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Shaded Coffee Landscapes in the Western Ghats: A Triple Benefit for Carbon Credits, Climate Resilience, and Soil Quality

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Abstract

Shaded coffee systems represent a promising strategy for maintaining healthier, carbon-rich soil ecosystems, while also offering opportunities for carbon credit generation for farmers, particularly in the Global South. This study evaluated the effects of five coffee-based land-use systems—forest coffee (CF), shaded coffee with high (CTS), medium (CMS), and low (CTnS) tree densities, and sole coffee (CS)—on soil quality, carbon storage, biomass accumulation, and carbon credit potential in the Western Ghats coffee-growing region. CF exhibited the highest soil quality index (SQI) and soil organic carbon (SOC), exceeding CS by 33.5% and 65.5%, respectively, followed by CTS, CMS, and CTnS (CTS: +13.8% SQI, + 43.1% SOC; CMS: +8.5% SQI, + 19.1% SOC; CTnS: +3.0% SQI, + 12.9% SOC). Shaded coffee systems significantly improve soil chemical and exchangeable properties. Across shaded systems, soil carbon sequestration (0.34–1.03 t C ha^{-1} yr^{-1}) and aboveground biomass carbon accumulation (1.8–15.1 t C ha^{-1} yr^{-1}) supported substantial carbon credit potential, ranging from USD 55.41 to 340.90 ha^{-1} yr^{-1}. Overall, shaded coffee systems provide both ecological and economic benefits, contributing to climate change mitigation while enhancing rural livelihoods through carbon financing.

Highlights

• Shaded coffee systems enhanced soil quality and exchangeable properties over sole coffee.

• Soil organic carbon stocks increased by 12.9–41.9% under shaded coffee systems.

• Shaded coffee systems showed carbon credit potential of USD 55–341 ha^{-1} yr^{-1}.

• Shaded coffee systems combined ecological benefits with yields comparable to sole coffee.

1. Introduction

The Sixth Assessment Synthesis Report of the Inter-governmental Panel on Climate Change (IPCC, 2023) highlights the critical need for persistent and large-scale reductions in greenhouse gas (GHG) emissions across all sectors to limit global temperature rise to between 1.5 and 2°C by the end of this century. In this context, carbon markets, both regulatory and voluntary, are gaining prominence as cost-efficient mechanisms to facilitate rapid and sustained emission reductions (Battocletti et al., 2024; Paraschiv et al., 2024). These markets increasingly prioritize nature-based solutions (NbS), particularly those that generate verifiable carbon credits through interventions such as afforestation, reforestation, and agroforestry. As defined by the United Nations Environment Assembly (UNEA-5, 2022), NbS encompass adaptive strategies aimed at protecting, managing and restoring ecosystems to address environmental and socio-economic challenges while delivering co-benefits related to biodiversity, ecosystem services, and human well-being. Among NbS, agroforestry systems (AFS) represent a promising strategy in the Global South, integrating woody perennials with agricultural crops to enhance productivity and ecological resilience. These systems support rural livelihoods and contribute to ecosystem functions including improved soil structure, water retention, and biodiversity conservation

(Nungula, 2024; George et al., 2025). Agroforestry acts as a carbon sink, mitigating climate change by storing carbon in both biomass and soil (Singh et al., 2024). When implemented at scale, agroforestry can lead to landscape-level transformations and support the achievement of multiple Sustainable Development Goals (SDGs) (FAO, 2013). For NbS to be effective, a deeper understanding of local enabling conditions and pathways for inclusive, community-led transitions is required, especially in low- and middle-income countries, where empirical data remain scarce (Standish and Parkhurst, 2024; Alghanmi et al., 2024).

Shaded coffee systems make efficient use of vertical space, optimizing light interception while facilitating the integration of mechanized farming practices (Jemal et al., 2021). Coffee-based agroforestry systems (AFS) are increasingly recognized for their capacity to sequester carbon, storing substantial amounts in both aboveground biomass and soil organic carbon pools (Lugo-Pérez et al., 2023; Niguse et al., 2022; Magalhães et al., 2025; Getachew et al., 2023). By mimicking forest-like conditions, shaded perennial systems often maintain significantly higher soil carbon stocks—up to 48% greater than monoculture systems—owing to sustained organic matter inputs and enhanced soil biological activity (Chatterjee et al., 2018, 2019; Petit-Aldana et al., 2019; Rigal et al., 2020). Continuous litter deposition from shade trees enriches soil organic matter and stimulates microbial communities, which are reported to increase by up to 64% relative to sole coffee systems (Rigal et al., 2020). In addition to carbon dynamics, shaded coffee systems improve multiple soil health indicators, including nutrient cycling, structural stability, and exchangeable nutrient status (Sauvadet et al., 2019; Niguse et al., 2022; Misgana et al., 2024). Deep-rooted shade trees access subsoil water and nutrients and redistribute them to the topsoil, enhancing resource availability for shallow-rooted coffee plants (Munroe et al., 2015). The shade-induced microclimate further reduces soil evaporation, plant transpiration, and erosion losses, thereby improving water-use efficiency and system resilience (Blanco-Sepúlveda et al., 2024). These benefits become more pronounced as agroforestry systems mature and under low-input management regimes (Vallejo et al., 2010; Rigal et al., 2020). Improved soil health and ecological functioning under shaded coffee systems directly contribute to yield stability and enhanced bean quality (Torrez et al., 2023). Reflecting their global relevance for sustainable land management and climate mitigation, shade-grown coffee systems currently account for nearly one-quarter of global coffee production (Jemal et al., 2021).

