https://doi.org/10.5194/egusphere-2025-2048
Preprint. Discussion started: 27 May 2025

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

Ph.D. Tao Anh Khoi

Bao Loc College of Techology and Economics, Lam Dong province, Vietnam

ORCID: https://orcid.org/0009-0008-7250-6920

Email: anhkhoibaoloc@gmail.com

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, 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. 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

https://doi.org/10.5194/egusphere-2025-2048
Preprint. Discussion started: 27 May 2025

Tea (Camellia sinensis) is among the most important perennial crops globally, occupying approximately 5.1 million hectares and serving as a livelihood source for millions of smallholder farmers in tropical and subtropical regions. Vietnam ranks among the top ten tea-producing countries, with the Central Highlands province of Lam Dong known as a national hub for high-quality green and oolong tea production. However, the long-term sustainability of tea plantations in the region is increasingly being questioned due to observable declines in crop productivity and deteriorating soil conditions.

Sustained monoculture cultivation, particularly on sloping terrain, poses serious threats to soil health. Tea plantations are often established by clearing forest land, followed by intensive cultivation with limited adoption of conservation practices. This leads to erosion, nutrient depletion, and soil compaction. The decline in soil quality, in turn, affects crop performance and economic returns, especially in older plantations.

Despite the growing concerns, empirical studies quantifying the long-term effects of tea cultivation on soil quality in Vietnam remain limited. Prior research has predominantly focused on short-term agronomic performance, with little attention given to soil degradation processes or their economic implications over time. Moreover, critical thresholds for soil parameters that support sustainable tea yields in highland agroecosystems have not been adequately established.

This study addresses these gaps by assessing changes in chemical, physical, and biological soil indicators in tea plantations of varying ages (5, 10, and 20 years), compared to undisturbed forest soils. Using field sampling, laboratory analyses, and regression modeling, we identify the most sensitive soil quality indicators and quantify their relationships with tea yield and economic performance. The study further proposes critical levels of these indicators to guide sustainable tea management and offers evidence-based recommendations for mitigating soil degradation in tropical highland tea systems.

2. Materials and Methods

2.1. Study Area

The study was conducted in Lam Dong province, located in the Central Highlands of Vietnam (11°46’N, 108°08’E). The region is characterized by a subtropical highland climate with an annual

https://doi.org/10.5194/egusphere-2025-2048
Preprint. Discussion started: 27 May 2025

average temperature of 20°C and annual rainfall exceeding 2,000 mm, distributed unevenly across the year. The terrain is predominantly sloped, with altitudes ranging from 800 to 1,500 meters above sea level, and soils are primarily Ferralsols derived from basaltic parent material.

2.2. Experimental Design

Tea plantations of three age groups—5, 10, and 20 years—were selected, alongside adjacent native forest sites serving as reference controls. Each age class was replicated in 3 to 6 fields across comparable topographic and edaphic conditions. Field selection accounted for uniform management practices and slope gradients to reduce confounding variability.

2.3. Soil Sampling and Analysis

Composite soil samples (n = 5 per field) were collected at three depth intervals: 0–10 cm, 10–20 cm, and 20–40 cm. Physical analyses were conducted on samples from the 0–20 cm depth. Samples were air-dried, sieved (<2 mm), and analyzed using standard methods. Parameters included:

- Soil organic carbon (SOC) and total N, S: Measured via dry combustion using a LECO CNS-2000 analyzer.
- Available P and K: Extracted using Bray I method and determined by spectrophotometry and flame photometry, respectively.
- Total K and P: Measured after wet digestion with H_2SO_4–H_2O_2.
- Soil pH: Measured in a 1:1 soil-water suspension.
- Bulk density: Determined using the core method.
- Plant-available water capacity (PAWC): Calculated as the difference between field capacity and permanent wilting point using pressure plates.
- Mechanical resistance: Assessed using a cone penetrometer.
- Aggregate stability (MWD): Determined through wet sieving.
- Earthworm population: Quantified by manual extraction from 0–20 cm soil blocks.

https://doi.org/10.5194/egusphere-2025-2048
Preprint. Discussion started: 27 May 2025

2.4. Crop Yield and Fertilizer Input

Tea yield (dry weight) was recorded monthly on 1 m^2 subplots randomly located within each field. Fertilizer input data were collected from farmers and classified into two categories: (i) adequate (≥150 kg N, 80 kg P_2O_5, 80 kg K_2O ha^{-1} yr^{-1}), and (ii) inadequate (< recommended rates).

2.5. Statistical and Economic Analyses

Analysis of variance (ANOVA) was used to evaluate differences in soil properties and yield among tea plantation ages, followed by post-hoc contrast analysis. Multiple linear regression was employed to identify the most influential soil indicators on yield. Variables with high multicollinearity (Variance Inflation Factor > 5) were excluded.

Cost-benefit analysis was conducted to assess economic sustainability. Total input costs (including labor, fertilizers, land rental, and equipment depreciation) were subtracted from gross revenue to calculate net benefit and the benefit-cost ratio (BCR). Threshold levels for key soil indicators were defined based on the 20-year-old plantations operating near economic break-even.

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 the surface 0–20 cm soil layer.

In contrast, bulk density and soil mechanical resistance increased significantly with plantation age, 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).

https://doi.org/10.5194/egusphere-2025-2048
Preprint. Discussion started: 27 May 2025

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)

3.2. Crop Yield Response

Tea yield declined significantly with increasing plantation age. The 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.

https://doi.org/10.5194/egusphere-2025-2048
Preprint. Discussion started: 27 May 2025

Regression Equation:

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

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

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 2. Economic performance of tea plantations by 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

4. Discussion

4.1. Soil Quality Decline Under Long-Term Tea Cultivation

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).

https://doi.org/10.5194/egusphere-2025-2048
Preprint. Discussion started: 27 May 2025

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.

