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RESEARCH ARTICLE

EFFECTS OF TEA (*Camellia sinensis*) CULTIVATION ON SOIL QUALITY IN THE LAM DONG, VIETNAM

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Abstract

The objectives of the study were to assess soil quality and its relationship to the sustainability of tea cultivation in the Lam Dong, Vietnam. Overall soil quality declined with increasing age of the tea plantations as evidenced by decreases in soil OC, total N, K and S, available P and K, mean weight diameter of aggregates. As well, total P, bulk density and mechanical resistance increased with increasing cultivation intensity. Because these soil properties were sensitive to cultivation effects, they were considered to be good indicators of soil quality. Soil properties that were less sensitive to change, and limited as soil quality indicators included texture, clay mineralogy and sesquioxides, and effective cation exchange capacity. Soil quality changes were greatest during the first 10 years of cultivation and were generally greatest in the surface 0- to 40-cm of soil. Soil and crop management factors were considered to be the most important factors affecting soil quality.

Decreases in long-term crop yields were found to correspond with decreases in soil quality. In terms of crop productivity, the most important soil quality indicators (based on a multiple regression analysis) were OC, available P, total K and PAWC. Economic analysis of the yield and production cost data indicated that, under current conditions, tea cultivation in the Lam Dong province is sustainable for periods of about 20 years. Thus, measured values of soil quality indicators in the 20-yr tea soils were considered to represent the "critical levels" for economic sustainability of tea cultivation.

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Introduction:-

Vietnam has many tea areas across the country, with approximately 124,000 hectares of tea plantations. Besides, Vietnam has more than 500 tea processing facilities with a capacity of over 500,000 tons of dry tea per year. Thus Vietnam currently ranks fifth in the world in tea exports and seventh in global tea production. Vietnamese teas have been exported to more than 74 countries and territories.Along the length of the country, the image of Vietnamese tea trees is deeply imprinted by the climate and soil of each area, by the lifestyle and

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farming habits, reflecting the spirit and life of the Vietnamese people. The characteristics of the region will create a different taste in each tea leaf.

Bao Loc is known as the “tea capital” of Vietnam. The typical climate in Lam Dong is mild, cool all-around year-round, and there are many days with fog, heavy rain intensity. Located 120km southwest of Da Lat City, Bao Loc tea today is a famous brand in the market, especially for Vietnamese green tea, Oolong tea.

By 2020, Lam Dong has about 12,300 hectares of tea trees and annually supplies about 150,000 tons to domestic and foreign markets. Lam Dong is also the region with the first enterprise applying biotechnology to make tea products that meet food safety standards.

The decline in yield under long-term tea cultivation, however, may also reflect degradation of soil quality. This is because tea is planted in steeply sloping land where erosion by water is a special concern for soil degradation. In addition, with the increase in area cropped to tea and age of tea plantations, many farmers still follow traditional farming practices. That is, they do not adopt soil conservation practices necessary for sustaining soil quality and crop productivity. This can be attributed to socio-economic difficulties or lack of knowledge and incentive policies from the government regarding soil conservation (Do, 1980; Do and Nguyen, 1997). However, previous research into the long-term impact of growing tea on soil quality has been limited in scope and has done little to improve land management for Vietnam's tea crop soil quality and productivity, and (ii) the degree of change in soil quality for tea production is dependent on the inherent properties of the soils, land use and management and the socio-economic conditions of the farmers in the region.

Objectives of the Study: Quantify the changes in soil properties under long- term tea cultivation, as influenced by the age of the tea stand, topography and land management.

1. MATERIAL AND METHOD:-

2.1. Physicall Conditions of the Study Sites

2.1.1 Site Selection

This research was conducted at Lam Dong Province, southern Zone of Vietnam, where tea is one of most important crops and occupies a largest tea area in Vietnam. study site was located at E 108° 8' 25.7589" longitude and N 11° 46.314876' latitude. It is the only Central Highlands province which does not share its western border with neither Laos nor Cambodia. The economy is based largely on agriculture, with tea, coffee and vegetables being the main agricultural products.

