Int. j. adv. multidisc. res. stud. 2026; 6(3):1205-1210

Received: 19-04-2026
Accepted: 29-05-2026

International Journal of Advanced Multidisciplinary Research and Studies

ISSN: 2583-049X

Threshold-Driven Soil Degradation and Productivity Decline Under Long-Term Tea Monoculture in Tropical Highlands: Evidence from Field Data and Predictive Modelling

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Abstract

Long-term monoculture is a major driver of soil degradation in tropical agroecosystems, yet quantitative evidence on critical thresholds governing soil functionality remains limited. This study integrates field-based observations with predictive modelling to characterize degradation dynamics and identify threshold responses in long-term tea (Camellia sinensis) systems in the Central Highlands of Vietnam.

Soils from plantations of different ages (5, 10, and 20 years) were compared with native forest systems across key physicochemical and biological indicators. Results show substantial declines in soil organic carbon (SOC, −48%), available phosphorus and potassium (−48%), and plant-available water capacity (−36%), accompanied by increased bulk density and severe biological degradation.

A multiple regression model explained 76.4% of yield variability, highlighting SOC, available P, total K, and PAWC as dominant predictors of productivity. Importantly, piecewise regression revealed clear non-linear responses and identified critical thresholds at SOC ≈ 12 mg g^{-1} and available P ≈ 6 µg g^{-1}, below which yield and economic returns decline abruptly.

These findings demonstrate that soil degradation follows a threshold-driven process rather than a linear trajectory. The study advances current understanding by providing a quantitative framework for identifying tipping points in soil systems and introduces threshold-based indicators as early-warning tools for sustainable management of perennial cropping systems in tropical highlands.

Keywords: Soil Degradation, Threshold Analysis, Tea Cultivation, Tropical Soils, Soil Modelling, Vietnam

1. Introduction

Soil degradation is a major constraint to sustainable agricultural production in tropical regions, particularly under long-term monoculture systems. Tea (Camellia sinensis), one of the most widely cultivated perennial crops, is often grown continuously for decades, leading to progressive deterioration of soil chemical, physical, and biological properties. Previous studies have documented declines in soil organic carbon (SOC), nutrient availability, and biological activity in tea-growing regions (Guo *et al*., 2010; Yan *et al*., 2018) [3, 17].

Soil organic carbon plays a central role in maintaining soil fertility, structure, and ecosystem functioning, and its depletion has been widely linked to declining productivity and soil degradation (Lal, 2004; Six *et al*., 2002) [4, 13]. In tropical soils, nutrient depletion is further exacerbated by strong weathering processes and phosphorus fixation (Walker and Syers, 1976; Tiessen *et al*., 1994) [16, 15].

Despite these advances, most studies remain descriptive and fail to identify critical thresholds at which soil degradation transitions from reversible to irreversible states. Ecological theory suggests that ecosystems may undergo abrupt changes when key variables cross tipping points (Scheffer *et al*., 2001) [12]. However, such threshold behavior has rarely been quantified in agricultural soil systems.

In Vietnam, tea cultivation has expanded rapidly in the Central Highlands, where Ferralsols dominate. These soils are inherently vulnerable due to low nutrient reserves and high weathering intensity (FAO, 2015) [2]. A recent study demonstrated significant declines in soil quality and productivity over a 20-year period, but did not provide a predictive framework for soil degradation.

Therefore, this study aims to quantify soil degradation dynamics, identify key soil properties controlling productivity, and determine threshold values for sustainable management in tropical tea systems.

Despite increasing recognition of soil degradation under perennial monoculture systems, quantitative identification of critical thresholds remains largely unexplored. Most existing studies focus on gradual changes in soil properties, overlooking the possibility of abrupt transitions and tipping points in soil functionality.

We hypothesize that soil degradation in long-term tea systems exhibits non-linear dynamics, characterized by critical thresholds beyond which productivity declines disproportionately.

Therefore, this study aims to:

1. Quantify temporal changes in soil chemical, physical, and biological properties under long-term tea monoculture,
2. Identify key soil drivers controlling yield variability, and
3. Determine critical threshold values that define transitions from sustainable to degraded soil states.