In India, coffee is traditionally cultivated in the southern states of Karnataka, Kerala, and Tamil Nadu, which collectively account for over 90% of national production—53% from Karnataka, 28% from Kerala, and 11% from Tamil Nadu (Singh et al., 2021). On a global scale, coffee remains one of the most economically significant agricultural commodities, serving as a vital source of foreign currency for many producing nations (Beer *et al.*, 1998; Bote and Struik, 2011). In addition to its trade value, coffee production provides direct employment for over a million individuals across value chain segments in Asia and Africa. The widespread removal of shade trees in favour of high-input sole coffee plantations to maximize short-term yield and profit poses a serious threat to the long-term sustainability of coffee production in the Western Ghats and globally (Sauvadet et al., 2019). There is an urgent need to reposition shaded coffee systems not only as agronomically and ecologically superior production

models, but also as viable climate-mitigation strategies through enhanced carbon sequestration. Importantly, the integration of shaded coffee into carbon-credit schemes and climate-finance mechanisms offers a tangible economic incentive for farmers, making these systems more attractive than sole coffee monocultures (Kurniawan et al., 2021; Singh et al., 2023). In this context of emerging climate-smart agriculture and ecosystem-based carbon markets, this study aims to evaluate: (i) the influence of shade tree–based agroforestry on soil quality and carbon storage within coffee systems and (ii) the potential for leveraging emerging carbon pricing and trading schemes to deliver both ecological and economic benefits to farmers.

2. Materials and Methods

2.1 Site description:

This study was carried out in the major coffee-producing regions of Karnataka, India, encompassing the Western Ghats escarpment and the Karnataka Plateau. Coffee cultivation in the state is predominantly concentrated in the hilly districts of Kodagu (Coorg), Chikkamagaluru, and Hassan. The Western Ghats escarpment serves as a significant orographic barrier, intercepting the southwest monsoon and resulting in high rainfall on the windward side, while creating adjacent rain shadow areas characterized by comparatively lower precipitation.

Site selection was guided by the variability in soil types, climatic conditions, topographic features, and the history of coffee cultivation under different land-use practices. The selected systems included: forest-based coffee cultivation (CF), coffee plantations integrated with shade trees, and monoculture or sole coffee systems (CS). Forest-based coffee systems are those where coffee is cultivated under existing tree cover or within historically forested land-use areas. Shade-grown coffee systems are those where shade trees are intentionally planted alongside coffee, and are further categorized based on the density of shade-tree cover: Coffee with Thick Shade (CTS; >500 trees ha^{-1}), Coffee with Moderate Shade (CMS; 100–500 trees ha^{-1}), and Coffee with Thin Shade (CTnS; <100 trees ha^{-1}). Shade-tree density was assessed using 10 m × 10 m sample plots or, where available, verified through plantation records maintained on site. Historical land-use records, supported by interviews with local farmers and government officials, were reviewed to identify mature plantations, and only those older than 15 years were included. Figure 1 presents the spatial distribution of sampling sites representing these coffee land-use systems across major coffee growing zones of Karnataka. At each location, survey sheets were used to document soil and nutrient management practices, agronomic inputs, coffee yields and supplementary income-generating activities adopted by the farmers.

2.2 Soil sampling and laboratory analysis

A total of 24 representative soil profiles (pedons) were excavated from various coffee-growing plantations, spanning above mentioned five predominant land use categories. These sites were strategically selected to represent the variability in soil types, topography, and climatic conditions, based

on the soil mapping units delineated for Karnataka. At each site, soil pits were dug down to the lithic contact or bedrock to expose complete soil horizons. Each profile was described and classified following the guidelines of the USDA Soil Taxonomy (Soil Survey Staff, 2022). Soil samples, weighing approximately 2 kg per horizon, were collected, air-dried, and passed through a 2 mm mesh sieve prior to laboratory analyses.

Soil texture was analyzed using the international pipette technique. The sand fraction (ranging from 2000 to 50 µm) was quantified via mechanical dispersion and sieving, whereas silt and clay contents were estimated based on sedimentation principles (Jackson, 1979). Bulk density (BD) was determined using the core sampling approach (Blake and Hartge, 1986). Soil reaction (pH) was measured potentiometrically in a 1:2.5 soil-to-water suspension. Exchangeable acidity was assessed through extraction with 1 N KCl, and extractable acidity was measured using a $BaCl_2$–triethanolamine (TEA) buffer solution at pH 8.2, with titrimetric determination, following the protocol by Sarma et al. (1987). Additionally, pH values were measured in 0.01 M $CaCl_2$ and 1 M KCl solutions as outlined by Reeuwijk (1992). The organic carbon (SOC) content in the < 2 mm soil fraction was determined using the Walkley and Black (1934) wet oxidation method, while total organic carbon (TOC) was analyzed through dry combustion at 1200°C using a LECO CN analyzer. Exchangeable cations, including Ca, Mg, K, and Na, were extracted with 1 N ammonium acetate (pH 7.0) and quantified using atomic absorption spectrophotometry (AAS), in accordance with Reeuwijk (1992). Exchangeable aluminum (Al) was extracted using 1 M KCl and estimated titrimetrically. Base saturation (BS) was computed as the percentage ratio of total exchangeable bases to the cation exchange capacity (CEC).

2.3 Soil quality evaluation

Principal Component Analysis (PCA) was applied to 23 soil physicochemical and exchangeable properties influenced by land use and pedogenesis to reduce dimensionality and identify a Minimum Data Set (MDS) for soil quality assessment. (Doran and Parkin, 1994; Mukherjee and Lal, 2014). Components with eigenvalues > 1.0 were retained (Kaiser, 1960). Varimax rotation enhanced correlations between variables and principal components (Waswa et al., 2013). Variables within 10% of the highest factor loading in each PC were selected, and among highly correlated variables, those with the highest total correlation were retained as indicators (Andrews and Carroll, 2001).

Selected indicators were normalized using linear scoring functions (LSF) or non-linear sigmoidal functions (NLSF), depending on their relationship to soil quality (Liebig et al., 2001; Raiesi, 2017). LSF followed "more is better" (Eq. 1) or "less is better" (Eq. 2) criteria based on observed values.

LSF = X/Xmax (Eq. 1)

LSF= Xmin/X (Eq. 2)

Where, X= observed value of each indicator, Xmin and Xmax=highest and lowest observed value of each indicator.

For NLSF, a sigmoidal function was used with a slope coefficient of ± 2.5 (Raiesi, 2017; Bandyopadhyay and Maiti, 2021) (Eq. 3). For indicators where optimal values lie within a threshold range, a Gaussian-type response was used to reflect the "midpoint is optimum" concept (Liebig et al., 2001).