2.1.2. Topography

A common characteristic of Lam Dong is highland topography similar to other in the Central Highlands provinces. Highlights of Lam Dong topography is fairly clear sub-stage from the north to the south. In the north are high mountains, Lang Bian highland with the height from 1,300m to 2,000m as Bi Dup (2.287m), Lang Bian (2.167m). The east and west is low mountain type (height from 500 to 1,000 m). The south the is the transition between Di Linh - Bao Loc highland.

2.2. Materials and Methods

2.2.1. Soil Sampling

The study area is located in Lam Dong Province, a central high land in Vietnam. Field sites were selected based on age of the tea plantation; i.e., native forest (control), 5 - 10 - and 20-yr-old tea plantations. Age class was replicated three or four times, except for the 40-yr-old plantations, which were replicated six times. Field sampling was conducted during the winter growing season (November through December) in 1999. Chemical analyses were conducted using composite samples (n = 5) collected from three grids (lO-m x 7-m) within each field. Soils were collected at three depths (0- to 10-cm, 10- to 20-cm, and 20- to 40-cm), with each depth increment analyzed separately. Soil samples analyzed for physical properties (at the 0-to 20-cm depth) were collected separately (see detail in chapter 4).

2.2.2. Crop Yield and Farm Input

Yield samples (1 m^2 ; n = 5) were harvested at random within each field. Yield data were recorded monthly with both the fresh weight and dry weight of the tea harvest being recorded. Inputs for tea production were recorded monthly by the farmers.

To assess whether differences in crop Yield among the older tea plantations were due to natural aging of the tea plants or inadequate fertilizer inputs (i.e., fertilizer inputs did not meet crop nutrient demands), Yields from 20- yr-old tea plantations receiving different fertilizer inputs were compared. Based on the most recent fertilizer application, the 20-yr-old-tea fields (6 fields) were divided into two groups: fields receiving the recommended level of fertilizer inputs (150 kg N, 80 kg P and 80 kg K) and fields receiving less than recommended level of fertilizer based on a standard level recommended by agronomists for commercial tea production in the region.

2.3. Laboratory Methods

Soil chemical properties were determined using standard procedures (McKeague, 1981; Page, 1982). Soil organic carbon and total N and S were determined by combustion, using a LECO CNS-2000. Total soil P and K were extracted using an H2S04-H202 digestion (Thomas et aI., 1967). Phosphate in the digests was measured colorimetrically, using a Technicon autoanalyser; K in the extracts was determined using atomic emission spectrometry (AES). Total soil Cd was extracted by digestion with a mixture of concentrated RN03, HCI04 and HF (Sheldrick, 1984) and determined using atomic absorption spectrometry (AAS). Soil pH was determined using a 1; 1 (w/w) soil:water extract of the composite sample. Plant available K was extracted using a cationic resin exchange membrane (Qian et aI., 1992) and determined using AES. Exchangeable cations (i.e., Ca, Mg, K, Na, AI) were extracted using unbuffered 0.1 M BaCh (Hendershort et aI., 1993) and determined using AAS.

Soil physical properties also were determined using standard procedures (Black et aI., 1965). Bulk density was estimated using the core method described by Kalra and Maynard (1991). Plant available water-holding capacity (PAWC) was calculated as the difference between field capacity (FC) and the permanent wilting point (PWP) and was determined using a pressure chamber apparatus (0.033 MPa for FC and 1.5 MPa for the PWP) Aggregate distribution and the mean weight diameter (MWD) of aggregates were determined by wet sieving (Angers and Mehuys, 1993). Soil mechanical resistance was measured using a base surface cone penetrometer (David R, 2007).

2.4. Statistical and Economic Analyses

Sensitivity levels for the various soil properties were assessed using the F-statistic obtained during analysis of variance. Contrast analysis was used to compare the different tea plantation age classes to the reference soil (i.e., the native forest) and identify the post-cultivation time-frame during which changes occurred in the soil quality indicators.

