# 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 one of the most important perennial crops worldwide, cultivated on more than 5.1 million hectares and providing livelihoods for millions of smallholder farmers (FAO, 2023). Vietnam ranks among the top ten tea-producing countries, with Lam Dong province recognized for high-quality green and oolong teas (Vietnam Tea Association, 2022). However, the long-term sustainability of tea plantations is increasingly questioned due to observed declines in yield and deterioration of soil quality. Continuous monoculture on sloping terrain, often without soil conservation practices, has been linked to erosion, compaction, and nutrient loss in tropical systems (Lal, 1998; Zhou et al., 2014; Chen et al., 2021).

Numerous studies in China, India, and Kenya have documented soil acidification, organic carbon decline, and nutrient depletion under long-term tea cultivation (Li et al., 2019; Das et al., 2020; Wachira et al., 2017). For example, SOC was reported to decrease by 25–30% within two decades of continuous tea monoculture in southern China (Li et al., 2019), while similar declines in nutrient availability were observed in Indian and Kenyan plantations (Das et al.,

45  2020; Wachira et al., 2017). These findings highlight the fragility of Ferralsols and Nitisols
46  under intensive management, emphasizing the need for better soil stewardship.
47  Nevertheless, empirical evidence from Southeast Asia, particularly Vietnam, remains scarce,
48  despite the country's growing role in global tea production.

49  Existing Vietnamese studies have focused primarily on short-term yield responses or
50  fertilizer management strategies (Nguyen et al., 2021), while systematic assessments of long-
51  term soil quality dynamics and their economic implications are lacking. In particular, critical
52  thresholds for soil indicators that sustain both yield and profitability under continuous tea
53  cultivation are poorly defined.

54  This study addresses these knowledge gaps by evaluating chemical, physical, and biological
55  changes in soils under tea plantations aged 5, 10, and 20 years in Lam Dong province,
56  compared with native forest controls. Specifically, we aimed to: (i) quantify changes in soil
57  organic carbon, nutrient availability, bulk density, plant-available water capacity, aggregate
58  stability, and earthworm populations across plantation ages; (ii) identify key soil indicators
59  most predictive of tea yield through regression analysis; and (iii) propose threshold values
60  of soil quality parameters that support sustainable tea production in tropical highland
61  systems.

62  **2. Materials and Methods (Revised Draft)**

63  **2.1 Study Area**

64  The study was conducted in Bao Loc district, Lam Dong province, Vietnam (11°32′–11°36′ N,
65  107°42′–107°47′ E), located at an elevation of 850–950 m. The region is characterized by a
66  tropical monsoon climate with an annual rainfall of 2,300–2,500 mm, mean temperature of
67  21–22 °C, and Ferralsols derived from basalt. Four land-use types were selected: native
68  evergreen forest (control), and tea plantations cultivated for 5, 10, and 20 years. Each plot
69  measured 0.5 ha, with GPS coordinates recorded for all sites.

70  **2.2 Experimental Design and Soil Sampling**

71  In each land-use type, five subplots were established, and composite soil samples (0–20 cm)
72  were collected using an auger at five random points per subplot. Bulk density was measured
73  using the core method (Topp et al., 1997). Plant-available water capacity (PAWC) was
74  determined with a pressure plate apparatus at 0.33 bar (field capacity) and 15 bar
75  (permanent wilting point). Soil mechanical resistance was measured with a cone
76  penetrometer (Ehlers et al., 1983).

77  **2.3 Soil Chemical and Biological Analyses**

78  SOC and total N were determined by dry combustion using an Elementar analyzer (Reeves et
79  al., 1997). Total P and K were analyzed after $H_2SO_4$–$HClO_4$ digestion (Lal, 1998). Available P
80  was extracted using the Bray-1 method, and available K was determined by ammonium
81  acetate extraction (Jackson, 1973). Soil pH was measured in a 1:2.5 soil-to-water suspension.

82  Earthworm populations were estimated by hand-sorting from 0.25 m$^2$ × 20 cm deep soil
83  monoliths.

84  **2.4 Fertilizer Management**

85  Fertilizer input was categorized into two levels based on farmer practices:

86  (i) Adequate fertilization: ~150 kg N ha$^{-1}$, 35 kg P ha$^{-1}$, 66 kg K ha$^{-1}$ year$^{-1}$.

87  (ii) Inadequate fertilization: <100 kg N ha$^{-1}$, <20 kg P ha$^{-1}$, <40 kg K ha$^{-1}$ year$^{-1}$.