NLSF = a/[1+(Xi/Ximean)b] (Eq. 3)

Soil Quality Index (SQI) was computed using a weighted approach. Weights were derived by calculating the proportion of each PC's variance to the cumulative total (Andrews et al., 2002; Ray et al., 2014). Horizon-wise SQI values were calculated for each pedon and averaged across depth intervals (0–30, 30–60, 60–100, > 100 cm) for each land use type.

2.4. Estimation Soil carbon stock

The soil organic carbon (SOC) stock (SOCstock) was derived from SOC concentration using the equation proposed by Ellert et al. (2001) and modified by Szatmári et al. (2021):

SOCstock = C %×d×BDd×(1-CF) (Eq. 4)

In this equation, d denotes the thickness of the soil layer (cm), C% represents the percentage of SOC concentration, BDd is the bulk density of the fine earth fraction (< 2 mm size fractions g cm^{-3}), and CF refers to the volumetric proportion of coarse fragments (CF; > 2 mm size fractions). The term (1 − CF) reflects the fine earth fraction (dimensionless). SOC stock was calculated for each depth interval (0–30, 30–60, 60–100 and > 100 cm) using a weighted mean approach to capture the influence of land-use types on both dynamic and intrinsic soil carbon stocks.

2.5. Estimation of above-ground and below ground biomass of the shade trees and total carbon sequestration potential of coffee growing systems:

Aboveground biomass of dominant shade tree species across varying coffee production systems was estimated using a random plot-based sampling approach. Within 20 m × 20 m plots, diameter at breast height (DBH) and tree density (trees ha^{-1}) were recorded. Biomass and volume were calculated using species-specific volumetric equations provided by the Forest Survey of India (FSI, 1996; 2021), as detailed in Supplementary Table S1.

Total carbon stock was derived by summing above- and belowground tree biomass carbon and soil organic carbon. Carbon sequestrationwas then calculated by converting total carbon stock to its CO_2 equivalent using the standard factor 44/12 (3.666) (Ajit *et al.*, 2013).

2.6 Carbon credit and pricing

A carbon credit represents one metric tonne of CO_2 equivalent (tCO_2e) either avoided or sequestered in soil or vegetation over a permanence period of 30 or 100 years (Mitchell et al., 2024). In this study, potential carbon credit generation was estimated following the prevailing guidelines of established carbon standards. As current standards do not permit afforestation or reforestation (A/R) activities

within existing forest ecosystems, only shaded coffee systems were considered eligible for carbon credit generation through both emission reductions and carbon removals. Consistent with these principles, CS was defined as the baseline scenario. Changes in soil carbon resulting from different land-use types were quantified, and annual SOC accrual was estimated using the mean plantation age for each system. These annual SOC gains were then used to assess the potential for carbon credit generation. Owing to international variability in carbon credit prices, valuation was based on the prevailing rate in the voluntary carbon market. As of 2025, the price of one carbon credit, equivalent to one Certified Emission Reduction (CER), was approximately ₹1,544 (USD 18.1) (VCM, 2025).

2.6 Statistical analysis

Statistical analysis was carried out using the IBM-SPSS-23.0. Differences between the coffee based land use systems were evaluated with Duncan's multiple range test at $P \leq 0.05$. PCA and correlation analysis was carried out through R studio.

3. Results

3.1 Changes in soil quality index (SQI) and principal soil properties

Principal component analysis (PCA) of 23 soil variables identified four principal components (PCs) with eigenvalues > 1, explaining 64% of total variance (Table 1). PC1 (24%) had high loadings for exchangeable Ca^{2+}, Mg^{2+}, CEC, and exchangeable bases, which were significantly correlated ($p < 0.01$); exchangeable bases were selected for the minimum data set (MDS) due to their relevance to nutrient availability in coffee-based systems. PC2 (19%) was dominated by pH_{H20}, selected as the MDS variable. PC3 and PC4 explained 11% and 10% of the variance, respectively, with bulk density (BDw) and sand chosen as MDS indicators.

Table 1
Principal components and component matrix variables

Prop. variance	PC1	PC2	PC3	PC4
	0.24	**0.19**	**0.11**	**0.1**
Cumulative variance	0.32	0.27	0.15	0.14
Sand	-0.15	-0.04	-0.12	**-0.96***
Silt	0.43	0.20	-0.02	0.34
Clay	-0.08	-0.07	0.16	0.90
Gravel	-0.18	-0.06	-0.36	0.03
BDw	-0.03	-0.02	**-0.89***	-0.11
BDd	-0.01	0.02	**-0.92**	-0.25
pH.W	0.35	**0.84***	0.09	-0.09
pH.CaCl2	0.32	**0.88**	0.10	0.05
pH.KCL	0.02	**0.87**	0.24	0.08
EC	0.47	0.04	0.34	-0.03
OC	0.43	-0.11	0.48	-0.26
Ca	**0.86**	0.34	0.11	-0.04
Mg	**0.87**	0.06	-0.09	0.23
Na	0	0.20	0.04	0.01
K	0.47	0.13	0.22	-0.02
Tolal.ex.cation	**0.93***	0.25	0.03	0.08
BaCl2.Acidity	0.28	-0.61	0.37	0.19
Ex.H	0.34	-0.44	-0.05	0.28
Ex.Al	-0.04	-0.64	0.20	0.01
CEC	**0.93**	-0.07	0.15	0.10
BS	0.5	0.72	-0.05	0.09
Al.Saturation	-0.11	-0.66	0.12	-0.08
CEC.Clay	0.8	0.05	0.16	-0.41

{Boldface factor loadings are considered highly weighted (weighted when within 10% of variation of the highest factor loading in each factor). Bold-stared soil attributes correspond to the indicators included in the MDS}

