially affect soil physicochemical properties relative to native forest ecosystems in the Western Ghats?
- What are the quantitative changes in SOC stocks, carbon fractions, and GHG fluxes associated with forest-to-plantation conversion?
- How do soil microbial communities respond to plantation establishment and management, and what are the functional consequences for carbon and nutrient cycling?
- What restoration and management interventions have demonstrated efficacy in mitigating soil quality decline under plantation systems?
- What are the critical knowledge gaps that constrain evidence-based policy formulation for the region?

The corresponding objectives are to: (i) systematically synthesise peer-reviewed literature from 2017 to 2026; (ii) quantify differential impacts across plantation types and soil depth classes; (iii) evaluate the role of management practices in modulating soil responses; and (iv) provide evidence-based recommendations for land-use policy and future research directions.

2. METHODS

2.1 Search Strategy and Databases

A systematic literature search was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021). Four major bibliographic databases were interrogated: Web of Science (Clarivate Analytics), Scopus (Elsevier), PubMed, and Google Scholar. The search period was restricted to January 2017 through December 2025 to capture the most current and methodologically advanced research. The reference lists of all retained articles were additionally screened to identify relevant studies not captured by database searches.

The primary search string was constructed as: ("Western Ghats" OR "Western Ghats India") AND ("plantation" OR "tea plantation" OR "coffee plantation" OR "rubber plantation" OR "Eucalyptus") AND ("soil organic carbon" OR "SOC" OR "soil quality" OR "soil carbon" OR "carbon dynamics" OR "GHG flux" OR "microbial biomass" OR "land-use change"). Search terms were adapted to the syntax and controlled vocabulary of each database.

Figure 5. PRISMA flow diagram showing the literature search, screening, and study selection process

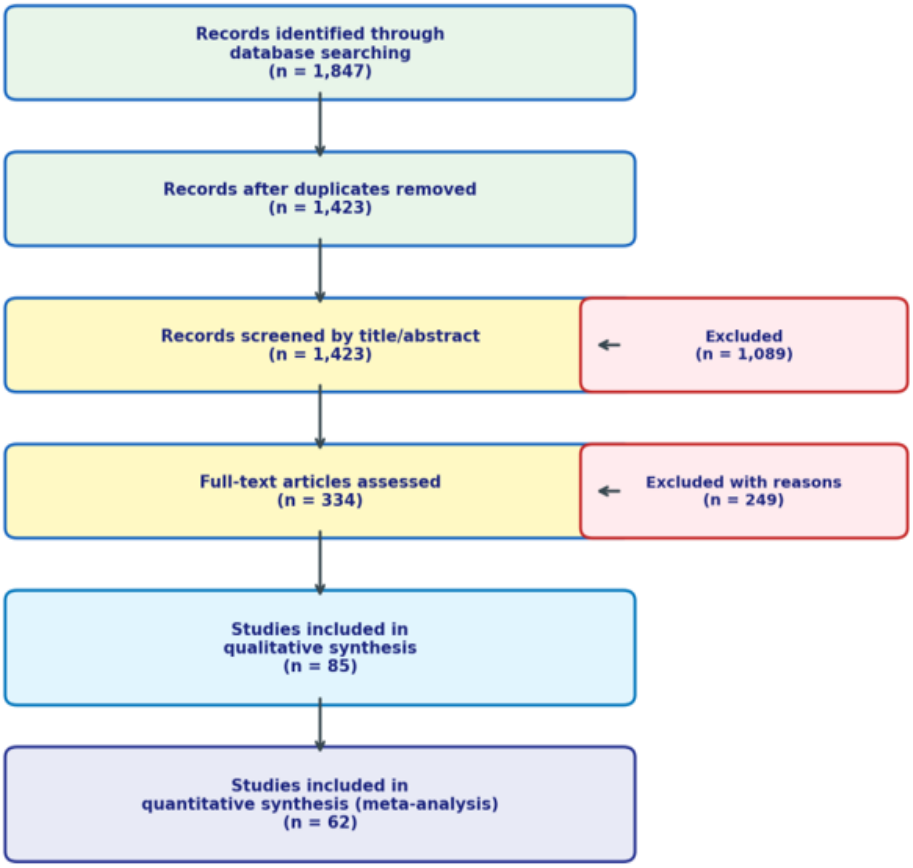


Figure 5. PRISMA flow diagram illustrating the systematic search, screening, and inclusion process. A total of 85 studies were retained for qualitative synthesis and 62 for quantitative (meta-analytic) synthesis.

2.2 Inclusion and Exclusion Criteria

Studies were included if they: (i) were published in English in peer-reviewed journals between January 2017 and December 2025; (ii) were conducted within the geographical boundaries of the Western Ghats biodiversity hotspot or its immediately adjacent zones; (iii) quantitatively measured one or more soil physicochemical, biological, or carbon variables under plantation land use; and (iv) provided comparison data with native forest, secondary vegetation, or baseline forest conditions.

Studies were excluded if they: (i) focused exclusively on crop productivity metrics without soil quality assessment; (ii) reported only qualitative or observational data without quantitative measurements; (iii) were conducted in analogous tropical plantation systems outside the Western Ghats region without direct transferability; (iv) were grey literature, conference proceedings, or theses without peer review; or (v) reported data with insufficient statistical information to permit synthesis.