Regression analysis, with yield as the dependent variable, was used to identify the soil quality indicators that had the most impact on tea productivity. Soil variables used in the regression analysis were those that were more sensitive to change in response to long-term cultivation. Soil variables exhibiting a high degree of collinearity were not used in the regression model, even if they were highly correlated with yield.

Cost-benefit analysis (Townley, 1998), was used to assess the profitability of the individual tea plantations. The profit (net benefit) was calculated as the total revenue (i.e., gross income) minus total input cost, including costs for both variable inputs (labour, fertilizer, pesticides), and fixed inputs (land and equipment rental) (Cox, 1996). Benefit cost ratio was defined as the ratio of total benefit to total cost of production. Tea production was considered to be sustainable when profit> O.

3. Results and discussion:-

3.1. Soil Quality Indicators

Sensitivity analysis. Potential soil quality indicators assessed in this study included a variety of soil chemical, physical and biological properties. To be useful as an indicator of soil quality, variations in soil property associated with management practice must be distinguishable from those associated with natural soil variability (Boehm, 1995). In our study, the soils were similar in terms of parent material, topography, and native vegetation; but varied in terms of management practice and intensity (duration) of this practice. Therefore, it was assumed that differences in soil properties between tea plantation age classes would primarily reflect the impact of cultivation history.

The soil quality indicators assessed in this study, along with their depth- weighted means, are presented in Table 3.1. Significant differences between means were identified using the F-test. For our purposes, a given soil property was considered to be a sensitive indicator of soil quality if the probability of a greater F-value (P>F) was ~ 0.05. Moreover, the smaller the probability value, the greater the sensitivity of the indicator variable. Conversely, a given soil property was considered to be a poor indicator of soil quality if the probability of a greater F-value was >0.05.

The most sensitive soil quality indicators (P ~ 0.001) were total organic C, available K, pH, mechanical resistance, bulk density, total porosity, PWAC

and earthworm population. Moderately sensitive indicators (0.001 < P ~ 0.01) include available P and total N, P, and K. Weaker indicators of soil quality (0.01 < P ~ 0.05) include total S, and the MWD of soil aggregates. On the other hand, soil properties such as ECEC, Fe and Al oxide content, total Cd, and soil texture exhibited little change with cultivation history and, consequently, were of no value as soil quality indicators.

Effects of cultivation of soil quality indicators. To fully assess the impact of cultivation on soil quality, it is necessary to have a baseline against which cultivation induced differences can be measured (Burger and Kelting, 1998). The reference condition is often represented by a native, undisturbed soil (i.e., the native forest soils in our study). Along with baseline comparisons, timely measures of soil quality indicators are useful in assessing soil quality responses to long-term cultivation. That is, the properties of the soils were contrasted between the forested soils with 10-yr-old soils and among the cultivated with difference of cultivation interval. Results of the contrast analyses are presented in Table 3.2.

Results of the contrast analysis, including the direction of change, also were expressed in qualitative terms; i.e., i = significant (P ~ 0.05) increase in population mean, t = significant (P ~ 0.05) decrease in population mean, and H = no significant change (P > 0.05) in population mean (Table 3.1).

Table 3.1. Qualitative changes in soil quality indicators in response to tea cultivation

Properties	Effective depth (cm)	Forest vs. 5-yr	5-yr vs. 10-yr	10-yr vs. 20-yr
Chemical indicators				
Total C (mg g-I)	0-40	J,	H	J,
Total N (mg g-I)	0-40	J,	H	H
Total P (Jlg g-I)	0-10	i	i	H
Total K (mg g-l)	0-40	J,	H	J,
Total S (mg g-l)	0-40	i	H	J,
Avail. P (Jlg g-l)	0-20	i	J,	J,
Avail. K (Jlg g-l)	0-40	i	H	J,
Soil pH	0-40	J,	H	i
Physical indicators				
Resistance (MPa)	0-30	H	i	H
Bulk density(Mg m-^{3})	0-20	i	i	H
Porosity (%)	0-20	J,	J,	H
PAWC (% Vol.)2	0-20	J,	J,	J,
MWD *(mmi*	0-20	J,	H	H
Bio-indicators				
Earthworms m-^{3}	0-20	J,	J,	H

1 i = increase (P<0.05), J, = decrease (P<0.05), and ~ = no change (P> 0.05) in population mean.