Figures 2a and 2b present the SQI-LSF and SQI-NLSF across different LUCs and soil depths. At the surface layer (0–30 cm), SQI varied significantly among the coffee-based plantation types, decreasing in the order: CF (33.5% higher than CS) > CTS (13.8% higher than CS) > CMS (8.5% higher than CS) > CTnS (3% higher than CS) ~ CS. At the sub-surface layer (30–60 cm), SQI-LSF was significantly higher under CF (29.2% higher than CS), with no significant differences among the other shaded and sole coffee systems. A comparable trend was observed for SQI-NLSF, with more pronounced effects attributed to individual MDS indicators. At 0–30 cm, Ex. Bases and BD were the primary contributors to significant variation in both SQI-LSF and SQI-NLSF (Fig. 2c and 2e). At 30–100 cm, Ex. Bases was identified as the major limiting factor contributing to lower SQI under CS (Fig. 2c). Soil pH significantly ($p < 0.05$) reduced over profile depth under CTnS and CS (Fig. 2d),

3.2 Changes in soil organic carbon stock (SOC stock)

SOC stocks in the 0–30 cm layer differed significantly among plantation types ($p < 0.05$; Fig. 3a), decreasing in the order: CF (65.5% higher than CS) > CTS (43.1% higher than CS) > CMS (19.1% higher than CS) > CTnS (12.9% higher than CS) > CS. In the 30–60 cm layer, SOC stock was significantly highest under CF, while no significant differences were observed among the other shaded and sole coffee systems. Below 60 cm soil depth, the influence of plantation type on SOC stocks was found to be statistically insignificant. The mean annual SOC stock increment over CS was highest in CTS (1.03 tC ha^{-1} yr^{-1}), followed by CMS (0.54 tC ha^{-1} yr^{-1}) and CTnS (0.34 tC ha^{-1} yr^{-1}) (Fig. 3b).

3.3 Total biomass carbon, annual emission reduction (ER) and estimated carbon credit under shaded coffee plantation

According to the principles outlined in leading carbon standards (CDM, 2006; Verra, 2023), only woody biomass of shade trees qualifies for emission reduction (ER) calculations, while the biomass from cultivated, pruned coffee plants is conservatively excluded as non-tree biomass. The total carbon (C) stock, comprising both above- and below-ground components, exhibited considerable variability across plantation types, following the descending order: CF (725.2 t ha^{-1}) > CTS (mean: 101.9 t ha^{-1}) > CMS (mean: 48.39 t ha^{-1}) >CTnS (mean: 5.06 t ha^{-1}) (Fig. 4a). The estimated annual ER potential from shade tree plantations varied significantly across systems: CTS (15.1 tC ha^{-1} yr^{-1}) > CMS (8.64 tC ha^{-1} yr^{-1}) > CTnS (1.8 tC ha^{-1} yr^{-1}) (Fig. 4b). In terms of economic valuation, CTS systems exhibited the highest potential carbon revenue, estimated at $340.9 USD ha^{-1} yr^{-1} (₹30,691 INR), followed by CMS ($192.9 USD ha^{-1} yr^{-1} or ₹17,253 INR) and CTnS ($55.41 USD ha^{-1} yr^{-1} or ₹5,028 INR) (Fig. 5).

4. Discussion

4.1 Influence of coffee based land use systems on soil quality and soil carbon storage

Soil quality index (SQI) is a by-product of soil characteristics that has a dominant impact on the productivity of a given land use system and soil functions (Vasu et al., 2016; Thoumazeau et al., 2019). In the present study, soils under CF exhibited the highest SQI followed by shaded coffee system (CT > CMS> CTnS) and least under CS for both SQI-LSF and SQI-NLSF irrespective of the assessed soil depth ($p < 0.05$; Fig. 2a and 2b). Both the chemical and physical components were found to be critical for overall SQI estimation, with a significant impact of Ex. Bases and BD. As the CF and shaded coffee plantation system considerably higher Ex Bases and lower BD than the CS (Fig. 2c), the former land use systems exhibited higher overall SQI than the later, consistent with findings by other studies (Rigal et al., 2020, Manson et al., 2022, Angadi *et al.*, 2025). Land use history revealed that all the study areas had been transformed from tropical forests to coffee plantations which causes rapid soil nutrient leaching (Zou et al., 2021) and lower BS over the soil exchangeable complexes. Lack of vegetation cover on soil surface and absence of deep root system under CS accelerates leaching of bases than CF and shaded coffee plantation system (Zhu et al., 2018) ($p < 0.01$; Fig. 2c). Soil pH decreased significantly ($p < 0.05$) with depth under CTnS and CS (Fig. 2d), increased with depth under CF, and remained statistically unchanged under CT and CMS. Enhanced sub-surface soil acidification under CTnS and CS may lead to increased concentrations of exchangeable H^+ ions and aluminium saturation within soil exchange complexes (data not presented), particularly in the high-rainfall, intensely weathered zones of the tropical humid Western Ghats. However, the presence of deep-rooted shade trees and intact natural forest ecosystems appears to mitigate this acidification process (Fujii et al., 2021). Similar positive impact of CF and shaded coffee plantation system on soil physical properties (Fig. 2e and 2f) can be observed over CS. Although the lower SQI under CS did not reflect on annual coffee yield, it expressed poor soil functioning over CF and shaded coffee system.

In the current study, coffee-based land use systems have received varied levels of inputs of plant materials such as fine roots and litter, as well as of management practices. Conversion of forests to coffee plantations or other arable crops leads to a reduction of SOC stock over time (Kissinger, 2020; Harvey et al., 2021; Chort and Öktem 2024; Cornelius et al., 2024). It is clear from this study that shade trees have the potential to be very important contributors to carbon storage (Fig. 3a), while thick shade tree plantation can lead to carbon storage capacity comparable to CF over time. Most tropical coffee-growing regions are established on lands converted from forest ecosystems, a process that has resulted in substantial losses of ecosystem carbon. CTS based systems have the potential to restore soil carbon stocks and partially reverse these land-use change–induced carbon losses by promoting long-term carbon stabilization in soils. Shade trees' contributions to the organic matter through leaves, branches, roots, and root exudate (Noponen et al., 2013; Tumwebaze and Byakagaba, 2016), ground cover also played key role to carbon storage (Lugo-Pérez et al., 2023). Significant positive correlation ($r2 = 0.52$; $p < 0.01$) with subsurface SOC stock and below ground root C content proves the importance of deep root carbon residue to the total carbon storage of soil. Several studies have showed the similar impact over deeper allocation of soil carbon storage under shade tree-based coffee systems (Lugo-Pérez et al., 2023; Sun et al., 2023). These results suggest that, factors such as tree density, root architecture, and biomass

carbon storage capacity must also be considered to accurately assess the overall contribution of trees to carbon storage in coffee farms.

