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), 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, indicating progressive soil compaction.

A multiple regression analysis revealed that SOC, available P, total K, and PAWC were the most predictive indicators of long-term tea productivity. Cost-benefit analysis suggested that tea cultivation remains marginally profitable after 20 years, provided that adequate fertilization is maintained. This study proposes threshold values for soil quality indicators to support sustainable tea production in tropical highland systems.

Keywords: Soil degradation, Tea cultivation, Organic carbon, Nutrient availability, Soil compaction, Economic sustainability, Ferralsols.

1. Introduction

Tea (Camellia sinensis) is among the most important perennial crops globally, covering approximately 5.1 million hectares and serving as a livelihood source for millions of smallholder farmers. Vietnam ranks among the top ten tea-producing countries, with Lam Dong province recognized as a hub for high-quality green and oolong tea.

However, the long-term sustainability of tea plantations is increasingly questioned due to observed declines in yield and deteriorating soil quality. Sustained monoculture on sloping terrain, often without conservation practices, can lead to erosion, compaction, and nutrient loss—challenges well documented in other tropical cropping systems (Lal, 1998; Zhou et al., 2014).

While short-term agronomic performance has been widely studied, long-term effects on soil health and economic viability in Vietnamese highlands remain under-researched. Additionally, critical thresholds for soil indicators supporting sustainable yields are not well established.

This study addresses these gaps by assessing chemical, physical, and biological changes in soil under tea plantations aged 5, 10, and 20 years, compared with native forest controls. We used field sampling, laboratory analysis, and regression modeling to identify sensitive soil indicators and define thresholds that guide long-term tea sustainability.

2. Materials and Methods

2.1 Study Area

The study was conducted in Lam Dong province, Vietnam (11°46′N, 108°08′E), a major tea-growing region located in the Central Highlands. The area is characterized by a subtropical highland climate, with an annual average temperature of 20°C and total annual rainfall exceeding 2,000 mm, mostly concentrated in the wet season (May to October).

Altitudes at the study sites ranged from 800 to 1,500 meters above sea level. Soils are predominantly classified as Ferralsols developed from basaltic parent material, known for their low cation exchange capacity and susceptibility to degradation. Slopes ranged from 10–18%, and all sampled fields had similar topographic and edaphic conditions to minimize confounding variables.

2.2 Experimental Design and Land Management

Tea plantations of three age classes—5, 10, and 20 years—were selected for comparison with adjacent native forest sites used as undisturbed controls. Each age class was replicated in 3 to 6 fields to ensure representation.

GPS coordinates of representative plots were recorded:

Forest: 11.7683°N, 108.0621°E

5-year plantation: 11.7655°N, 108.0703°E

10-year plantation: 11.7611°N, 108.0742°E

20-year plantation: 11.7567°N, 108.0786°E

All plantations were managed using standard local practices, including mechanical harvesting. Machinery traveled between rows approximately every 7–10 days during the cropping season. Estimated ground pressure exerted on the soil surface was approximately 120 kPa, based on typical tire load and inflation pressure of field equipment.

2.3 Soil Sampling and Laboratory Analysis

Composite soil samples (n = 5 per field) were collected from three depth intervals: 0–10 cm, 10–20 cm, and 20–40 cm. Physical property measurements were performed on samples from the 0–20 cm layer.

All samples were air-dried and sieved through a 2 mm mesh before laboratory analysis. Standard procedures were used as follows:

- Soil organic carbon (SOC) and total nitrogen (N): Measured by dry combustion using a LECO CNS-2000 analyzer (Reeves et al., 1997).

- Available phosphorus (P) and potassium (K): Extracted using the Bray I method and analyzed via spectrophotometry and flame photometry, respectively.

- Total K and total P: Determined after wet digestion with H_2SO_4–H_2O_2 (Lal, 1998).

- Soil pH: Measured in a 1:1 soil-to-water suspension.

- Bulk density (BD): Determined using the core method (Topp et al., 1997).

- Plant-available water capacity (PAWC): Calculated as the difference between field capacity (measured at 0.33 bar) and permanent wilting point (15 bar) using pressure plate apparatus.

- Mechanical resistance: Evaluated with a cone penetrometer (Ehlers et al., 1983).

- Aggregate stability: Measured as mean weight diameter (MWD) via wet sieving.
- Earthworm population density: Quantified by manual extraction from 20 cm × 20 cm × 20 cm soil blocks.

All analyses were conducted at the Soil and Agrochemistry Laboratory of Lam Dong Department of Agriculture.

