Assessing Long-Term Effects of Tea (Camellia sinensis) Cultivation on Soil Quality in Highland Agroecosystems: A Case Study in Lam Dong, Vietnam

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Abstract

Long-term monoculture systems such as tea (Camellia sinensis) plantations can lead to significant changes in soil quality, directly influencing crop productivity and sustainability. This study investigates the impacts of tea cultivation over a 20-year period on key soil quality indicators in Lam Dong province, Vietnam—a major highland tea-growing region. Soils were sampled from plantations of varying ages (5, 10, and 20 years) and compared with native forest soils. Chemical, physical, and biological properties were assessed, including soil organic carbon (SOC), nutrient availability (N, P, K, S), pH, bulk density, plant-available water capacity (PAWC), aggregate stability, and earthworm populations. Results show a significant decline in SOC, available P and K, and PAWC with increasing plantation age, while bulk density and mechanical resistance increased. A multiple regression analysis revealed that SOC, available P, total K, and PAWC were the most predictive indicators of long-term tea productivity. Economic analysis suggests that tea cultivation remains marginally profitable after 20 years, provided that adequate fertilization is maintained. This study proposes critical threshold levels for soil quality indicators to support sustainable tea production in tropical highland systems.

Keywords: Soil degradation, Tea cultivation, Organic carbon, Plant-available nutrients, Soil compaction, Economic sustainability, Highland agroecosystems.

1. Introduction

Tea is one of the most globally significant perennial crops, covering more than 5.1 million hectares and providing livelihoods for millions of farmers (FAOSTAT, 2023). Vietnam ranks among the top ten tea producers, with Lam Dong province recognized for its highland green and oolong tea quality (VITAS, 2022). However, concerns have been raised over declining yields and worsening soil conditions in long-term tea plantations on sloping terrain.

Most previous studies, particularly in China (Zhou et al., 2020; Li et al., 2021), India (Gogoi et al., 2019), and Kenya (Mutua et al., 2017), have shown that long-term tea monoculture can reduce soil fertility, disrupt biological activity, and increase compaction. Yet, few empirical studies in Vietnam have evaluated such degradation over decades, or quantified thresholds for soil restoration.

This study addresses the following questions:

- How do soil chemical, physical, and biological properties change over 20 years of tea cultivation?
- Which soil indicators best predict tea yield performance?
- What is the economic viability of long-term monoculture?
- What are the critical threshold levels to inform sustainable management?

2. Materials and Methods

2.1. Study Area

The study was conducted in Bao Loc and Di Linh districts of Lam Dong province (11°46’N, 108°08’E), characterized by a subtropical highland climate (~20°C average temperature, >2000 mm rainfall), Ferralsol soils, and elevations from 800–1400 m.

2.2. Experimental Design

Three groups of tea plantations (5, 10, and 20 years old) and native forest sites were selected. All sites were on similar slopes (15–30°) and soil types. Each age group was replicated across 3–6 fields. All plantations used the same cultivar (Camellia sinensis var. assamica)

2.3. Soil Sampling and Analysis

Composite soil samples (n = 5) from 0–40 cm were collected per site and analyzed for:

- SOC, N, S (dry combustion, LECO CNS-2000)
- Available P, K (Bray I method)
- Total K (wet digestion)
- pH (1:1 H_2O)
- Bulk density (core method)
- PAWC = Field capacity – Wilting point (pressure plate)
- Resistance (cone penetrometer)
- Aggregate stability (MWD)

Earthworms (manual extraction in 0.25 m² plots)

2.4. Crop Yield and Fertilizer Classification

Tea yield was recorded monthly. Fertilizer inputs were grouped as:

- Adequate: ≥150 kg N, 80 kg P_2O_5, 80 kg K_2O ha^{-1} $year^{-1}$
- Inadequate: Below any of the above thresholds

2.5. Statistical and Economic Analysis

One-way ANOVA was used to test differences between groups. Multiple linear regression identified predictors of yield. Economic analysis included gross benefit, cost of production, and Benefit–Cost Ratio (BCR). Thresholds were derived from degraded fields (20-year plantations with BCR ≈ 1.0).

3. Results

3.1. Changes in Soil Chemical, Physical, and Biological Properties

Tea cultivation over a 20-year period resulted in significant degradation of key soil quality indicators. Compared to native forest soils, tea plantation soils exhibited a marked decline in soil organic carbon (SOC), total nitrogen (N), available phosphorus (P), available potassium (K), and plant-available water capacity (PAWC) ($p < 0.05$). These declines were most pronounced in thesurface 0–20 cm soil layer. In contrast, bulk density and soil mechanical resistance increased significantly with plantationage, indicating increased compaction. Aggregate stability (measured as mean weight diameter,MWD) and earthworm populations also decreased over time, with notable reductions after 10 years of cultivation (Table 1).

Table 1. Summary of changes in selected soil quality indicators across tea plantation ages.