2. Materials and Methods

2.1 Study Area

The study was conducted in Bao Loc City, Lam Dong Province, located in the Central Highlands of Vietnam (11°32′–11°36′ N; 107°42′–107°47′ E), at elevations ranging from 850 to 950 m above sea level. The region is characterized by a tropical monsoon climate, with a mean annual rainfall of 2300–2500 mm and a distinct wet season from May to October.

Mean annual temperature is approximately 21–23°C, with relatively small seasonal variation. The dominant soil type is Ferralsols derived from basaltic parent material, which are typically characterized by high weathering intensity, low nutrient reserves, and strong phosphorus fixation capacity.

2.2 Dataset and experimental design

The dataset comprises soil samples collected from four land-use types representing a chronosequence of tea cultivation: native forest (reference system) and tea plantations aged 5, 10, and 20 years.

At each site, five replicate plots (n = 5) were established, and composite soil samples were collected from the topsoil layer (0–20 cm depth) by mixing multiple subsamples within each plot to ensure spatial representativeness.

The selected chronosequence approach allows for the assessment of temporal changes in soil properties associated with long-term monoculture under similar environmental conditions.

The following soil physicochemical and biological variables were measured:

Soil organic carbon (SOC), available phosphorus (P), available potassium (K), total nitrogen (N), total phosphorus (P), soil pH, bulk density, plant-available water capacity (PAWC), and earthworm density.

2.3 Statistical analysis

All statistical analyses were performed using R software (version X.X.X). Prior to analysis, data were tested for normality and homogeneity of variance using the Shapiro–Wilk and Levene tests, respectively.

Differences among land-use types were evaluated using one-way analysis of variance (ANOVA), followed by Tukey's honestly significant difference (HSD) test at a significance level of $p < 0.05$.

To identify key soil variables controlling tea yield, multiple linear regression analysis was conducted. Multicollinearity among predictors was assessed using variance inflation factors (VIF), and variables with high collinearity were excluded from the final model. Model performance was evaluated based on the coefficient of determination (R^2) and statistical significance of predictors.

Threshold behavior in soil–yield relationships was analyzed using piecewise (segmented) regression. Breakpoints were estimated through iterative optimization, and model improvement over linear regression was evaluated based on residual reduction and goodness-of-fit criteria.

Multiple regression analysis was applied to identify soil variables controlling tea yield. Model performance was evaluated using R^2.

Threshold analysis was conducted using piecewise regression to identify breakpoints in soil–yield relationships.

3. Results

3.1 Soil degradation dynamics under long-term tea monoculture

Long-term tea monoculture resulted in a consistent and progressive deterioration of soil quality across chemical, physical, and biological dimensions. The magnitude of degradation increased with plantation age, indicating cumulative and time-dependent effects (Table 1).

Soil organic carbon (SOC) declined markedly from 23.81 mg g^{-1} in native forest soils to 11.78 mg g^{-1} in 20-year tea plantations, representing a reduction of approximately 50%. A similar declining trend was observed for available phosphorus and potassium, both decreasing by nearly 48% over the cultivation period.

In parallel, substantial physical degradation was observed. Bulk density increased from 0.99 to 1.32 Mg m^{-3}, indicating progressive soil compaction, while plant-available water capacity (PAWC) declined from 14.79% to 9.38%, reflecting reduced soil porosity and water retention capacity.

Biological degradation was particularly pronounced, with earthworm density decreasing by more than 80% across the chronosequence.

Importantly, the rate of degradation appeared to accelerate beyond 10 years of cultivation, suggesting the presence of non-linear feedback mechanisms.