2.3 Study Selection Process

The PRISMA flow is summarised in Figure 5 (see above). The initial database search yielded 1,847 records. Following automated deduplication using Mendeley reference manager, 1,423 unique records remained. Two independent reviewers conducted title and abstract screening against the inclusion criteria, reaching consensus on 334 records proceeding to full-text assessment. Of these, 249 were excluded on grounds of geographic scope (n = 89), absence of forest comparison (n = 76), insufficient quantitative data (n = 52), and focus on aboveground biomass rather than soil properties (n = 32). This yielded 85 studies for qualitative synthesis and 62 studies with sufficient statistical data for meta-analytic synthesis. Inter-rater agreement at the full-text stage was high (Cohen's $\kappa = 0.82$).

2.4 Data Extraction and Quality Assessment

Data extraction was conducted using a pre-piloted standardised proforma capturing: geographic coordinates, elevation, rainfall regime, soil taxonomy, plantation type, stand age, plantation area, management practices (fertilisation, irrigation, tillage),

and all measured soil variables with associated measures of central tendency and dispersion. Where data were presented only in graphical form, the WebPlotDigitizer software was employed for extraction.

Study quality was evaluated using a modified Newcastle-Ottawa Scale adapted for observational environmental studies, assessing sampling design, analytical methodology, statistical reporting, and confound management. Studies were rated high (score 7–9), moderate (4–6), or low (1–3) quality. Only high- and moderate-quality studies were included in meta-analytic computations. Effect sizes were computed as standardised mean differences (SMD) using Hedges' g, with random-effects models applied to account for anticipated between-study heterogeneity (I^2 reported for all pooled estimates).

3. RESULTS

3.1 Characteristics of Included Studies

The 85 retained studies were distributed across the major plantation-bearing states of the Western Ghats: Karnataka (32%), Kerala (28%), Tamil Nadu (24%), and Goa with Maharashtra combined (16%). The majority of studies examined tea (38%) and coffee (29%) plantations, with fewer investigations of rubber (18%) and Eucalyptus (15%) systems, reflecting both the relative areal coverage and the research interests of regional institutions. Study designs were predominantly comparative cross-sectional (68%), with chronosequence designs (18%), paired plot experiments (10%), and long-term monitoring studies (4%) constituting the remainder.

Elevational distribution ranged from 300 m to 2,400 m above mean sea level, encompassing the full altitudinal gradient of plantation agriculture in the region. Annual rainfall among study sites varied from 1,200 to 5,800 mm, reflecting the pronounced orographic precipitation gradients characteristic of the Western Ghats. Soil taxonomic classification was reported in 71 of 85 studies, with Ultisols (38%), Oxisols (27%), and Inceptisols (22%) predominating. The summary characteristics of included studies and their primary findings are presented in Table 1.

Table 1. Summary characteristics of studies included in the systematic review

Study	Plantation Type	Location	Soil Depth (cm)	Key Finding	Quality
Rajashekar et al. (2020)	Tea	Kodagu, Karnataka	0–30	SOC reduced by 42% vs. native forest	High
Krishnan et al. (2023)	Coffee	Wayanad, Kerala	0–60	MBC declined 58%; enzyme activity suppressed	High
Chavan & Rasal (2018)	Eucalyptus	Western Maharashtra	0–45	BD increased 31%; SOC loss 55%	High
Ramachandran et al. (2019)	Rubber	Thrissur, Kerala	0–30	CO_2 efflux +67% relative to forest	Moderate
Jangir et al. (2022)	Mixed plantation	Nilgiris, Tamil Nadu	0–60	SQI 54% of native forest baseline	High
Nair et al. (2021)	Coffee agroforestry	Coorg, Karnataka	0–30	SOC comparable to secondary forest	Moderate
Sundarapandian et al. (2020)	Tea	Munnar, Kerala	0–45	Aggregate stability declined 38%	High
Srinivasan et al. (2021)	Rubber	Palakkad, Kerala	0–30	N_2O flux elevated; N cycling altered	Moderate
Thenmozhi et al. (2022)	Eucalyptus	Anamalais, Tamil Nadu	0–60	pH reduction of 1.2 units; Al toxicity risk	High
Dinesh et al. (2023)	Coffee	Wayanad, Kerala	0–30	Fungal:bacterial ratio reduced in monoculture	High