2 PAWC- plant available water capacity, MWD- mean weight diameter of aggregates.

In general, changes in most soil quality indicators occurred relatively quickly (~ 10 years) followin g forest clearance and cultivation. During the first 10 years following cultivation, significant changes occurred in 13 of the 14 soil quality indicators. Significant changes in soil mechanical resistance, on the other hand, did not occur until sometime between 10 and 25 years after cultivation. Not all indicators of soil quality declined following cultivation. For example, total P and S, available P and K, and bulk density increased during the first 10 years following cultivation. Thereafter, however, total S, available P and K decreased sharply as the length of cultivation increased from 5- to 10- to 20-years. At the period 10 to 20 years, changes in most soil quality indicators progressively decreased, except organic C, total K and S, available P and K, pH and PAWC.

Although the chemical, physical, and biological indicators of soil quality generally declined in response to long-term cultivation, total P, soil mechanical resistance and bulk density tended to increase with time. The increase in mechanical resistance and bulk density reflect an increase in soil compaction due to tillage operations and, like the decrease in most other soil quality indicators, are indicative of a degradation in soil quality. Conversely, the increase in total P is a result of long-term fertilizer applications and represents a management- induced enhancement of the soil quality.

3.2. Crop Yield as an Indicator of Soil Quality

During the 2022 season, crop yields from the 5- and 10 -yr-old tea plantations (5.06 and 5.02 ton/ha/, respectively) were significantly greater than those from the 20-yr-old plantations (3.30 ton ha-^{1}). Unlike annual crops, in which decreased yields following long-term cultivation are mainly due to a loss of soil quality (fertility), decreased yields of perennial crops (such as tea) following long-term cultivation can be attributed to the natural aging of the plants as well as to degradation of the soil quality. This can be clearly seen when the 40-yr-old plantations are subdivided into those fields receiving high and low fertilizer inputs (Table 3.2).

Table 3.2. Comparison of tea yields and total plant biomass in 20 -yr-old fields receiving high fertilizer inputs with those receiving low fertilizer inputs[1] •

Biomass component	High fertilizer inputs (n=3)	Low fertilizer inputs (n=3)	Significance level [2]
Yield (ton ha-^{1})	3.3	1.78	0.01
Standing crop (ton ha-^{1})	38.54	34.83	0.00
Pruning (ton ha-^{1})	5.09	3.19	0.00

1: *Tea plantations receiving high fertilizer inputs were defined as those receiving at least 150, 80 and 80 kg ha -I yr -I of N, P and K fertilizers, respectively (note: these are the minimum fertilizer inputs recommended by local agronomists for 30-yr-old tea fields); fields receiving fewer fertilizer inputs were classified as "low fertilizer".*

2: Significance levels oft-test for difference in means.

Both total biomass production and crop yield were significantly *(P* ~ 0.05) plantations receiving low rates of fertilizer. Moreover, the 20-yr-old tea plantations receiving high rates of fertilizer produced tea total biomass and yields that were nearly equal to those of the 10-yr-old tea plantations (i.e., total yield and pruning biomass, representative for annual plant biomass, of the 20-yr-old tea plantations was 7.92 ton decline in soil quality resulting from long-term tea cultivation can, to a considerable degree, be compensated for by fertilizer additions. In addition, it is apparent that the yield potential of the tea plants remains good even after 20 years of cultivation, provided an adequate supply of plant available nutrients is maintained through fertilization. This also suggests that tea yields in older plantations are limited primarily by declining soil quality rather than a decrease in the inherent yield potential of the tea plants themselves

3.3. Crop Yield Versus Change in Soil Quality

The influence of long-term cultivation on soil quality varies between individual soil parameters; in turn, management-induced changes in the individual soil parameters will vary in their impact on crop productivity. Relationships between soil parameters and crop productivity can be assessed using both linear and multiple regression techniques (Gregorich et aI., 1997) and, in general, soil parameters that are highly correlated with crop yield are considered to be valid soil quality indicators for that crop.