2.4 Crop Yield and Fertilizer Input

Tea yield (dry weight) was recorded monthly from 1 m² subplots randomly placed in each field. Fertilizer inputs were classified as:

- Adequate: ≥150 kg N, ≥80 kg P_2O_5, and ≥80 kg K_2O per hectare per year
- Inadequate: below recommended rates

To improve clarity, nutrient contents were recalculated in elemental form:

- 80 kg P_2O_5 ha^{-1} ≈ 35 kg P ha^{-1}

- 80 kg K_2O ha^{-1} ≈ 66 kg K ha^{-1}

2.5 Statistical and Economic Analyses

One-way analysis of variance (ANOVA) was performed to evaluate differences in soil properties and yield across plantation ages. Tukey's HSD post hoc tests were applied to detect pairwise differences at significance levels of $p < 0.05$ and $p < 0.01$.

Multiple linear regression was used to identify key soil quality indicators that predict tea yield. Variables with high collinearity (variance inflation factor > 5) were excluded from the final model.

Economic performance was assessed via cost-benefit analysis. Net benefit and benefit-cost ratio (BCR) were calculated from gross returns minus total input costs, including labor, fertilizer, land rent, and equipment depreciation. Threshold levels for key soil indicators were derived based on the 20-year-old plantations operating near the economic break-even point.

3. Results

3.1 Changes in Soil Chemical, Physical, and Biological Properties

Tea cultivation over a 20-year period resulted in significant changes in key soil quality indicators. Compared to native forest soils, plantation soils exhibited marked declines in soil organic carbon (SOC), available phosphorus (P), available potassium (K), total nitrogen (N), and plant-available water capacity (PAWC). These reductions were most pronounced in the surface 0–20 cm layer.
In contrast, bulk density and mechanical resistance increased significantly with plantation age, indicating progressive soil compaction. Aggregate stability, measured as mean weight diameter (MWD), and earthworm population density also decreased substantially, particularly after 10 years of continuous cultivation.All differences between control and treatment groups were statistically significant at *p* < 0.05 or *p* < 0.01.

3.2 Soil Properties Across Plantation Ages

Table 1. Soil quality indicators across tea plantation ages (0–20 cm depth).

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**	↓
Avail. P (µg g^{-1})	11.5 ± 0.6	8.4 ± 0.4*	6.9 ± 0.5**	6.0 ± 0.3**	↓
Avail. K (µg g^{-1})	18.7 ± 1.1	14.0 ± 1.3	12.1 ± 1.0*	9.8 ± 0.7**	↓
Total N (%)	0.21 ± 0.01	0.18 ± 0.01	0.15 ± 0.01*	0.12 ± 0.01**	↓
Total P (mg g^{-1})	0.82 ± 0.04	0.69 ± 0.03	0.58 ± 0.02*	0.50 ± 0.02**	↓
pH (H_2O)	5.7 ± 0.1	5.3 ± 0.1	5.1 ± 0.2	5.0 ± 0.2	↓
Bulk density (Mg m^{-3})	0.98 ± 0.04	1.10 ± 0.03*	1.22 ± 0.05**	1.33 ± 0.04**	↑
PAWC (% vol.)	14.6 ± 0.8	11.2 ± 0.5*	10.0 ± 0.6**	9.4 ± 0.4**	↓
Earthworm density (m^{-3})	22.5 ± 2.3	14.3 ± 2.1*	9.8 ± 1.8**	4.1 ± 0.7**	↓

Values are means ± standard error. Asterisks indicate significance level of difference from forest control ($p < 0.05$, ** $p < 0.01$).*

Soil quality indicators across tea plantation ages (0–20 cm depth). Values are means ± standard error. Asterisks indicate significance level of difference from forest control (* $p < 0.05$, ** $p < 0.01$).

2.3 Crop Yield Response

Tea yield declined progressively with plantation age. The 5-year-old plantations produced 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).

In the 20-year group, fields with adequate fertilizer inputs yielded significantly more (3.84 tons ha^{-1}) than inadequately fertilized fields (2.82 tons ha^{-1}), suggesting that nutrient supplementation partially compensated for declining soil fertility.

2.4 Soil–Yield Relationship

Multiple regression analysis identified four variables—SOC, available P, total K, and PAWC—as the most predictive indicators of tea yield. The final regression model explained 76.4% of yield variation (*R^2 = 0.764*, *p* < 0.001). **Regression equation:** Yield (tons ha^{-1}) = 0.141 × SOC + 0.018 × Avail. P + 0.054 × Total K + 0.090 × PAWC (*R^2* = 0.764; *p* < 0.001) Bulk density and mechanical resistance were negatively correlated with yield but excluded from the final model due to high collinearity with SOC and PAWC.