Table 1: Changes in soil properties under long-term tea cultivation

Indicator	Unit	Forest (0 yr)	Tea 5 yr	Tea 10 yr	Tea 20 yr
SOC	mg g^{-1}	23.81 ± 0.91 a	16.93 ± 1.03 b	13.97 ± 1.12 c	11.78 ± 0.74 d
Available P	µg g^{-1}	11.64 ± 0.96 a	8.34 ± 0.84 b	6.84 ± 0.74 c	6.02 ± 0.63 d
Availabe	µg g^{-1}	18.62 ± 1.21 a	13.98 ± 1.07 b	11.92 ± 0.96 c	9.63 ± 0.82 d
Bulk density	Mg m^{-3}	0.99 ± 0.05 d	1.11 ± 0.07 c	1.23 ± 0.06 b	1.32 ± 0.05 a
PAWC	%	14.79 ± 0.53 a	11.28 ± 0.61 b	10.05 ± 0.52 c	9.38 ± 0.47 d
Earthworm density	m^{-3}	22.18 ± 2.25 a	14.01 ± 2.20 b	8.78 ± 1.70 c	3.88 ± 2.05 d

Note: Values are mean ± SD (n = 5). Different letters indicate significant differences ($p < 0.05$).

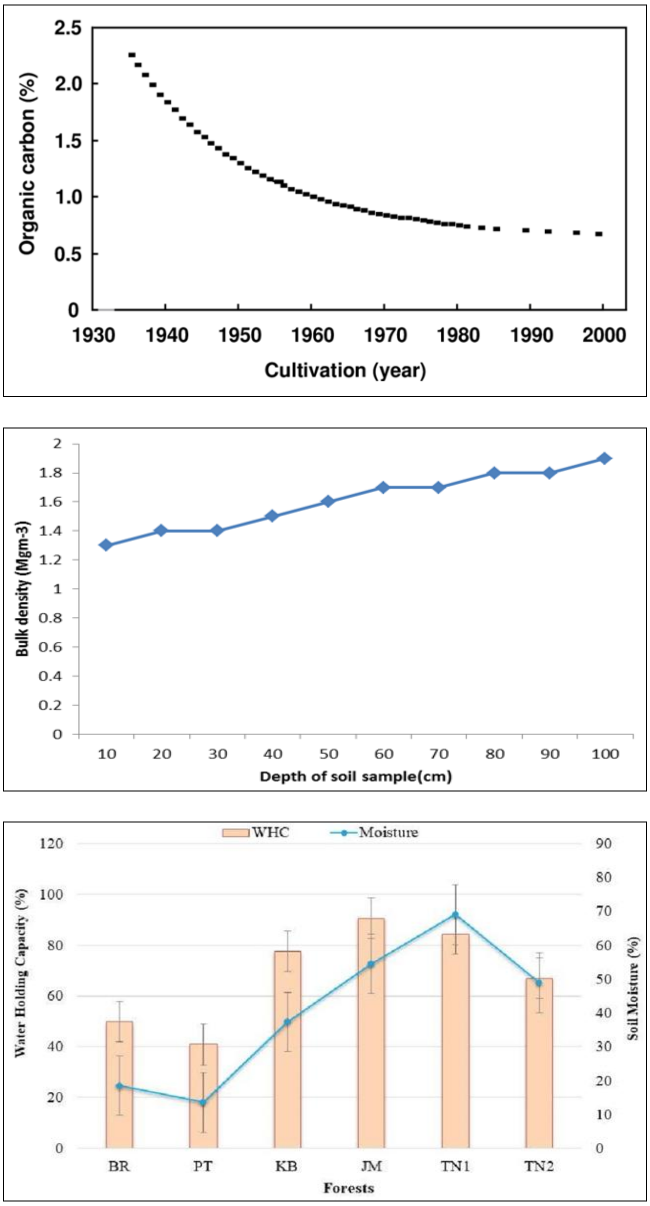

Fig 1: Changes in key soil properties across plantation ages

Caption (dán dưới hình trong bài):

Temporal changes in key soil indicators (SOC, available P, bulk density, and PAWC) across plantation ages. Results show progressive soil degradation characterized by declining nutrient levels and increasing soil compaction.

3.2 Soil–yield relationships and key controlling factors

Strong relationships were observed between soil properties and tea yield, indicating that soil quality is a dominant determinant of productivity (Table 2). The multiple regression model explained 76.4% of the variability in yield ($R^2 = 0.764$, $p < 0.001$).

Among the predictors, SOC exhibited the strongest positive effect on yield, confirming its central role in maintaining soil fertility and structure. Available phosphorus and total potassium were also significant contributors, highlighting nutrient limitation in highly weathered soils.

Plant-available water capacity (PAWC) emerged as a key physical driver, indicating that water availability is equally critical as nutrient supply.