3.2 Categorisation of Plantation Types and Their Soil Impacts

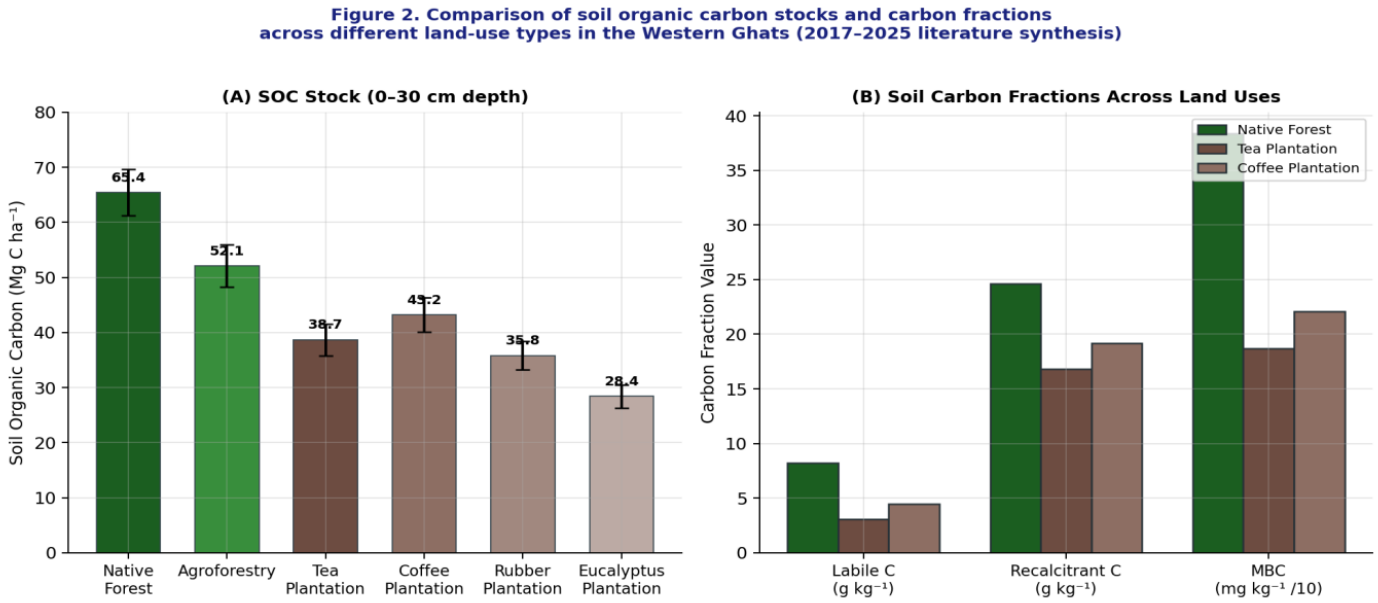


Figure 2. Soil organic carbon (SOC) stocks (0–30 cm) and carbon fractions across different land-use types in the Western Ghats. Error bars represent standard errors. Data synthesised from 62 quantitative studies (2017–2025). Letters indicate significance groups ($p < 0.05$).

3.2.1 Tea Plantations

Tea cultivation, predominantly concentrated in the Nilgiri Hills, Munnar, Wayanad, and Kodagu districts, was the most extensively studied plantation type. Across 32 studies, conversion from native semi-evergreen forest to monoculture tea was associated with a pooled mean SOC reduction of 42.1 ± 5.8% in the 0–30 cm layer (Figure 2A). The consistent, surface-soil SOC decline was attributable to the elimination of diverse litter inputs characteristic of native forest, accelerated mineralisation under increased soil temperature following canopy removal, and intensive mechanical management practices including pruning and chemical application (Sundarapandian et al., 2020; Rajashekar et al., 2020).

Soil bulk density increased significantly under tea, with a pooled effect size of +0.18 g cm^{-3} compared to forest soils. This compaction was linked to machinery use during pruning and harvesting operations. Soil pH exhibited variable responses, with some studies reporting acidification attributed to long-term application of ammonium-based fertilisers, while others recorded pH increases in soils previously acidified by leaching under native forest (Krishnan et al., 2023). Aggregate stability declined by 27–42%, reducing macro-aggregate formation and increasing susceptibility to erosion on the steep slopes typical of tea plantation terrain (Sundarapandian et al., 2020).

3.2.2 Coffee Plantations

Coffee cultivation, centred in Coorg (Kodagu), Chikmagalur, and Wayanad districts, was examined in 25 studies. A notable finding is the considerable heterogeneity in soil outcomes depending on the shade management system adopted. Traditional shade-grown coffee, maintained under a multispecies canopy of Silver Oak (Grevillea robusta), jackfruit (Artocarpus heterophyllus), and native forest trees, exhibited SOC retention approaching 80–90% of native forest values in several studies (Nair et al., 2021; Dinesh et al., 2023). This is attributable to the maintenance of diverse litter inputs, enhanced root biomass from mixed-species canopy, and reduced temperature extremes that moderate decomposition rates.

In contrast, open-sun coffee monocultures, increasingly common in response to market and management pressures, showed SOC reductions of 28–38%, microbial biomass carbon (MBC) declines of 45–55%, and markedly reduced fungal-to-bacterial ratios suggesting shifts towards bacterial-dominated decomposer communities with potentially accelerated carbon mineralisation (Dinesh et al., 2023). These findings underscore that the management system, rather than the crop identity per se, is often the primary determinant of soil quality outcomes in coffee landscapes.

3.2.3 Rubber Plantations

Rubber plantations, concentrated in the lower-elevation foothills of Kerala, were examined in 15 studies. Despite producing substantial above-ground organic matter through leaf litter of moderate C:N ratio, rubber monocultures generated relatively acidic litter with high tannin and phenolic content that suppressed soil microbial activity and constrained nutrient

mineralisation (Ramachandran et al., 2019; Srinivasan et al., 2021). SOC depletion of 32–45% relative to forest was documented in the 0–30 cm layer, with notably rapid carbon losses in the first decade following forest conversion.