4.2 Carbon credit potential under coffee based land use systems

Carbon crediting offers an additional economic incentive for farming communities by recognizing the value of practices that enhance biomass accumulation, increase soil organic carbon (SOC) stocks, and improve the carbon sink potential of land-use systems, thereby contributing to atmospheric CO_2 mitigation. Agri-silvicultural systems, in particular, have been reported to exhibit high carbon credit potential, primarily due to their elevated biomass production and carbon sequestration capacity (Awazi, 2025; Kumara et al., 2023). Under prevailing carbon accounting standards and voluntary carbon market (VCM) guidelines, afforestation and reforestation (A/R) activities implemented within existing natural forests are typically excluded from eligibility, as such interventions may alter or degrade ecologically sensitive forest ecosystems. Accordingly, the present study focuses solely on quantifying the annual carbon sequestration potential of coffee agroforestry systems managed with shade trees, considering both aboveground biomass and soil carbon components. Results indicate that the annual increase in soil carbon stocks was highest in the CTS, followed by CMS and CTnS. The corresponding carbon credit potential from soil carbon ranged from USD 22.7 to USD 68.7 ha^{-1} yr^{-1}. Aboveground biomass carbon sequestration varied substantially among systems, with the lowest value recorded under CTnS (1.8 tC ha^{-1} yr^{-1}) and the highest under CTS (15.1 tC ha^{-1} yr^{-1}), translating to a potential carbon credit value of USD 33.21 to USD 272.2 ha^{-1} yr^{-1}. When combined, the CTS system demonstrated the highest overall carbon revenue potential, estimated at USD 340.9 ha^{-1} yr^{-1} (approximately ₹29,309 INR), followed by CMS (USD 192.9 ha^{-1} yr^{-1} or ₹16,550 INR) and CTnS (USD 55.41 ha^{-1} yr^{-1} or ₹4,813 INR). These findings highlight the significant role of shade tree-based coffee systems in enhancing carbon sequestration and supporting sustainable livelihoods through access to carbon finance.

The transition from monoculture coffee cultivation to agroforestry systems has emerged as a promising strategy for carbon credit generation and climate change mitigation. Shaded coffee systems, in particular, have demonstrated a significantly higher potential for emissions reduction compared to unshaded systems (Cornelius et al., 2024). The widespread adoption of such systems, with varying shade tree densities, presents a viable pathway toward carbon-neutral coffee production. However, a critical consideration in this transition is the potential impact of shade on coffee yield. If not properly managed, excessive shade may reduce productivity (Schnabel et al., 2018; Mokondoko et al., 2022). Nevertheless, similar with the results of the current study (Fig S1), several studies indicate that moderate shade levels can sustain coffee yields relative to unshaded systems (Piato et al., 2020; Haggar et al., 2021; Koutouleas et al., 2022). Although, cultivated coffee variety also plays an important role to maintain the yield level. It is important to recognize that much of the global coffee production, including that in the Western Ghats of India, has historically replaced forested landscapes (Gaucherel et al., 2017; Sreeja et al., 2021; Karthika et al., 2022; Kissinger, 2020; Harvey et al., 2021; Chort and Öktem, 2024). This ongoing land-use change underscores the need to prioritize climate mitigation and ecological

restoration. In this context, efforts by institutions such as the Karnataka Forest Department and the Coffee Board of India, which have supported on-farm tree planting through subsidized seedlings, are commendable (Nath et al., 2011). However, the lack of clear legal frameworks governing the harvest of native and naturalized tree species remains a significant barrier, discouraging farmers from adopting agroforestry practices (Vijaya, 2000). This regulatory uncertainty often leads to mistrust among farmers regarding government-led climate initiatives (Nandakishor et al., 2022). In the context of accelerating climate change, communicating only the environmental benefits of carbon sequestration and soil health improvement is insufficient to drive farmer adoption. It is equally important to demonstrate that shade-tree management can provide direct economic incentives without compromising coffee yield. In the Global South, where most coffee producers are small and marginal farmers, the promotion of sustainable coffee landscapes will be most effective when supported by carbon-finance mechanisms that reward farmers for their contribution to climate-neutral production systems.

Conclusion

This study evaluated the effects of various coffee-based land use systems—namely, forest-based coffee cultivation (CF), shaded coffee plantations with high (CTS), medium (CMS), and low (CTnS) tree densities, and sole coffee systems (CS)—on soil quality, carbon (C) storage, biomass carbon accumulation, and carbon credit potential. Among the systems studied, CF demonstrated the highest soil quality and total carbon stocks, followed by CTS, CMS, CTnS, and CS. Notably, improvements in soil quality did not translate into higher coffee yields; however, CMS and CTnS produced yields comparable to those of the sole coffee system (CS). Shaded coffee systems showed substantial potential for carbon credit generation under internationally recognized carbon accounting frameworks, driven by both soil carbon sequestration and aboveground biomass accumulation. These systems also significantly improved soil quality throughout the soil profile in comparison to CS. The findings highlight both soil and economic advantages of shaded coffee systems, particularly for environmentally sensitive regions such as the Western Ghats. Their adoption could support climate change mitigation efforts while enhancing the livelihoods of rural farming communities through carbon financing. Future research should aim to expand the geographic applicability of these systems across similar agro-climatic zones and refine management practices to maintain yield, while maximizing carbon sequestration potential.