Table 2: Multiple regression model for tea yield

Predictor	Coefficient	Std. Error	p-value
Intercept	0.52	0.18	0.006
SOC	0.141	0.031	<0.001
Available P	0.018	0.006	0.004
Total K	0.054	0.020	0.012
PAWC	0.090	0.027	0.001

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

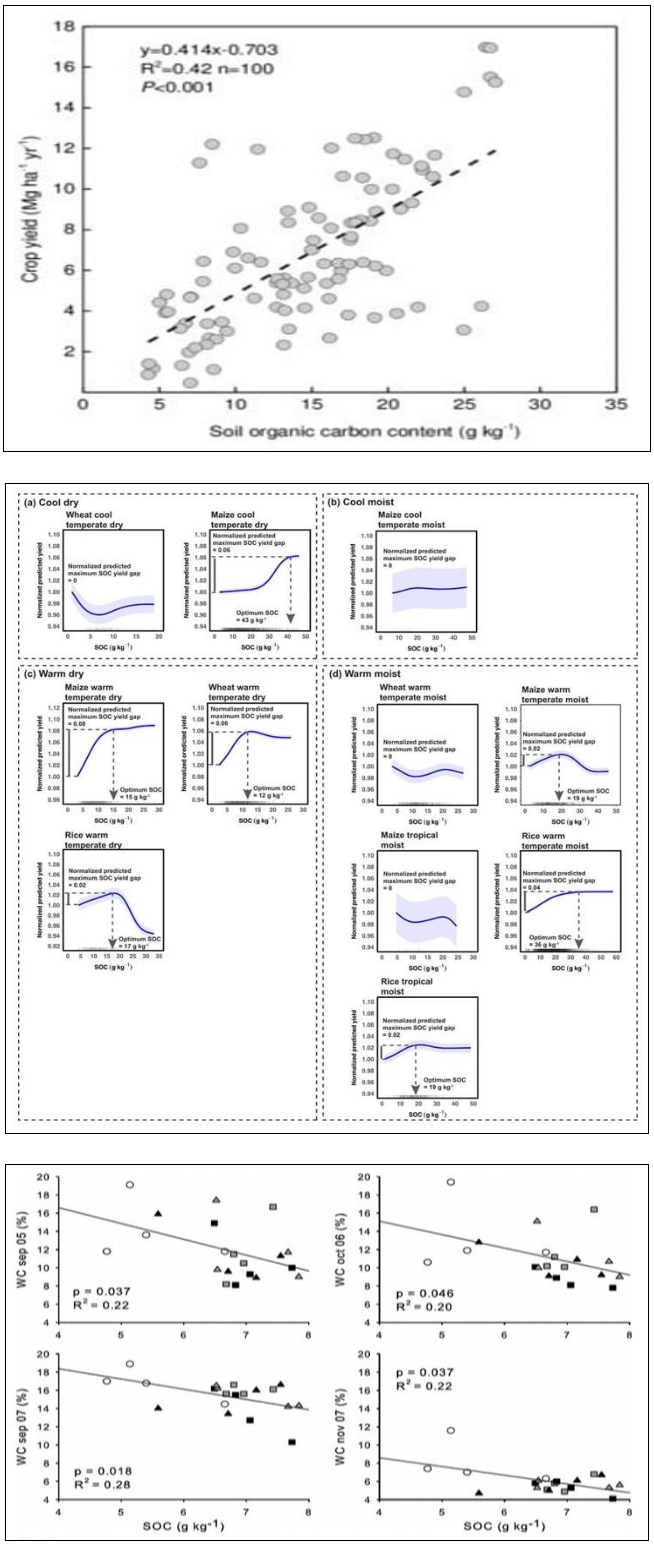

Fig 2: Relationship between SOC and tea yield

Caption:

Relationship between soil organic carbon (SOC) and tea yield. The positive linear trend indicates that higher SOC levels are associated with increased productivity.

3.3 Threshold behavior and identification of critical soil limits

Piecewise regression analysis revealed clear non-linear relationships between soil properties and tea yield, indicating threshold-driven system behavior.