4.2. Soil Compaction and Water Dynamics

Increasing bulk density and mechanical resistance observed in older plantations are indicators of soil compaction—likely resulting from mechanized field operations and the absence of organic amendments. Elevated bulk density limits root proliferation, reduces infiltration, and impairs gas exchange, leading to physiological stress in tea plants (Topp et al., 1997). Although soil resistance did not directly enter the final regression model, its rise with plantation age aligns with known thresholds for root restriction reported in various crops (Ehlers et al., 1983).

The concurrent decrease in PAWC and porosity suggests that soil structure deteriorated due to both loss of organic matter and increased compaction. These structural shifts reduce the soil's ability to buffer moisture fluctuations, thus exacerbating drought stress during dry seasons—especially in highland climates with uneven rainfall distribution.

4.3. Soil Fertility as a Limiting Factor to Yield

Regression results highlight SOC, available P, total K, and PAWC as the strongest predictors of yield in long-term tea plantations. These variables are interrelated: for instance, lower SOC reduces microbial activity and nutrient cycling, while declining PAWC limits nutrient mobility in the root zone.

The sharp drop in yield from 5- to 20-year-old plantations—despite constant inputs in some cases—indicates that soil fertility becomes a yield-limiting factor beyond 10–15 years of continuous cultivation. However, fields with adequate fertilizer inputs maintained yields closer to 10-year levels, suggesting that supplemental nutrition can temporarily compensate for soil degradation. This finding aligns with previous research in China and India where balanced fertilization delayed productivity declines in aged tea fields (Zhou et al., 2014; Baruah et al., 2010).

https://doi.org/10.5194/egusphere-2025-2048
Preprint. Discussion started: 27 May 2025

4.4. Economic Implications and Thresholds

The decline in economic returns, as reflected by reduced net benefits and BCR values in 20-year-old plantations, supports the hypothesis that soil degradation directly undermines profitability. The estimated "critical levels" of key soil indicators—such as 12.09 mg g^{-1} for SOC and 6.02 µg g^{-1} for available P—correspond to the minimum levels required for economic sustainability. These thresholds can serve as early warning benchmarks for intervention in tea-growing regions.

Importantly, the study reveals that economic sustainability does not only depend on yield quantity but also on input efficiency. Plantations with sub-optimal fertilization experienced both yield and profit losses, while those with balanced inputs remained viable despite soil aging. This has policy implications for extension programs promoting site-specific nutrient management.

4.5. Contribution to the Literature

To the best of our knowledge, this is the first study to quantify both the agronomic and economic thresholds of soil quality degradation in a tropical highland tea system using empirical data and regression modeling. While previous work has highlighted the qualitative impacts of soil degradation on tea, this study provides critical quantitative benchmarks and integrates them into a decision-support framework for long-term sustainability.

5. Conclusion

This study provides compelling evidence that long-term tea (Camellia sinensis) cultivation in the highland region of Lam Dong, Vietnam leads to substantial degradation in soil quality. Key soil indicators—including organic carbon, available phosphorus and potassium, and plant-available water capacity—deteriorate significantly with plantation age, directly reducing crop productivity and economic viability.

The integration of agronomic data, regression modeling, and cost-benefit analysis revealed that tea yields and profits begin to decline significantly after 10 years of cultivation, reaching near break-even levels by year 20. However, adequate fertilization can partially offset the negative effects of long-term cultivation, extending the economic lifespan of plantations.

https://doi.org/10.5194/egusphere-2025-2048
Preprint. Discussion started: 27 May 2025

Critical threshold values for essential soil indicators were established, providing a practical decision-support tool for farmers and policymakers. These findings emphasize the urgent need for proactive soil fertility management, organic matter restoration, and integrated conservation practices to maintain both productivity and profitability in tea-growing regions. Future work should explore soil restoration strategies and the integration of organic amendments or cover cropping in older tea plantations.

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.

8. References

1. Baruah, T. C., & Das, M. (2010). Fertility status of tea garden soils in Barak Valley of Assam. Agropedology, 20, 27–34.

2. Ehlers, W., Köpke, U., Hesse, F., & Böhm, W. (1983). Penetration resistance and root growth of oats in tilled and untilled loess soil. Soil & Tillage Research, 3, 261–275.

3. Gregorich, E. G., Angers, D. A., Campbell, C. A., et al. (1995). Changes in soil organic matter. In: Acton, D.F. & Gregorich, E.G. (eds.), The Health of Our Soils: Toward Sustainable Agriculture in Canada, Agriculture Canada, pp. 23–50.

4. Lal, R. (1998). Soil quality and agricultural sustainability. In: Lal, R. (ed.), Soil Quality and Agricultural Sustainability, Sleeping Bear Press, Michigan, USA, pp. 3–13.

5. Reeves, D. W., Domzal, H., & Rejman, J. (1997). The role of soil organic matter in maintaining soil quality in continuous cropping systems. In: Proceedings of the XIV ISTRO Conference, Pulawy, Poland. Soil & Tillage Research, 43, 131–167.

6. Topp, G. C., Reynolds, W. D., Kirby, J. M., & Carter, M. R. (1997). Physical attributes of soil quality. In: Gregorich, E.G. & Carter, M.R. (eds.), Soil Quality for Crop Production and Ecosystem Health, Elsevier, pp. 21–52.

7. Zhou, Q., Wang, S., & Zhang, Y. (2014). Effects of long-term tea plantation on soil nutrients and heavy metals in China. Environmental Monitoring and Assessment, 186(10), 6405–6416. https://doi.org/10.1007/s10661-014-3872-6