Declarations

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Author Contribution

Kaushik Saha: Conceptualization, Data curation, Methodology, Data analysis, Visualisation, Original draft, Review & Editing.K. S. Anilkumar: Supervision, Visualisation, Funding acquisition, Project administration, Review & editing.Samrat Ghosh: Data curation, Methodology, Review & EditingNair, K. M.: Supervision, Visualisation, Project administrationLalitha, M.: Review & Editing, SupervisionKarthika, K. S.: Review & EditingParinita Das: Software and data analysisParvathy, S.: Laboratory analysisRamamurthy, V.: Review & EditingPatil, N. G.: Review & Editing

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Figures

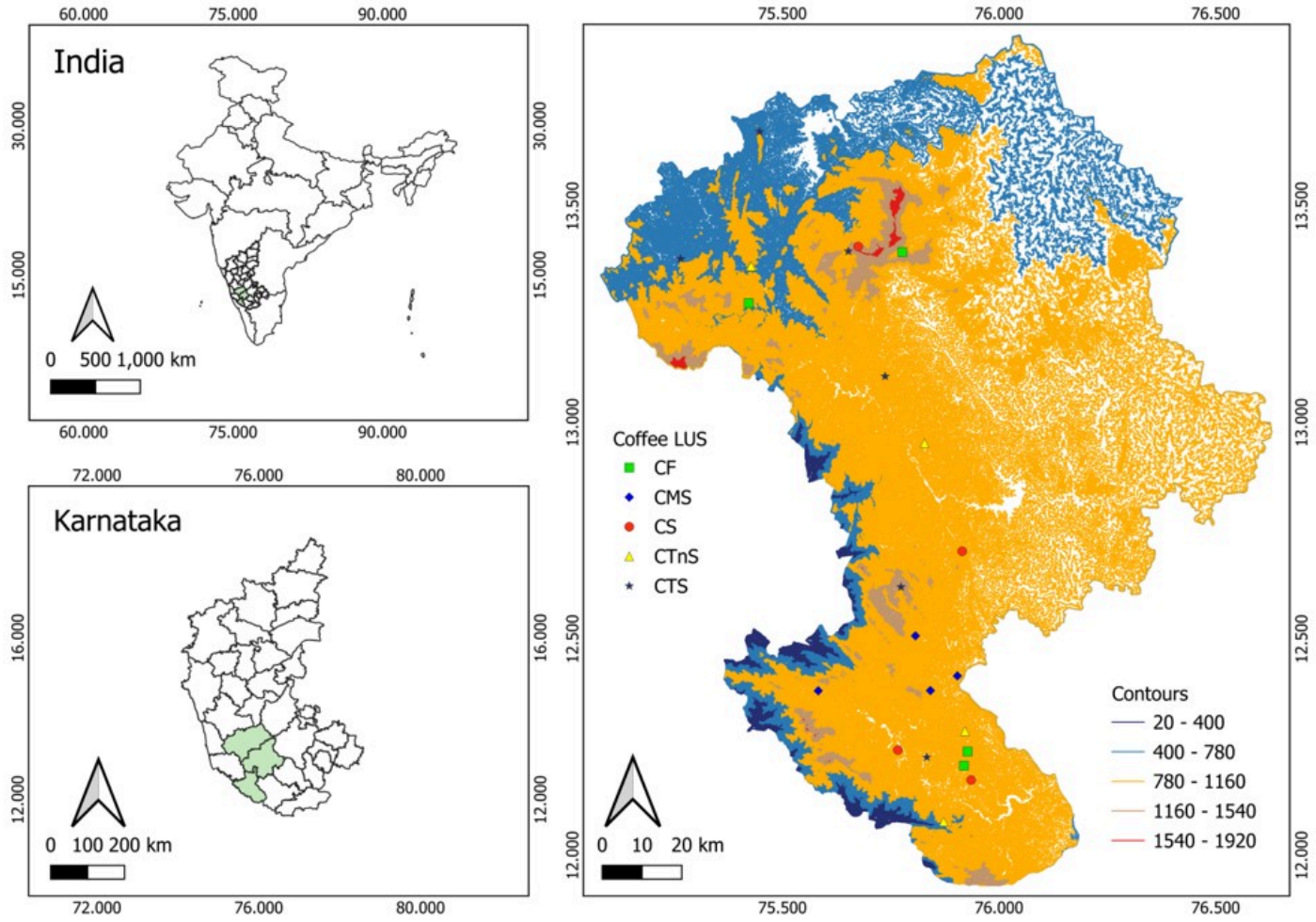


Figure 1

Location map of different study sites. CF: Forest based coffee cultivation, CTS: Coffee with thick shade tree population, CMS: Coffee with Moderate Shade population, CTnS: Coffee with thin shade population; CS: Sole coffee plantation