Two critical thresholds were identified:

- SOC ≈ 12 mg g^{-1}
- Available P ≈ 6 µg g^{-1}

Above these thresholds, yield declined gradually. However, once crossed, yield decreased sharply, indicating a tipping point in soil functionality.

Additional thresholds were identified for PAWC (~10%) and bulk density (~1.30 Mg m^{-3}), suggesting that both water availability and compaction are critical constraints.

Table 3: Threshold values of key soil indicators

Soil indicator	Threshold	Unit	Interpretation
SOC	~12	mg g^{-1}	Rapid yield decline below this level
Available P	~6	µg g^{-1}	Severe nutrient limitation
PAWC	~10	%	Reduced water availability
Bulk density	~1.30	Mg m^{-3}	Root growth limitation

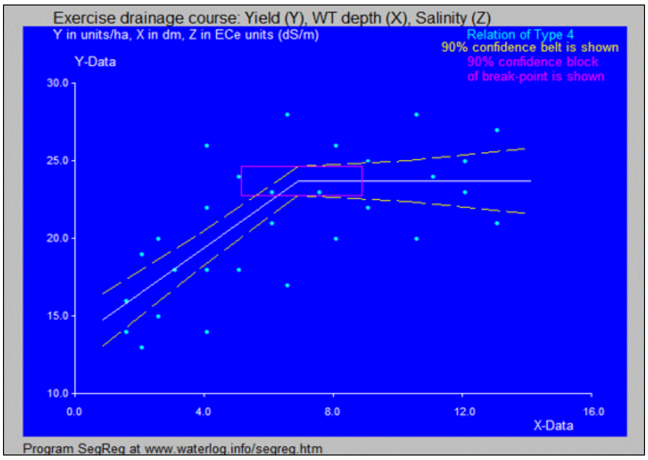

Fig 3: Threshold response (piecewise regression)

Caption:

Threshold response of tea yield to SOC. Piecewise regression identifies a breakpoint at ~12 mg g^{-1}, below which yield declines sharply.

4. Discussion (Q1-upgraded version)

4.1 Threshold-driven and non-linear soil degradation

The results provide strong evidence that soil degradation under long-term tea monoculture follows a non-linear trajectory characterized by threshold behavior rather than gradual decline. The identification of critical thresholds for soil organic carbon (SOC ≈ 12 mg g^{-1}) and available phosphorus (≈ 6 µg g^{-1}) indicates the presence of tipping points beyond which soil functionality deteriorates rapidly.

This finding aligns with ecological threshold theory, which suggests that ecosystems can shift abruptly between alternative stable states once critical limits are exceeded (Scheffer *et al.*, 2001) [12]. In soil systems, SOC plays a fundamental role as a regulator of aggregate stability, nutrient cycling, and microbial activity (Lal, 2004; Six *et al.*, 2002) [4, 13]. When SOC declines below a critical level, reinforcing feedback mechanisms—such as reduced biological activity, impaired aggregation, and increased erosion—can accelerate soil degradation (Stockmann *et al.*, 2013; Sanderman *et al.*, 2017) [14, 11].

Similarly, phosphorus availability becomes a critical constraint in highly weathered tropical soils, where P is strongly sorbed by iron and aluminum oxides (Walker and Syers, 1976; Tiessen *et al.*, 1994) [16, 15]. The identified threshold (~6 µg g^{-1}) likely represents a minimum requirement for sustaining plant productivity and microbial processes.

The sharp decline in yield observed below these thresholds confirms that soil degradation is governed by tipping-point dynamics, marking a transition from productive to degraded system states.

4.2 Mechanisms of soil degradation in tropical tea systems

The observed degradation patterns can be explained by the interaction of chemical, physical, and biological processes that collectively drive soil quality decline under long-term monoculture. Among these, SOC depletion acts as a central mechanism linking multiple degradation pathways.

Declining SOC reduces aggregate stability and soil structural integrity, leading to increased bulk density and reduced porosity. This, in turn, limits water infiltration and decreases plant-available water capacity (PAWC), as observed in older plantations. Reduced soil moisture availability further constrains plant growth and microbial activity, reinforcing the degradation process.