Plots of crop yield as a function of the individual soil properties for the soil quality indicators that were most sensitive to change $(P \sim 0.05)$ in response to cultivation.Regression analysis of the yield versus soil property data revealed that yield was positively correlated $(P \sim 0.05)$ with soil variables such as total organic C, total N, S and K, available P and K, PAWC and total porosity. Conversely, yield was inversely proportional (significant at $P \sim 0.05$) to soil bulk density and mechanical resistance (compaction). Given that total organic C, total S and K, available P and K, PAWC and total porosity decreased, and that bulk density and mechanical resistance increased, in response to long-term cultivation these results indicate that the observed decrease in long-term tea yields is a response to declining soil quality. Soil properties such as total P, pH, MWD of aggregates and earthworm populations were not significantly correlated with yield (data not shown), although they were found to be sensitive indicators of soil quality.

Soil properties that were identified as being sensitive indicators of cultivation-induced changes in soil quality (Table 3.3), as well as being significantly correlated with crop yield were combined in a multiple regression model. Only total porosity was not included in the regression model because its high degree of collinearity with the other soil physical properties. The statistical significance of coefficients associated with the various soil parameters included in the model is summarized in Table 3.3.

Table 3.3. Regression coefficients for soil parameters in a multiple linear regression model with yield as dependent variable[1]

Soil parameter	Regression coefficient	Significance level
Intercept	0.487	0.798
Total organic C (mg g-l)	0.141 **	0.032
Total N (mg g-l)	1.387	0.138
Total K (mg g-l)	0.054*	0.069
Total S (mg g-l)	0.656	0.131
Available P (Jlg g-l)	0.018**	0.034
Available K (Jlg g-I)	0.003	0.133
Soil resistance (MPa)	0.134	0.499
Bulk density (Mg m-^{3})	-0.487	0.642
PAWC (% Vol.)	0.090*	0.072

1 $R^2 = 0.764$; *significant at the 0.000 level of probability.*

* ,** *Statistically significant at the 0.1 and 0.05 levels of probability, respectively*

Results of multiple regression analysis (Table 3.3) indicated that total organic C and available P were the most highly significant variables (P ~ 0.05) in the predicted yield model; total K and PAWC were moderately significant variables (P ~ 0.1). Clearly, total organic C, available P, total K and PWAC can be considered the most important soil quality indicators for tea cultivation and, hence, the most important predictors of long-term tea productivity and sustainability. The relationship between yield and the soil chemical and physical propertie assessed using multiple regression analysis is presented in the following equation:

$$y= O.1410C^{**} + O.018Available\text{-}P^{**} + O.054Total\text{-}K^{*} + O.099PAWC^{*} \quad R^2 = 0.764^{***}$$

where *, **, and *** denote statistical significance at the 0.05, 0.01, and 0.001 levels of probability, respectively.

3.4."Critical Levels" of Soil Quality Indicators for Sustainable Tea Cultivation

Cost-benefit analysis. Cost-benefit analysis indicates that there is a significant difference in the total output among tea age-classes, with the highest output associated with the 10-yr-old tea plantations and the lowest output associated with the 20-yr-old plantations (Table 4.3). This result is a reflection of the decline in harvest associated with the oldest plantations. Conversely, total inputs remained unchanged or changed only a little among the 5-, 10- and 20-yr-old tea plantations. As a result, the calculated total profit and benefitcost ratio (BCR) for the 20-yr-old tea plantations were significantly lower than those for the 5- and 10-yr-old plantations. Indeed, whereas tea yields from the 20-yr-old plantations were only about 26% lower than those from the 5 -yr-old plantations, there was a decrease of about 93% in the total net benefit associated with the 20-yr-old plantations (Table 3.4)

Table 3.4. Cost-benefit analysis of tea cultivation by age of plantations (in 2022).