2.5 Economic Performance of Tea Plantations

Cost-benefit analysis revealed a substantial decline in economic returns after 10 years of continuous cultivation. The benefit–cost ratio (BCR) fell from 1.27 (5-year plantations) to 1.02 (20-year plantations), approaching economic break-even. Inadequately fertilized fields showed BCR values below 1.0.

Table 2. Economic Performance by Plantation Age**

Plantation Age	Yield (t ha^{-1})	Net Benefit (1,000 VND ha^{-1})	BCR
5 years	5.06	6,434	1.27
10 years	4.72	6,021	1.26
20 years	3.30	488	1.02

Critical thresholds for soil indicators (e.g., SOC = 12.1 mg g^{-1}, Avail. P = 6.0 μg g^{-1}) were identified as minimum levels needed to sustain profitable yields.

4. Discussion

4.1 Changes in Soil Quality Under Long-Term Tea Cultivation

This study reveals clear and progressive changes in soil quality indicators with increasing tea plantation age. Significant declines in SOC, available P and K, total N, and PAWC were observed after 20 years of cultivation. These results are consistent with previous findings in long-term monoculture systems on tropical soils (Lal, 1998; Zhou et al., 2014).

The reduction in SOC was particularly rapid during the first decade, likely due to frequent tillage, low organic inputs, and lack of ground cover. Since SOC is a central determinant of soil biological activity, nutrient retention, and structure (Reeves et al., 1997), its decline compromises the overall soil health and resilience.

4.2 Compaction and Soil Structural Decline

Increased bulk density and mechanical resistance, as observed in 10- and 20-year-old plantations, point to soil compaction—most likely due to repeated machinery traffic and limited organic amendments. Elevated compaction restricts root growth, impairs aeration, and reduces infiltration (Topp et al., 1997).

The accompanying decline in PAWC suggests a reduction in soil porosity and water-holding capacity, which further stresses tea plants during dry periods. These structural changes have been similarly documented in other Ferralsol-based systems under intensive cultivation (Hartemink, 2006).

4.3 Soil Fertility as a Limiting Factor to Yield

Regression analysis confirmed that SOC, available P, total K, and PAWC are the strongest predictors of tea yield. These indicators reflect both nutrient supply and physical support for root development. Notably, fields receiving adequate fertilizer inputs maintained yields similar to younger plantations, underscoring the importance of nutrient replenishment.

However, such compensation is likely temporary. In the long term, soil physical degradation may outweigh the benefits of fertilization, as nutrient cycling and moisture buffering decline.

4.4 Broader Relevance: Ferralsols and Other Cropping Systems

While the study focused on tea, the findings resonate with broader research on Ferralsols and similar weathered tropical soils (e.g., Nitisols, Acrisols). These soils are inherently fragile and prone to degradation under continuous cropping without organic matter replenishment (Craswell & Lefroy, 2001).

Research in coffee, cassava, and maize systems has shown comparable declines in soil organic matter, fertility, and structure when conservation practices are neglected. This highlights the need to incorporate cover cropping, mulching, and composting into long-term cropping strategies on such soils.

4.5 Economic Implications and Thresholds

The decline in net benefit and BCR in older plantations reflects the direct impact of soil degradation on profitability. Estimated critical thresholds—e.g., SOC = 12.1 mg g^{-1} and available P = 6.0 µg g^{-1}—represent tipping points beyond which productivity losses can no longer be economically sustained.

These thresholds serve as practical benchmarks for early intervention and targeted soil management in tea-growing regions.

4.6 Contribution to Literature

To our knowledge, this is one of the first empirical studies to jointly assess agronomic and economic thresholds of soil quality decline in highland tea systems of Southeast Asia. The integration of soil analysis, yield modeling, and profitability metrics provides a robust framework for sustainable plantation management on tropical Ferralsols.

5. Conclusion

This study provides compelling evidence that long-term tea (Camellia sinensis) cultivation on tropical Ferralsols in Lam Dong province, Vietnam, leads to substantial changes in soil quality. Key indicators—including organic carbon, available phosphorus and potassium, total nitrogen, and plant-available water capacity—deteriorate progressively with plantation age.

These changes are closely associated with declines in tea yield and profitability. While adequate fertilization can temporarily offset yield reductions, it does not prevent underlying structural degradation. Regression analysis and economic evaluation reveal that tea productivity begins to decline significantly after 10–15 years of cultivation, with 20-year plantations approaching economic break-even.

Critical threshold levels were established for key soil properties, providing a practical framework for monitoring and early intervention. These findings emphasize the urgent need for improved soil management practices—including organic matter restoration, reduced compaction, and tailored nutrient inputs—to sustain long-term productivity and profitability in tea agroecosystems.

Future research should explore the effectiveness of integrated soil conservation measures such as cover cropping, composting, and reduced tillage to rehabilitate degraded tea soils.

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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