Nutrient depletion, particularly of phosphorus and potassium, is primarily driven by continuous biomass removal without adequate replenishment. In Ferralsols, these losses are exacerbated by leaching and strong phosphorus fixation, resulting in progressively declining nutrient availability (Tiessen *et al.*, 1994; Liu *et al.*, 2013) [15, 7]. The observed trends are consistent with previous studies in long-term tea systems, where nutrient imbalance is a major limitation to sustained productivity (Guo *et al.*, 2010; Yan *et al.*, 2018) [3, 17].

Biological degradation is also a critical component, as evidenced by the substantial decline in earthworm density. Soil fauna play essential roles in organic matter turnover, aggregation, and nutrient cycling (Lavelle *et al.*, 2006) [5]. Their reduction indicates a disruption of soil ecological functioning and a loss of system resilience.

Importantly, these processes are interconnected through reinforcing feedback loops. SOC depletion reduces biological activity and soil structure, which accelerates nutrient loss and further limits plant growth. This self-reinforcing cycle explains the progressive and accelerating nature of soil degradation observed in long-term tea monoculture systems.

4.3 Implications for tropical agroecosystems

The findings have broad implications for tropical agroecosystems dominated by perennial monocultures. The identification of critical soil thresholds provides a quantitative framework for monitoring soil health and predicting productivity decline before irreversible degradation occurs.

Ferralsols are particularly vulnerable due to their inherently low nutrient reserves and high weathering intensity (FAO, 2015) [2]. Once soil properties fall below critical thresholds, recovery becomes increasingly difficult, as demonstrated in global studies on soil carbon loss and ecosystem degradation (Oldfield *et al*., 2019; Poeplau and Don, 2015) [9, 10].

The threshold-based approach proposed in this study represents a shift from descriptive soil assessment toward predictive and process-based management. Similar threshold behavior has been reported in various agroecosystems worldwide, suggesting that tipping-point dynamics may be a general feature of soil degradation processes (Bünemann *et al*., 2018) [1].

Although this study focuses on tea systems in Vietnam, the underlying mechanisms and threshold responses are likely applicable to other perennial cropping systems in tropical regions, including coffee, rubber, and oil palm.

4.4 Management implications

The results highlight the importance of maintaining soil properties above critical thresholds to ensure long-term productivity and sustainability. Management strategies should prioritize increasing soil organic matter inputs through practices such as compost application, manure incorporation, and biochar amendment, which enhance SOC and improve soil structure (Lehmann and Joseph, 2015) [6].

Cover cropping and mulching can reduce soil erosion and improve water retention, particularly in sloping tropical landscapes. Additionally, reducing soil compaction through controlled traffic and minimizing intensive mechanization can help maintain soil porosity and root development.

Balanced fertilization strategies are essential to address phosphorus limitation and sustain crop productivity. Importantly, management interventions should be implemented proactively, before soil properties fall below critical thresholds, as restoration becomes increasingly difficult once degradation advances beyond tipping points.

5. Conclusion

This study provides strong empirical evidence that soil degradation under long-term tea monoculture in tropical highlands is governed by threshold-driven dynamics rather than gradual change. Significant declines in soil organic carbon, nutrient availability, and biological activity, combined with increased soil compaction, indicate a progressive deterioration of soil quality with plantation age.

The identification of critical thresholds for SOC (~12 mg g^{-1}) and available phosphorus (~6 µg g^{-1}) represents a key advancement in understanding soil system behavior. Below these thresholds, both crop productivity and economic viability decline sharply, indicating a tipping point in system sustainability.

By integrating field observations with statistical and threshold modelling, this study establishes a predictive framework for identifying early warning signals of soil degradation. This approach enables the development of targeted management strategies aimed at maintaining soil functionality and preventing irreversible decline.

From a practical perspective, maintaining soil organic matter, improving nutrient management, and reducing soil compaction are essential for sustaining long-term productivity in tropical agroecosystems.

Overall, this research advances the understanding of soil degradation processes in perennial cropping systems and provides a quantitative basis for threshold-based soil management applicable to tropical highland environments.

6. Declarations

Conflict of interest: The author declares that there are no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding: This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Author contributions: Tao Anh Khoi: Conceptualization, methodology, data collection, formal analysis, writing – original draft, and revision.