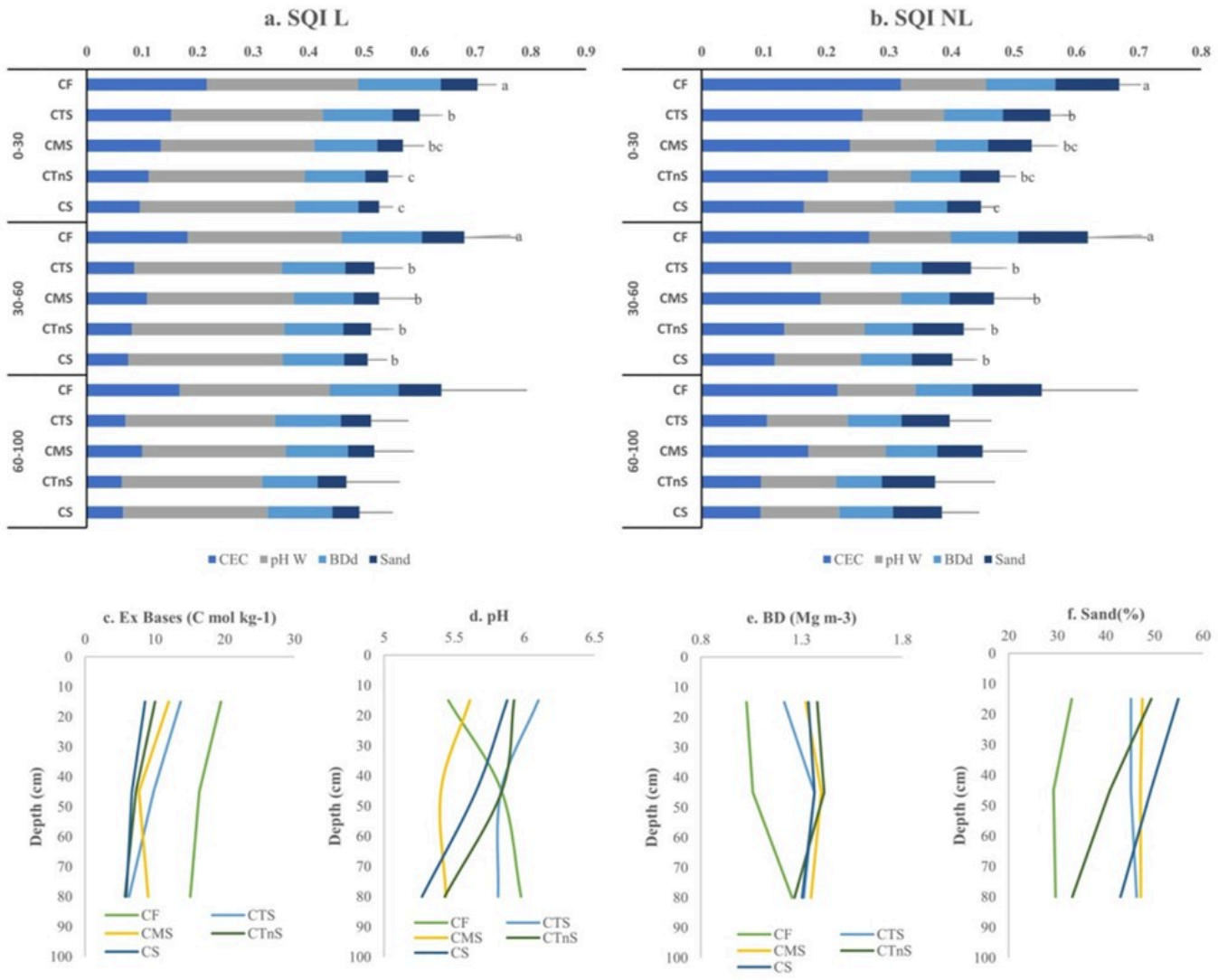


Figure 2

Vertical distribution of Soil quality index (SQI) and soil properties selected through minimum data set (MDS) under different coffee based land use systems (LUS). (a) SQI-Linear scoring function under different soil depth function of each LUSs; (b) SQI-nonlinear scoring function under different soil depth function of each LUSs; (c) Exchangeable bases; (d) pH; (e) Wet Bulk Density (f) Sand percentage. Data are expressed as the mean of LUSs and depth points with different lowercase letters indicate significant differences among the LUSs ($p < 0.05$; the tested method was one-way analysis of variance (ANOVA, $p < 0.05$) followed by Duncan's Multiple Range Test test.). Study sites are CF: Forest based coffee cultivation, CTS: Coffee with thick shade tree population, CMS: Coffee with Moderate Shade population, CTnS: Coffee with thin shade population; CS: Sole coffee plantation.

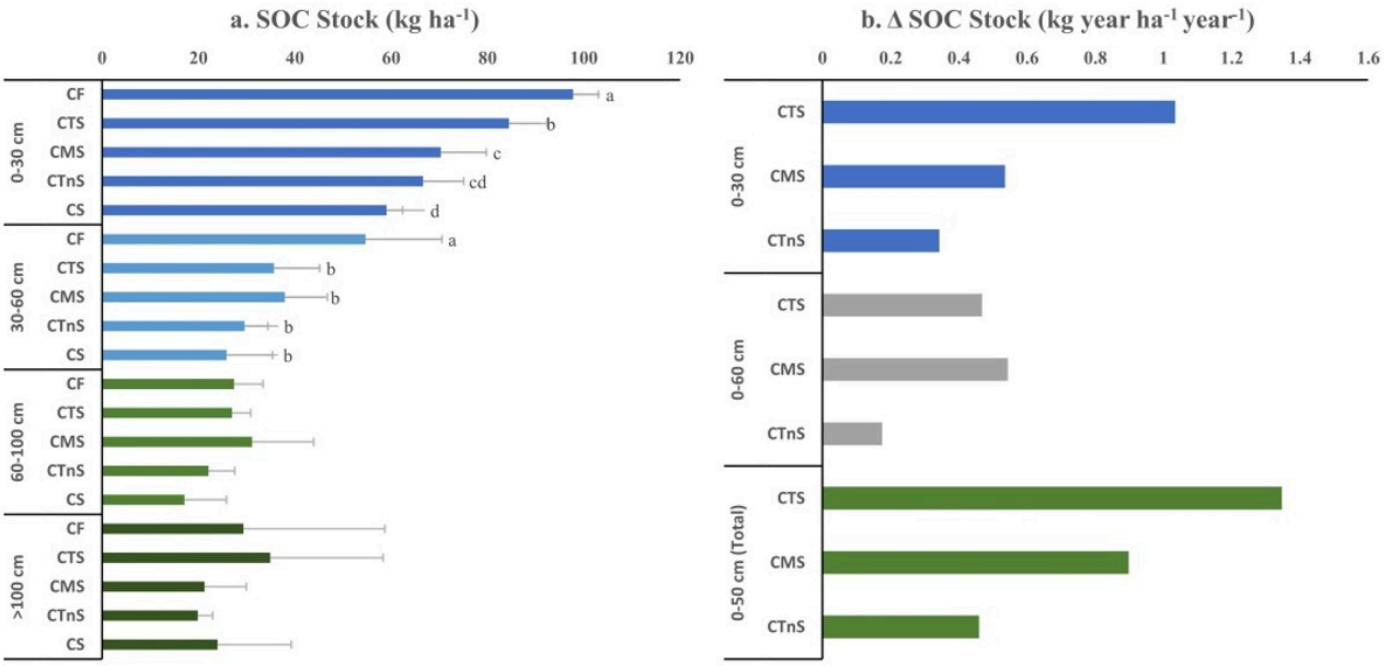


Figure 3

Soil organic carbon stock (SOCs) under different coffee based land use systems (LUS). and soil depth. (a) Annual increment of SOCs under different LUSs at varied soil depth function; (b) Change in the SOCs stocks under shaded coffee based LUSs. Data are expressed as the mean and bars with different lowercase letters indicate significant differences among the LUTs ($p < 0.05$). Study sites are CF: Forest based coffee cultivation, CTS: Coffee with thick shade tree population, CMS: Coffee with Moderate Shade population, CTnS: Coffee with thin shade population; CS: Sole coffee plantation.