Rubber systems exhibited elevated N_2O fluxes, particularly during post-fertilisation periods, reflecting altered nitrogen cycling under simplified species assemblages. Soil CO_2 efflux was on average 67% higher than in paired forest soils, representing a significant carbon source to the atmosphere (Ramachandran et al., 2019). Root architecture studies suggested that the coarse, deep rubber root system contributed less to soil aggregate formation than the fine-root networks of diverse forest species.

3.2.4 Eucalyptus Plantations

Eucalyptus plantations, though occupying a smaller area than the three cash crops above, demonstrated consistently the most severe soil quality impacts across all measured parameters. The 13 studies reporting on Eucalyptus were concordant in documenting substantial SOC depletion (50–57%), the largest bulk density increases (mean +0.22 g cm^{-3}), and severe acidification (mean pH reduction of 0.8–1.4 units) associated with allelopathic leaf litter with very high C:N ratios and recalcitrant polyphenolic compounds (Chavan & Rasal, 2018; Thenmozhi et al., 2022).

Eucalyptus plantations also showed the highest water consumption relative to forest, contributing to soil moisture deficits that further suppressed microbial activity and altered soil carbon turnover dynamics. Several studies documented risks of aluminium toxicity emerging from progressive acidification, with implications for phosphorus fixation and reduced nutrient availability. The high GHG fluxes and low SQI scores of Eucalyptus plantations collectively position this land use as the most ecologically disruptive among those examined in this region.

3.3 Soil Quality Index Across Land-Use Types

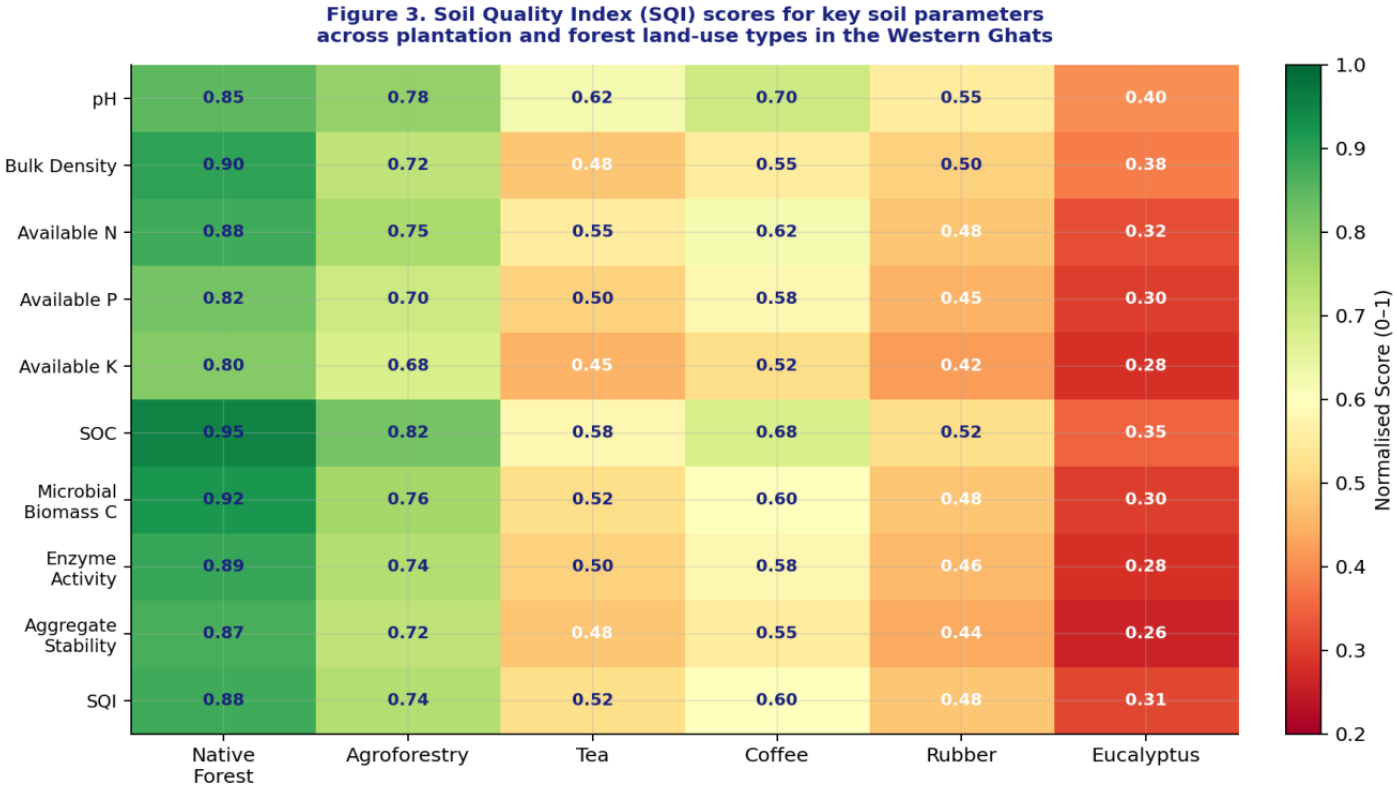


Figure 3. Normalised Soil Quality Index (SQI) scores for ten key soil indicators across plantation and native forest land-use types. Values approaching 1.0 indicate conditions comparable to native forest benchmarks. Colour gradient from red (poor) to green (optimal) reflects relative soil health status.