88  Nutrient contents are expressed as % element rather than oxide forms, in accordance with
89  reviewer suggestions.

90  **2.5 Crop Yield and Economic Analysis**

91  Fresh leaf yield was measured from ten randomly selected bushes per subplot and scaled to
92  per-hectare yields. Economic analysis was based on farm-gate prices, production costs
93  (fertilizer, labor, mechanization), and calculated net benefit and benefit–cost ratio (BCR).

94  **2.6 Statistical Analysis**

95  One-way ANOVA with Tukey's post hoc test was applied to detect differences among land-
96  use types. Regression analysis was used to identify soil indicators predictive of yield.
97  Statistical significance was set at $p < 0.05$.

98  **3. Results**
99  **3.1 Changes in Soil Properties**

100  Table 1 presents the chemical, physical, and biological soil indicators across plantation ages
101  and the forest control.

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

| Indicator | Forest | 5 years | 10 years | 20 years | Direction |
|---|---|---|---|---|---|
| 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$_2$O) | 5.7 ± 0.1 | 5.3 ± 0.1 | 5.1 ± 0.2 | 5.0 ± 0.2 | ↓ |

| Indicator | Forest | 5 years | 10 years | 20 years | Direction |
|---|---|---|---|---|---|
| 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 ± SE. Asterisks indicate significance level compared with forest control ( $p <$ 0.05, ** $p < 0.01$).*

Analysis:

SOC showed a progressive decline of ~48% after 20 years, reflecting loss of organic matter inputs and accelerated decomposition under monoculture. Available P and K decreased by nearly half, suggesting nutrient mining and insufficient replenishment through fertilization. The decline in PAWC (−36%) indicates deteriorating soil structure and porosity, while the ~82% reduction in earthworm populations highlights severe biological degradation. These findings are consistent with reports from China (Li et al., 2019) and India (Das et al., 2020), but the magnitude of change in Lam Dong appears stronger, reflecting the fragility of Ferralsols under intensive management.

**3.2 Crop Yield**

**Table 2. Tea yield under different plantation ages and fertilizer inputs.**

| Plantation Age | Yield (t ha$^{-1}$) | Adequate Fertilization | Inadequate Fertilization |
|---|---|---|---|
| 5 years | 5.06 | 5.20 | 4.91 |
| 10 years | 4.72 | 4.95 | 4.50 |
| 20 years | 3.30 | 3.84 | 2.82 |

Analysis:

Tea yield declined steadily with plantation age (−35% from 5 to 20 years). Adequate fertilization consistently improved yields compared with inadequate fertilization, particularly at 20 years where the difference reached +1.02 t ha$^{-1}$. However, even with sufficient fertilization, yields at 20 years remained significantly lower than at 5 years, indicating that soil degradation outweighed fertilizer effects. This aligns with long-term studies in Kenya showing declining productivity despite fertilizer application (Wachira et al., 2017).

**3.3 Soil–Yield Relationships**

125 **Table 3. Regression model predicting tea yield from soil indicators.**

| Predictor | Coefficient | Std. Error | p-value |
|---|---|---|---|
| SOC | 0.141 | 0.031 | <0.001 |
| Avail. P | 0.018 | 0.006 | 0.004 |
| Total K | 0.054 | 0.020 | 0.012 |
| PAWC | 0.090 | 0.027 | 0.001 |

126 Model $R^2$ = 0.764; p < 0.001.

127 Analysis:

128 The regression model explained 76.4% of yield variation, confirming that SOC, available P,
129 total K, and PAWC are key drivers of productivity. SOC had the strongest effect, indicating its
130 central role in maintaining soil fertility, nutrient cycling, and water retention. The
131 significance of PAWC emphasizes that soil physical properties, not only chemical fertility, are
132 critical for sustaining yields. Bulk density and mechanical resistance were excluded due to
133 collinearity, but their indirect impacts on SOC and PAWC cannot be ignored.

134 **3.4 Economic Performance**

135 **Table 4. Economic performance of tea plantations by age.**

| Plantation Age | Net Benefit (1,000 VND ha$^{-1}$) | BCR |
|---|---|---|
| 5 years | 6,434 | 1.27 |
| 10 years | 6,021 | 1.26 |
| 20 years | 488 | 1.02 |

136 Analysis:

137 Economic returns declined drastically with plantation age. Net benefit at 20 years was
138 reduced by >90% compared with 5-year plantations, and the BCR dropped close to unity,
139 indicating that continued cultivation at this stage provides minimal financial advantage.
140 These results highlight the need for soil management interventions before plantations reach
141 20 years to avoid economic unsustainability. Comparable studies in China also reported
142 declining profitability after 15–20 years due to soil fertility loss (Zhou et al., 2014).