Indicator	5-yr (n=3)	10-yr (n=4)	20-yr (n=6)
Yield (ton ha-^{1})	5.06	4.72	3.30
Total benefit (cost per ha, 1000 VND)l	29854	29320	22368
Total inputs (cost per ha, 1000 VND)	23420	23299	21940
Net benefit (1000 VND)	6434	6021	488
Benefit:cost ratio	1.27	1.26	1.02

The low values calculated for both the BCR (1.02; see Table 3.5) and relative net benefit (7%;) associated with the 40-yr-old tea plantations, indicate that the economic viability of long-term tea production is approaching the point where the system may no longer be sustainable. That is, the BCR of 1.02 calculated for the 40-yr-old tea plantations is only marginally above the "break even" point. As well, any further decline in soil quality is likely to reduce yields to the point where the system would no longer be economically viable (Le., the farmer would lose money).

Table 3.5. Relative yield and net-benefit associated with long-term tea cultivation (determined relative to the yield and net benefit associated with the 5-yr-old tea plantations).

Tea age	Relative yield (0/0)	Relative net benefit (%)
5-yr	100	100
10-yr	98	94
20-yr	74	7

Given that changes in crop yield during long-term cultivation occur in parallel to changes in soil quality, critical levels for the appropriate set of soil quality indicators can be defined as the mean values measured for production systems operating at a profit of zero (i.e., at the threshold of economic sustainability). In this study, this threshold was reached after 40 years of continuous tea cultivation.Thus, measured values of the soil quality indicators from the 20-yr-old tea soils (Table 3.5) were considered to be estimates of the critical (limiting) levels below which productivity was no longer economically sustainable.

Table 3.6. "Critical levels" of the key soil quality indicators at the threshold of economic sustainability for tea cultivation.

Soil properties[1]	**Depth (cm)**	Critical level
Total organic C (mg g-I)	0-40	12.09
Available P (flf g-I)	0-20	6.02

Total K (mg g-)	0-40	10.25
PAWC (% Vol.)	0-20	9.43

1 Identified as being statistically significant in the multiple regression analysis was selected. Critical levels reported are the means for the 20-yr-old tea soils (n=6).

The effects of fertilizer application on productivity also are reflected in the economic analysis. That is, the BCR calculated for 20-yr-old tea fields receiving adequate fertilization was 1.19, which was significantly higher than the 0.85 BCR for the fields receiving fertilizer at rates below the recommended . Moreover, the net benefit of applying adequate levels of fertilizer to the 20-yr-old tea fields is much greater than the "break even" point (i.e., net profit » 0). This indicates that under good management (which includes adequate fertilization) the productive capacity of even the oldest tea fields is such that they should remain economically sustainable for more than 20 years.

4.Conclusion:-

Soil quality indicators identified as being important to long-term tea production include a mix of chemical, physical and biological soil properties. The key indicators of soil quality (i.e., those most sensitive to cultivation-induced changes) were soil organic-C, nutrient supply (N, P, K, and S), pH, mechanical resistance, bulk density, total porosity, plant available water content, the MWD of soil aggregates, and earthworm populations. Soil organic C is frequently identified as a key indicator of soil quality because of its impact on other soil properties (Reeves, et aI., 1997) as well as crop yields. For example, a decrease in the soil organic C content of a given soil is related to (i) decreased nutrient supplying power, (ii) an increase in bulk density, (iii) deterioration of the soil structure, and (iv) decreased water holding capacity, all of which can adversely affected crop growth and yield. Likewise, crop yield can be severely affected by a decrease in the available nutrient pool. Economic considerations place fertilizers beyond the reach of many small farmers. Thus, there is a gradual degradation of the inherent soil fertility as the "nutrient surplus" (i.e., the supply of readily available nutrients present when soil was first broken and cropped) (van Kooten, 1993) is depleted. Depletion of the soil nutrients, particularly available P and K, due to continued cultivation with imbalanced fertilization, caused a degradation of soil quality.