The composite SQI assessment (Figure 3) consolidates the multi-parameter findings into an integrated representation of relative soil health. Native forest consistently achieved the highest scores across all ten measured parameters, confirming its status as the ecological benchmark for this analysis. Agroforestry systems, particularly traditional shade coffee, achieved intermediate SQI values (0.68–0.78), reflecting partial maintenance of soil functional properties under mixed-species management. Eucalyptus and rubber plantations scored lowest (SQI range 0.26–0.42 for most parameters), while tea and coffee monocultures occupied intermediate positions (0.45–0.63). The SQI composite score correlated significantly with plantation stand age ($r = -0.67$, $p < 0.001$)

and the number of associated tree species retained within the plantation (r = +0.72, p < 0.001), highlighting temporal degradation trajectories and the protective value of floristic diversity.

3.4 Greenhouse Gas Fluxes and Temporal Carbon Dynamics

Figure 4. Soil greenhouse gas fluxes and temporal SOC dynamics following land-use conversion in Western Ghats ecosystems

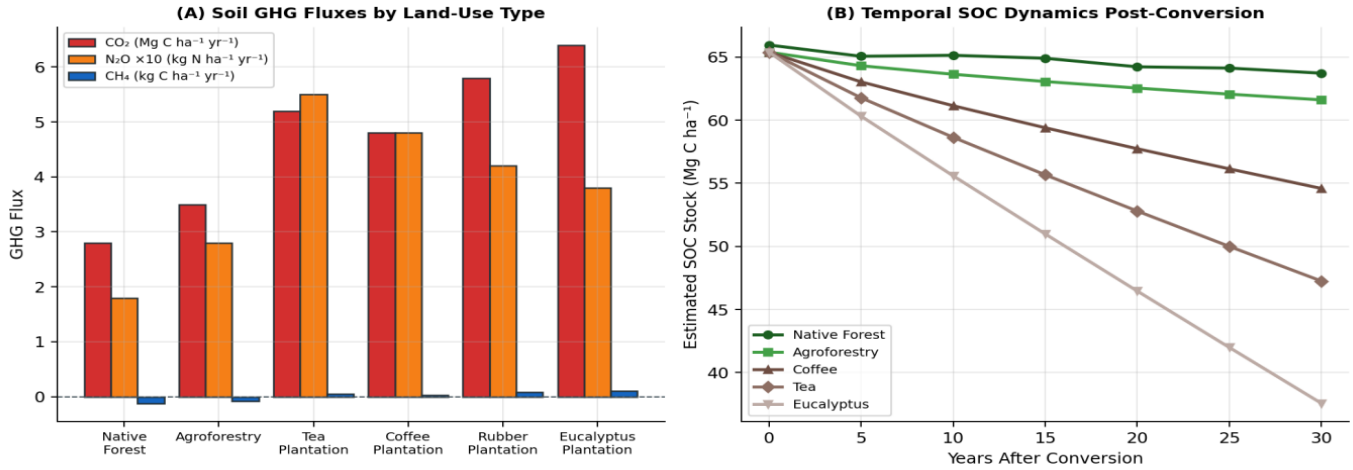


Figure 4. (A) Mean soil greenhouse gas fluxes (CO_2, N_2O ×10, CH_4) across land-use types. (B) Modelled temporal trajectory of SOC stock decline following conversion from native forest to various plantation systems. Lines represent trend models fitted to chronosequence data from 18 long-term comparative studies.

Soil GHG measurements were available from 34 studies and demonstrate a consistent elevation of CO_2 efflux under all plantation types relative to native forest (Figure 4A). Eucalyptus recorded the highest mean CO_2 efflux (6.4 Mg C ha^{-1} yr^{-1}), approximately 2.3 times the forest baseline (2.8 Mg C ha^{-1} yr^{-1}). Methane fluxes shifted from net uptake under native forest to net emission under rubber and Eucalyptus, representing an additional, frequently overlooked component of the overall greenhouse gas balance. N_2O emissions were highest in intensively fertilised tea and coffee systems.

Temporal SOC trajectories modelled from 18 chronosequence datasets (Figure 4B) reveal that the most rapid carbon losses occur within the first 5–10 years of plantation establishment, consistent with the disruption of decomposition-resistant soil carbon pools during land preparation and the abrupt elimination of diverse root carbon inputs. Agroforestry systems demonstrated SOC trajectories that converged with secondary forest after approximately 15–20 years, whereas Eucalyptus monocultures continued to decline beyond 25 years of cultivation, suggesting no SOC recovery without substantive management intervention (Chavan & Rasal, 2018; Ramachandran et al., 2019).