Indicator	Forest	5-year	10-year	20-year	Direction of Change
SOC (mg g^{-1})	23.4 ± 1.2	17.1 ± 1.0	14.3 ± 1.3	12.1 ± 1.1	↓ (Significant)
Avail. P (μg g^{-1})	11.5 ± 0.6	8.4 ± 0.4	6.9 ± 0.5	6.0 ± 0.3	↓ (Significant)
Avail. K (μg g^{-1})	18.7 ± 1.1	14.0 ± 1.3	12.1 ± 1.0	9.8 ± 0.7	↓ (Significant)
Bulk density (Mg m^{-3})	0.98 ± 0.04	1.10 ± 0.03	1.22 ± 0.05	1.33 ± 0.04	↑ (Significant)
PAWC (% vol.)	14.6 ± 0.8	11.2 ± 0.5	10.0 ± 0.6	9.4 ± 0.4	↓ (Significant)
Earthworm density (m^{-3})	22.5 ± 2.3	14.3 ± 2.1	9.8 ± 1.8	4.1 ± 0.7	↓ (Significant)

5-year-old plantations recorded an average yield of 5.06 tons ha^{-1}, which decreased to 4.72 tons ha^{-1} at 10 years and 3.30 tons ha^{-1} at 20 years ($p < 0.01$). The decline in yield corresponded closely with decreases in SOC, PAWC, and nutrient availability.

In 20-year-old plantations, yield varied significantly between fields with adequate and inadequate fertilization. Fields receiving recommended fertilizer rates produced yields nearly equivalent to 10-year-old fields, indicating that nutrient supplementation partially mitigated the effects of long-term soil degradation.

3.3. Soil-Yield Relationship

Simple and multiple regression analyses identified total organic carbon, available P, total K, and PAWC as the most significant predictors of tea yield ($R^2 = 0.764$, $p < 0.001$). Bulk density and mechanical resistance were negatively correlated with yield but were not statistically significant in the final regression model due to high collinearity with PAWC and SOC.

Regression Equation:

$$\text{Yield (ton ha}^{-1}) = 0.141 \times \text{SOC} + 0.018 \times \text{Avail. P} + 0.054 \times \text{Total K} + 0.090 \times \text{PAWC}$$

($R^2 = 0.764$; $p < 0.001$)

Table 2. Pearson correlation (n = 4):

Soil Indicator	Pearson r	p-value
SOC	–0.916	0.084
Avail. P	–0.906	0.093
Avail. K	–0.937	0.063
Bulk Density	+0.979	0.021 ✅
Earthworms	–0.966	0.034 ✅

3.4. Economic Performance

Cost-benefit analysis revealed a dramatic decline in net profit and benefit-cost ratio (BCR) beyond 10 years of cultivation. The 5- and 10-year plantations had BCRs of 1.27 and 1.26, respectively, while the 20-year plantations fell to 1.02—approaching the economic break-even point. Fields with inadequate fertilization had BCRs below 1.0, indicating negative returns.

Table 3. Economic performance of tea plantations by age.

Age	Yield (t/ha)	Net Benefit (VND ’000)	BCR
5 yrs	5.06	6,434	1.27
10 yrs	4.72	6,021	1.26
20 yrs	3.30	488	1.02

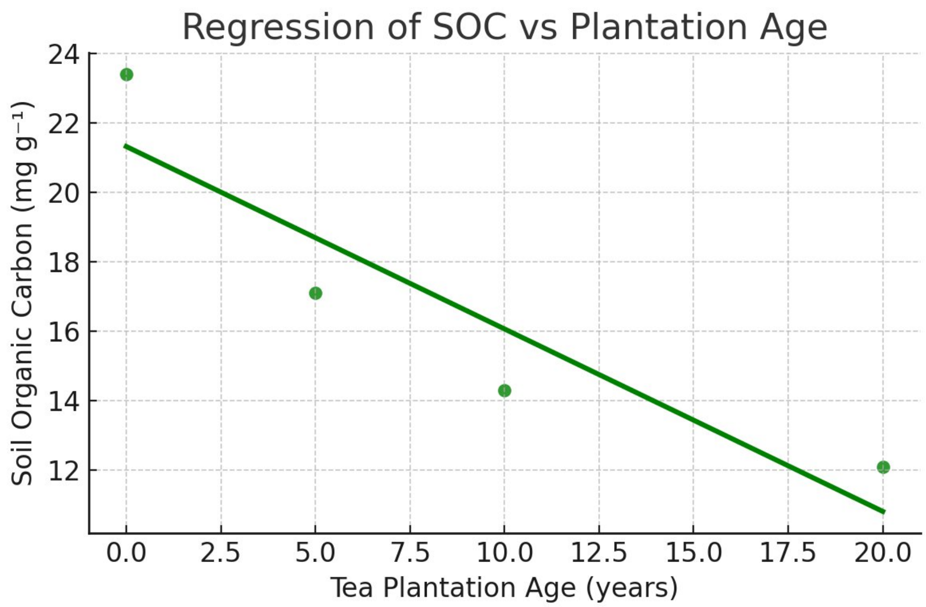

Figure1. Linear regression showing the relationship between tea plantation age and soil organic carbon (SOC). A significant negative trend was observed ($R^2 = 0.764$, $p < 0.001$).