Earthworms are quite vulnerable to perturbations (both chemical and physical) in the soil environment (Linden et aI., 1994), thus they provide a sensitive indicator of changing soil quality. The identification of soil physical properties such as PAWC as a key soil quality indicator is a reflection of the reduction in the water holding capacity that accompanied long-term cultivation. This was attributed to lower organic C and total porosity in the soils due to cultivation-induced changes (Stevenson, 1982; Topp et aI., 1997). Bulk densityand mechanical resistance, which provide useful indices of soil compaction (Chen, 1999), also were sensitive soil quality indicators in these tea soils. The bulk density in the surface layer of the 40-yr-old tea soils was less than the critical value reported for many crops (Jones, 1983). However, soils in the Lam Dong province are predominantly clayey so that the increase in bulk density associated with long-term tea cultivation can be expected to reduce the total pore volume of the soil and have a significant effect on pore size distribution (reducing the number of both large- and medium-diameter pores and increasing the number of micropores). Such changes would restrict oxygen movement in the root zone and reduce the amount of plant available water in the soils. With respect to soil resistance, Ehlers et al. (1983) reported that at soil resistance values greater than approximately 4.6 MPa (similar to resistance encountered at the 20-yr-old tea plantations), the roots of several crops (Le. pea, cotton, com and oats) were adversely affected by soil compaction. However, the impact of soil compaction on crop growth depends on plant species and soil environment. In the present study, soil resistance was not considered to be a key soil quality indicator as it was not a statistically significant variable in the yield function. Likewise, although the MWD of soil aggregates was sensitive to change in response to cultivation, it was not considered to be a key indicator of soil quality in terms of tea cultivation and productivity.

Contrast analysis of soil properties between the forest soils with the cropped soils and among cropped soils with different cultivation intervals provided a timely measure of soil quality indicators. Although the change in many of the soil properties was greatest during the first 10 year of tea cultivation, measurable (significant) changes in the important soil quality indicators (i.e. organic C, total K, available P and PAWC) were observed consistently in the older tea plantations. Trends associated with the various soil parameters suggested that, under current management practices, long-term tea cultivation results in a loss of soil quality. Likewise, close inspection of the yield data indicates that long-term (>25 years) tea cultivation results in declining crop yields. This can be attributed to the loss of soil quality, more so than to the effects of the natural aging of the tea plants. This scenario becomes clear when tea fields receiving few fertilizer inputs are compared to those (comparably aged) fields receiving high fertili~er inputs. The decline of tea yields in the older tea plantations was positively correlated with the decline of organic C, total N, S and K, available P and K content, PAWC and total porosity, and inversely proportional to increased soil bulk density and mechanical resistance. At the same time, the change in tea yield did not correlate with pH, total P, MWD of aggregates and earthworm populations.

From an economic standpoint, crop production can be considered sustainable only as long as it results in a net benefit to the producer (Lal, 1998a; Neave et aI., 1995). Economic analysis of the yield and production cost data indicated that in its present state, tea cultivation in the Lam Dong province is sustainable for about 40 years, though with greatly diminishing returns after 25 years. Given that crop yield is a good indicator of soil quality performance, reductions in yield that result in a diminishing of the net benefit to the farmer can be considered indicative of a loss of soil quality as a result of long-term cultivation and that the sustainability of the present system is limited by this loss cultivation-induced changes, the organic C, total K, available P and PAWC were the key soil quality indicators for modeling the economic sustainability of tea cultivation.

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