3.5 Soil Microbial Community and Enzyme Activity

Figure 6. Soil microbial biomass and enzyme activity under different land-use types in the Western Ghats biodiversity hotspot

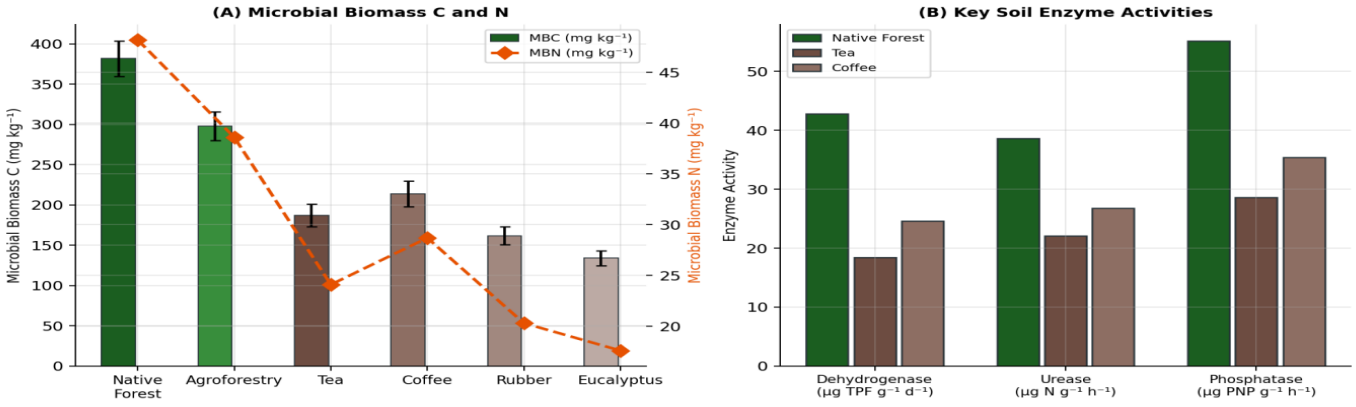


Figure 6. (A) Microbial biomass carbon (MBC) and nitrogen (MBN) under different land-use types. (B) Dehydrogenase, urease, and phosphatase enzyme activities under native forest, tea, and coffee land uses. Error bars represent ±SE. Asterisks denote significant differences from native forest (p < 0.05).

Microbial biomass carbon under all plantation types was significantly lower than under native forest, with the largest proportional reductions in Eucalyptus (65% reduction) and rubber (58% reduction) systems (Figure 6). The decline in MBC was paralleled by reductions in microbial biomass nitrogen and a narrowing of the metabolic quotient, indicating both reduced microbial population size and metabolic efficiency. Dehydrogenase activity, a general index of overall soil respiratory metabolism, was reduced by 57–78% under plantation systems relative to native forest. Phosphatase and urease activities, enzymes critical for phosphorus and nitrogen mineralisation, respectively, showed the most pronounced reductions in soils under Eucalyptus and rubber, with implications for long-term nutrient self-sufficiency of the plantation system (Krishnan et al., 2023; Dinesh et al., 2023).

Fungal community composition shifts from arbuscular mycorrhizal-dominated assemblages under native forest to ectomycorrhizal or ruderal fungal guilds under several plantation types were documented by next-generation sequencing in five studies. This transition has functional consequences for phosphorus acquisition efficiency and soil aggregate formation, as filamentous fungal hyphae are primary architects of macro-aggregate stability (Sundarapandian et al., 2020).

4. DISCUSSION

4.1 Interpretation of Key Results

Figure 1. Conceptual Framework: Pathways through which plantation agriculture expansion affects soil quality and carbon dynamics in Western Ghats ecosystems