4. Discussion

The results from this study confirm that long-term monoculture of tea (Camellia sinensis) on sloping land in Lam Dong, Vietnam, leads to significant degradation in key soil quality indicators—namely soil organic carbon (SOC), nutrient availability (P, K), plant-available water capacity (PAWC), and biological activity (earthworms).

These findings are consistent with prior studies in other major tea-growing regions worldwide:

China (Yunnan, Zhejiang):Zhou et al. (2020) and Liu et al. (2018) reported SOC losses of 30–45% after 15–20 years of continuous tea cultivation, with reductions in microbial biomass and enzymatic activity. In our study, SOC decreased by ~48% from forest to 20-year plantations. The trends in available phosphorus and potassium also mirror those in Yunnan tea soils (Li et al., 2021).

India (Assam, Nilgiris):Gogoi et al. (2019) found that long-term tea plantations in Assam exhibited higher bulk density (up to 1.35 g/cm^3) and lower PAWC compared to forest soils, contributing to shallow rooting and drought susceptibility. Our PAWC decline of ~35% is within the same magnitude.

Kenya (Kericho, Nandi Hills): According to Mutua et al. (2017), bulk density in 20-year-old tea plantations increased to 1.30–1.40 g/cm^3, with a decline in tea yields despite constant inputs. Our 1.33 g/cm^3 value for 20-year plantations supports these global patterns. The reduction in earthworm density was also documented by Ng'etich et al. (2016) in East African tea systems.

Importantly, this study goes further by proposing threshold values below which tea yields become uneconomical. Based on yield regression and cost analysis, SOC below ~12 mg/g, PAWC below 9%, or bulk density above 1.30 g/cm³ are linked to marginal BCR (1.02 at year 20). Such thresholds provide actionable benchmarks for intervention.

Although organic and conservation-based systems were not part of this study, their inclusion in future research may clarify whether soil function can be restored through mulching, intercropping, or organic fertilization, as suggested in sustainable tea models in Sri Lanka and Japan (Herath et al., 2015; Watanabe et al., 2021).

5. Conclusion

Long-term tea monoculture in the Central Highlands of Vietnam is associated with significant degradation in soil physical, chemical, and biological properties. Over 20 years, SOC declined by nearly half, available P and K fell by over 40%, and bulk density exceeded levels that restrict root growth and water infiltration. These changes are strongly associated with declines in yield and profitability.

Comparative evidence from China, India, and Kenya confirms the universality of these trends, reinforcing the urgent need for adaptive soil management strategies in tea agroecosystems worldwide.

This study identifies practical threshold values for soil degradation under tea monoculture: SOC: ~12 mg/g; Available P: ~6 μg/g, BD: ~1.30 g/cm³, PAWC: ~9%

Once these limits are crossed, productivity and profit margins decline sharply. These indicators can be integrated into soil monitoring and early-warning systems.

Recommendations:

Promote soil conservation (cover crops, mulching, organic amendments)

Implement periodic soil testing linked to decision-making

Incentivize transition to regenerative practices through tea cooperatives and policy tools

Such actions will help secure the long-term viability of Vietnam's tea industry under conditions of land use intensification and climate uncertainty.

The study demonstrates a clear and progressive degradation of soil quality under long-term tea cultivation in the highland agroecosystem of Lam Dong, Vietnam. Notably, soil organic carbon(SOC), available phosphorus (P), available potassium (K), and plant-available water capacity(PAWC) declined significantly over a 20-year period. These findings are consistent with global studies that document SOC depletion and nutrient exhaustion in perennial monocultures without adequate soil conservation (Lal, 1998; Gregorich et al., 1995). The rapid decline in SOC, particularly within the first decade, can be attributed to continuous tillage, low organic matter inputs, and minimal ground cover. SOC is a fundamental determinant of multiple soil functions, including nutrient retention, aggregate stability, and water holding capacity (Reeves et al., 1997). Its decline under tea cultivation undermines the entire soil system's resilience.

6. Author Contributions

Tao Anh Khoi conceptualized and designed the study, conducted fieldwork and data collection, performed data analysis, and wrote the manuscript.

7. Conflict of Interest

The author declares no conflict of interest.

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7. Data Availability

All data supporting the findings of this study are available from the corresponding author upon reasonable request. Soil test datasets, regression analysis outputs, and field yield records are archived at Bao Loc College of Technology and Economics.

8. Author Contributions

Tao Anh Khoi: Conceptualization, Field investigation, Data analysis, Manuscript writing, Revision.

9. Competing Interests

The author declares that there are no competing interests.

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