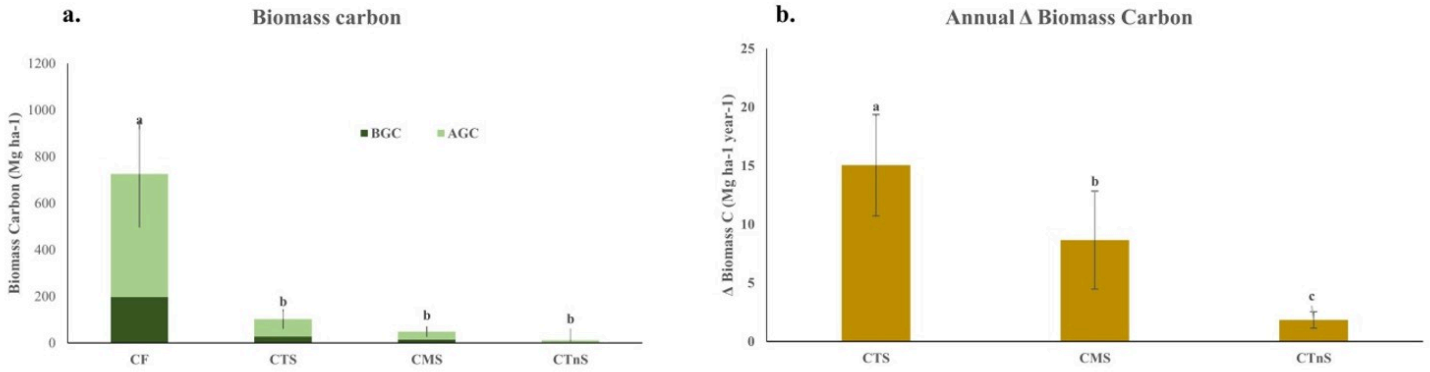


Figure 4

Biomass carbon stock (SOCs) under different coffee based land use systems (LUSs). (a) Above ground carbon (AGC) and below ground carbon (BGC) under different LUSs; (b) Annual increment of biomass carbon change under shaded coffee based LUSs. Data are expressed as the mean and bars with

different lowercase letters indicate significant differences among the LUTs ($p < 0.05$). Study sites are CF: Forest based coffee cultivation, CTS: Coffee with thick shade tree population, CMS: Coffee with Moderate Shade population, CTnS: Coffee with thin shade population.

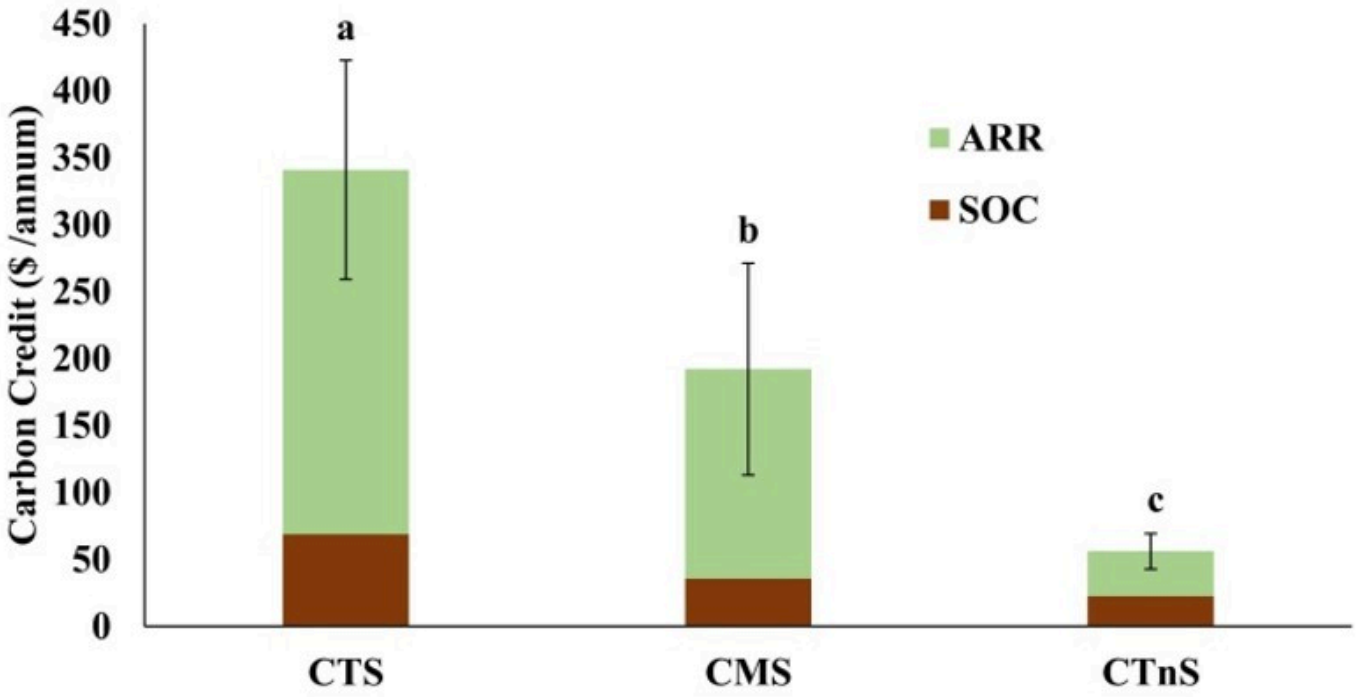


Figure 5

Carbon credit estimation under shaded coffee based land use systems. ARR indicates the credit generated through afforestation of shade trees and SOC indicates credit generated through soil organic carbon increment. Data are expressed as the mean and bars with different lowercase letters indicate significant differences among the LUTs ($p < 0.05$). Study sites are CTS: Coffee with thick shade tree population, CMS: Coffee with Moderate Shade population, CTnS: Coffee with thin shade population.

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