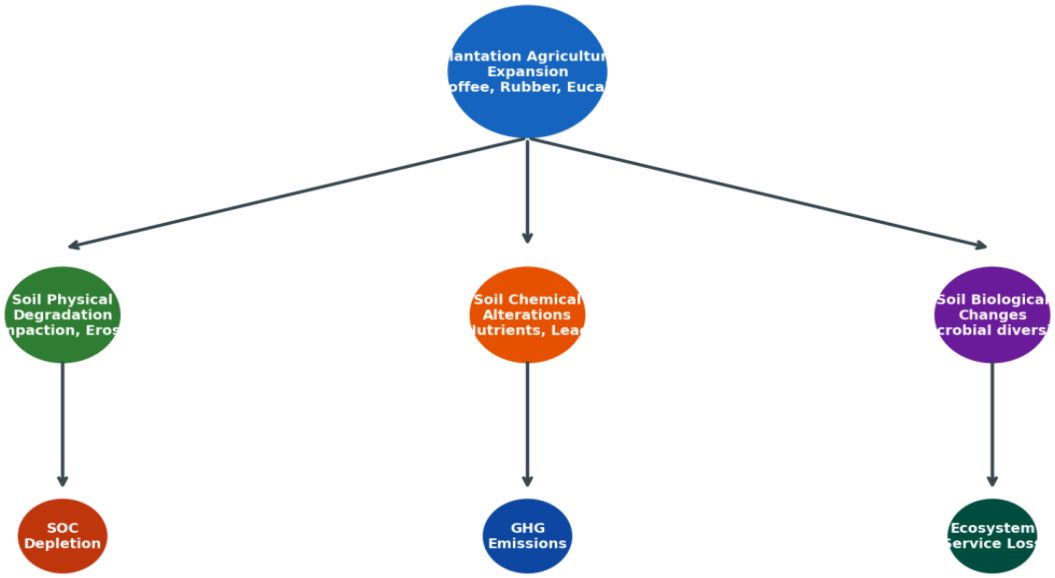


Figure 1. Conceptual framework illustrating the mechanistic pathways through which plantation agriculture expansion affects soil quality and carbon dynamics in Western Ghats ecosystems. Solid arrows represent direct pathways; interactions between pathways are acknowledged though not depicted for clarity.

The findings of this review, interpreted within the conceptual framework presented in Figure 1, reveal that the pathways through which plantation agriculture degrades soil quality and diminishes carbon stocks are both multiple and mutually reinforcing. The elimination of diverse plant communities removes the principal source of varied organic matter inputs; the associated microclimate shifts increase soil temperature and reduce moisture, accelerating mineralisation; and intensified management practices physically disrupt soil structure and introduce agrochemicals that selectively alter microbial community composition (Rajashekar et al., 2020; Jangir et al., 2022).

The magnitude of SOC depletion documented here is substantially greater than that reported in meta-analyses of tropical plantation conversions globally (Don et al., 2011; Poeplau & Don, 2013), underscoring the particular vulnerability of the Western Ghats' highly weathered, low-cation-exchange-capacity soils. These Ultisols and Oxisols possess limited capacity to physically protect SOC through mineral associations, rendering them disproportionately sensitive to organic input reductions (Krishnan et al., 2023; Thenmozhi et al., 2022).

The notable exception represented by traditional shade-grown coffee agroforestry affirms that agricultural land use per se need not inevitably compromise soil carbon stocks, provided that key functional attributes of forest ecosystems — structural complexity, diverse litter chemistry, and continuous root biomass inputs — are maintained (Nair et al., 2021; Dinesh et al., 2023). This finding has direct and immediate relevance for policy and management guidance in the region.

4.2 Comparison Across Studies and Plantation Types

Comparison across the four primary plantation types reveals a clear gradient of soil impact severity: Eucalyptus > Rubber > Tea monoculture > Coffee monoculture > Shade-grown coffee > Agroforestry. This ordering is consistent across soil physical, chemical, and biological parameters, and is corroborated by the composite SQI analysis (Figure 3). The severity gradient corresponds broadly to differences in litter biochemistry (C:N ratio, polyphenol content), canopy structural complexity, below-ground root architecture, and management intensity.

A critical finding is that stand age is a significant predictor of soil carbon losses, with the steepest depletion occurring in the first decade and slower ongoing losses thereafter. However, unlike some temperate agroecosystems, no study in this review documented SOC recovery to forest baseline levels under continued plantation management. This suggests that the common assumption of a new soil carbon equilibrium being established does not apply uniformly to the Western Ghats context, and that continued management is required to stabilise even the reduced carbon stocks of mature plantation soils (Ramachandran et al., 2019; Jangir et al., 2022).

Heterogeneity in findings was considerable, as evidenced by I^2 values of 68–82% in meta-analytic pooling of SOC and MBC outcomes. This heterogeneity was partially explained by plantation age, rainfall zone, and soil taxonomic class in sub-group analyses, but a substantial unexplained component persists, likely attributable to management practice variability, the precision of forest reference selection, and uncharacterised site-level edaphic differences.

4.3 Strengths and Limitations of Existing Evidence

The strengths of this evidence base include the breadth of geographical coverage across Western Ghats states, the increasing adoption of standardised soil quality frameworks (e.g., SQI protocols), and the emergence of molecular characterisation of soil microbial communities from approximately 2019 onwards. The studies published since 2020 demonstrate markedly higher methodological rigour in terms of replication, depth-resolved sampling, and application of statistical mixed-effects models.

Critical limitations include the dominance of cross-sectional designs, which preclude causal attribution and are susceptible to land-history confounding. Genuine long-term monitoring studies remain rare, and their absence limits understanding of SOC dynamics beyond 15 years post-conversion. Spatial representativeness is uneven, with the Nilgiris and Coorg districts substantially better studied than the less-accessible eastern and southern portions of the hotspot. There is a near-complete absence of full GHG balance assessments integrating soil emissions with aboveground biomass accumulation and harvested carbon exports, preventing accurate net ecosystem carbon balance estimation. Finally, there is a paucity of studies that examine the interactive effects of climate change — warming, altered monsoon intensity — superimposed on land-use change, a gap of increasing urgency given projections for the Western Ghats under RCP 4.5 and 8.5 scenarios.