143 **4. Discussion**

## 4.1 Soil degradation under long-term tea monoculture

The study demonstrated that tea monoculture significantly reduced soil fertility, physical quality, and biological activity compared with native forest. After 20 years of continuous cultivation, SOC declined by nearly 48%, available P and K by ~48%, and earthworm populations by ~82%. These results corroborate findings from China (Li et al., 2019; Chen et al., 2021), India (Das et al., 2020), and Kenya (Wachira et al., 2017), where long-term tea cultivation similarly depleted SOC and nutrients. However, the magnitude of decline in Lam Dong appears more severe, reflecting both the fragility of Ferralsols and the steep slopes common in the Vietnamese highlands.

## 4.2 Soil physical degradation and biological decline

Increased bulk density ($0.98 \rightarrow 1.33$ Mg m$^{-3}$) and reduced PAWC ($14.6 \rightarrow 9.4\%$) indicate structural deterioration, likely driven by frequent mechanized operations (~120 kPa ground pressure) and low organic matter return. This is consistent with studies on Ferralsols in Brazil and Indonesia, which highlight their susceptibility to compaction and water stress under intensive use (Craswell & Lefroy, 2001; Hartemink, 2006). The sharp decline in earthworm density confirms the loss of soil biological resilience, which further exacerbates poor aggregation and nutrient cycling.

## 4.3 Linking soil quality with yield performance

Regression analysis revealed SOC, available P, total K, and PAWC as the strongest predictors of yield ($R^2 = 0.764$). SOC contributed 0.141 t ha$^{-1}$ per mg g$^{-1}$, underscoring its role in nutrient supply, moisture retention, and soil structure. Similar associations have been reported in Chinese and Kenyan tea systems (Li et al., 2019; Wachira et al., 2017). Bulk density was excluded due to collinearity, but its indirect effects on SOC and PAWC highlight the importance of maintaining favorable soil structure.

## 4.4 Economic implications and sustainability thresholds

Declining soil fertility directly translated into reduced economic returns. Net benefits dropped from $6{,}434 \times 10^3$ VND ha$^{-1}$ at 5 years to only $488 \times 10^3$ VND ha$^{-1}$ at 20 years, with the BCR approaching unity. This suggests that without intervention, plantations older than 20 years are no longer economically viable. Threshold values identified in this study—SOC $\approx$ 12 mg g$^{-1}$ and available P $\approx$ 6 µg g$^{-1}$—represent critical limits below which both yield and profitability collapse. These thresholds provide practical benchmarks for monitoring soil health in tropical tea systems.

## 4.5 Management recommendations

The findings highlight the urgent need for improved soil management strategies in Vietnamese tea plantations. Potential interventions include: (i) organic matter amendments (compost, green manure), (ii) cover cropping to reduce erosion and enhance SOC, (iii) reduced mechanization to limit compaction, and (iv) balanced nutrient application tailored

181  to site-specific conditions. Such measures have proven effective in rehabilitating degraded
182  tea soils in China and India (Das et al., 2020; Chen et al., 2021).

183  **5. Conclusion**

184  This study demonstrated that long-term tea (Camellia sinensis) cultivation on Ferralsols in
185  Lam Dong province, Vietnam, leads to severe soil degradation and declining economic
186  returns. After 20 years of monoculture, SOC declined by ~48% (23.4 → 12.1 mg g$^{-1}$), available
187  P and K by ~48%, PAWC by ~36% (14.6 → 9.4%), and earthworm density by ~82% (22.5 →
188  4.1 m$^{-3}$), while bulk density increased by ~36% (0.98 → 1.33 Mg m$^{-3}$). These changes
189  corresponded to yield reductions from 5.06 to 3.30 t ha$^{-1}$ and a drop in benefit–cost ratio
190  from 1.27 to 1.02.

191  Regression analysis confirmed SOC, available P, total K, and PAWC as the strongest predictors
192  of yield ($R^2$ = 0.764), with critical thresholds identified at SOC ≈ 12 mg g$^{-1}$ and available P ≈
193  6 µg g$^{-1}$. Beyond these thresholds, both yield and profitability collapse.

194  To sustain tea productivity in tropical highlands, integrated soil management is essential,
195  including organic matter addition, cover crops, reduced mechanization, and balanced
196  nutrient inputs. The threshold values identified here provide practical benchmarks for
197  monitoring and managing soil quality in Vietnamese tea plantations and similar
198  agroecosystems.

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