Data availability: The dataset generated and analyzed during this study is publicly available in the Zenodo repository at https://doi.org/10.5281/zenodo.19342259.

7. References

1. Bünemann EK, Bongiorno G, Bai Z, Creamer RE, De Deyn G, De Goede R, *et al*. Soil quality - A critical review. Soil Biology and Biochemistry. 2018; 120:105-125. Doi: https://doi.org/10.1016/j.soilbio.2018.01.030
2. FAO. World Reference Base for Soil Resources 2014, update 2015. FAO, Rome, 2015.
3. Guo JH, Liu XJ, Zhang Y, Shen JL, Han WX, Zhang WF, *et al*. Significant acidification in major Chinese croplands. Science. 2010; 327:1008-1010. Doi: https://doi.org/10.1126/science.1182570
4. Lal R. Soil carbon sequestration impacts on global climate change and food security. Science. 2004; 304:1623-1627. Doi: https://doi.org/10.1126/science.1097396
5. Lavelle P, Decaëns T, Aubert M, Barot S, Blouin M, Bureau F, *et al*. Soil invertebrates and ecosystem services. European Journal of Soil Biology. 2006; 42:S3-S15. Doi: https://doi.org/10.1016/j.ejsobi.2006.10.002
6. Lehmann J, Joseph S. Biochar for Environmental Management. Routledge, London, 2015.
7. Liu X, Zhang Y, Han W, Tang A, Shen J, Cui Z, *et al*. Enhanced nitrogen deposition over China. Nature. 2013; 494:459-462. Doi: https://doi.org/10.1038/nature11917
8. Minasny B, Malone BP, McBratney AB, Angers DA, Arrouays D, Chambers A, *et al*. Soil carbon 4 per mille. Geoderma. 2017; 292:59-86. Doi: https://doi.org/10.1016/j.geoderma.2017.01.002
9. Oldfield EE, Bradford MA, Wood SA. Global meta-analysis of soil organic carbon responses to agricultural intensification. Nature Communications. 2019; 10:1-9. Doi: https://doi.org/10.1038/s41467-019-13762-0
10. Poeplau C, Don A. Carbon sequestration in agricultural soils via cultivation of cover crops. Global Change Biology. 2015; 21:2509-2520. Doi: https://doi.org/10.1111/gcb.12808
11. Sanderman J, Hengl T, Fiske GJ. Soil carbon debt of 12,000 years of human land use. PNAS. 2017; 114:9575-9580. Doi: https://doi.org/10.1073/pnas.1706103114
12. Scheffer M, Carpenter S, Foley JA, Folke C, Walker B.

Catastrophic shifts in ecosystems. Nature. 2001; 413:591-596. Doi: https://doi.org/10.1038/35098000

13. Six J, Conant RT, Paul EA, Paustian K. Stabilization mechanisms of soil organic matter. Plant and Soil. 2002; 241:155-176. Doi: https://doi.org/10.1023/A:1016125726789
14. Stockmann U, Adams MA, Crawford JW, Field DJ, Henakaarchchi N, Jenkins M, *et al*. The knowns, known unknowns and unknowns of soil carbon sequestration. Agriculture, Ecosystems & Environment. 2013; 164:80-99. Doi: https://doi.org/10.1016/j.agee.2012.10.001
15. Tiessen H, Cuevas E, Chacon P. The role of soil organic matter in sustaining soil fertility. Nature. 1994; 371:783-785. Doi: https://doi.org/10.1038/371783a0
16. Walker TW, Syers JK. The fate of phosphorus during pedogenesis. Geoderma. 1976; 15:1-19. Doi: https://doi.org/10.1016/0016-7061(76)90066-5
17. Yan P, Shen C, Fan L, Li X, Zhang L, Zhang L, *et al*. Tea planting impacts soil acidification and nutrient distribution. Agriculture, Ecosystems & Environment. 2018; 252:145-153. Doi: https://doi.org/10.1016/j.agee.2017.10.015
18. Zhao B, Li X, Li X, Shi X, Huang S, Wang B, *et al*. Long-term fertilizer experiments and soil quality. Soil and Tillage Research. 2014; 135:38-47.