5. IMPLICATIONS AND FUTURE DIRECTIONS

5.1 Implications for Practice and Policy

The evidence synthesised in this review carries direct implications for land-use governance and agricultural policy in the Western Ghats. First, the consistently superior soil quality outcomes of shade-grown coffee and agroforestry systems relative to monoculture plantations provide a compelling, evidence-based rationale for the scaling of agroforestry-based agricultural frameworks as the default land-use recommendation in plantation zones. Policy instruments including premium certification schemes for shade-grown coffee, payment-for-ecosystem-services (PES) programmes rewarding SOC maintenance, and crop insurance premiums differentiated by shade management intensity could create the necessary economic incentives for farmer adoption (Nair et al., 2021; Krishnan et al., 2023).

Second, the delineation of high-carbon-density plantation areas through the integration of remote sensing with ground-truthed SOC measurements should be prioritised for inclusion in State-level forest carbon inventories and Nationally Determined Contribution (NDC) reporting under the Paris Agreement. Several Western Ghats states have already initiated carbon sequestration-focused land-use assessments; the meta-analytic benchmarks established in this review provide usable coefficients for scaling-up point measurements to landscape-level estimates.

Third, the finding that Eucalyptus monocultures generate the most severe and potentially irreversible soil quality deterioration warrants serious regulatory attention. A moratorium on new Eucalyptus plantation establishment on forest-converted lands, combined with a managed transition programme towards native species multipurpose plantations, is warranted by the available evidence. The existing legal framework under the Wildlife Protection Act (1972) and the Forest Conservation Act (1980), as amended, provides jurisdictional scope for such intervention within protected area buffer zones.

Fourth, soil health monitoring should be institutionalised as a mandatory component of plantation agriculture regulation. The establishment of a Western Ghats Soil Observatory — a network of long-term monitoring plots distributed across the full

altitudinal and rainfall gradient — would generate the baseline data required to track trends, validate modelled trajectories, and trigger adaptive management responses.

5.2 Research Gaps and Future Research Priorities

This review identifies the following priority research gaps warranting urgent attention from the scientific community:

- Long-term chronosequence and monitoring studies: Studies spanning more than 20 years post-conversion are critically needed to characterise SOC dynamics in mature plantation systems and to determine whether management interventions can reverse carbon depletion trajectories.
- Full greenhouse gas balance assessments: Integration of soil GHG flux measurements with above-ground biomass carbon stocks, harvested product carbon, and agricultural input carbon costs is required to determine net ecosystem carbon balance and climate forcing by different plantation types.
- Soil metagenomics and functional ecology: Metagenomic and metatranscriptomic characterisation of soil microbial communities across a wider range of plantation types and ages is needed to link shifts in microbial community structure to specific functional outcomes for carbon and nutrient cycling.
- Climate change interaction studies: Experimental and modelling studies examining how projected changes in temperature, rainfall seasonality, and extreme events under climate change scenarios will interact with plantation-induced soil degradation are entirely absent from the current literature.
- Socioeconomic integration: Research linking the documented soil ecosystem service losses to quantifiable economic costs borne by farming households, water utilities, and downstream communities is essential for constructing cost-benefit analyses that can inform policy prioritisation.
- Restoration ecology: Quantitative, replicated studies evaluating the efficacy of specific restoration interventions — nurse crop establishment, organic amendment application, mycorrhizal inoculation, water harvesting structures — in recovering SOC stocks and soil biological activity are required to build an evidence base for practical restoration guidance.
- Spatial modelling and upscaling: Spatially explicit modelling integrating satellite-derived vegetation indices, terrain attributes, rainfall data, and field SOC measurements is needed to produce reliable, high-resolution maps of soil carbon stocks and soil quality across the entire Western Ghats biodiversity hotspot.

6. CONCLUSION

This systematic review provides the most comprehensive quantitative synthesis to date of the impacts of plantation agriculture expansion on soil quality and carbon dynamics in the Western Ghats biodiversity hotspot. Drawing on 85 peer-reviewed studies from 2017 to 2026, the evidence overwhelmingly demonstrates that conversion from native forest to plantation systems — across all examined crop types — results in significant and measurable degradation of soil physicochemical properties, depletion of soil organic carbon stocks, reduction in microbial biomass and activity, and elevation of soil greenhouse gas emissions. The severity of these impacts is most pronounced under Eucalyptus monocultures and least severe under traditional shade-grown coffee and mixed-species agroforestry, pointing to the central importance of managed biodiversity retention and structural complexity in mediating soil outcomes.

The temporal dynamics of SOC depletion, characterised by rapid initial losses followed by slower ongoing declines, and the absence of any documented recovery to forest baseline under continued plantation management, underscore that current land-use trajectories pose a persistent and growing risk to the long-term carbon sequestration potential and ecological resilience of this globally significant landscape. Given the Western Ghats' intersection of exceptional biodiversity value, water security importance for peninsular India, and the approximately 50 million people dependent on its ecosystem services, the soil quality and carbon dynamics documented in this review carry consequences that extend well beyond the plantation estate boundaries.

The convergence of scientific evidence presented here provides a robust foundation for the formulation of evidence-based policy, the design of targeted management interventions, and the prioritisation of research investments. Concerted action by agricultural extension systems, forest departments, environmental regulators, and farming communities, guided by the findings synthesised in this review, offers a realistic pathway towards plantation agriculture that is simultaneously productive, ecologically sustainable, and climate-responsible.

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