EFFECTS OF TEA CULTIVATION ON SOIL QUALITY IN THE NORTHERN MOUNTAINOUS ZONE, 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 Northern Mountainous Zone, 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, total porosity, plant available water capacity (PAWC), and earthworm populations. 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, Cd concentration, 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 (e.g., fertilization) 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 Northern Mountainous Zone is sustainable for periods of about 40 years. Thus, measured values of soil quality indicators in the 40-yr tea soils were considered to represent the "critical levels" for economic sustainability of tea cultivation.

In addition to quantitative assessments of soil quality, qualitative assessments involving farmer interviews were used to evaluate the overall efficiency of current management practices to sustain long-term tea production. The major socio-economic indicator of sustainability was farm prosperity, which reflected the willingness of farmers to adopt soil conservation technologies. Government policies related to land ownership and market access also were important factors influencing sustainability.

Generally, farmer observations of the changes in soil quality were in good agreement with the quantitative assessments. Qualitative information obtained from on-farm surveys supplement the quantitative data obtained through soil analyses, and should be incorporated into future studies.

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1. Introduction

Soil is vital to agricultural production and is non-renewable within a human time frame. When native soils are converted to agricultural production various changes in soil properties may occur. The changes in soil properties, either upgrading, sustaining, or degrading, are dependent on land use as well as management practices. The concept of soil quality is closely linked with sustainable agriculture (Lal, 1998a), in which degradation of soil quality is well recognized as having a major effect on agricultural systems. Thus, maintenance of soil quality is a prerequisite to the sustainability of agriculture.

Maintaining soil quality is not only of interest to scientists, but also to farmers. Farmers recognize the important role of soil as a non-exchangeable asset for agriculture. The sustainability of agricultural systems, therefore, is dependent on not only production technologies, but also the farmers' socio-economic conditions and their attitudes towards soil conservation (Lynam and Herdt, 1992).

Tea *(Camellia sinensis)* is one of the most important perennial crops in the Northern Mountainous Zone of Vietnam. It is a significant cash crop used for domestic consumption and export. Because of its economic value, many farmers have replaced their traditional food crops with tea. Many tea enterprises and tea co-operatives, where hundreds of hectares of agricultural land are devoted to tea, have been formed in the mountainous zone. Both the area planted and yields of tea increase every year. According to Vietnamese statistical data, the total tea plantation area for the country was 66,789 ha in 1995, of which the Northern Mountainous Zone accounted for 43,566 ha. In 1998, the total area was 79,180 ha (an increase of 19% from 1995), and in the Northern Mountainous Zone was 49,650 ha (an increase of 14% from 1995). During the same period, the yields of tea increased 23% nationally and 21% in the Northern Mountainous Zone.

Tea is a perennial crop and fields where tea has been grown for two or three decades or more are common in the upland areas. Although the life cycle of tea is long, yields tend to decline after two or three decades (Do and Nguyen, 1997) and plant death or stunted growth is a common occurrence in 40-yr-old tea fields. The decline in yield, as well as the increase in plant mortality or stunted growth associated with the older tea stands is traditionally attributed to the natural aging of the plant (Do, 1980).

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.

The research hypotheses are that: (i) long-term cultivation of tea degrades 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

General objective. The general objective of the study is to assess changes in soil quality under tea cultivation following forest clearance in the Northern Mountainous Zone of Vietnam, and to relate these changes to productivity and sustainability.

Specific objectives. 1) Quantify the changes in soil properties following forest clearance and under long-term tea cultivation, as influenced by the age of the tea stand, topography and land management.

2) Develop indicators of soil quality that relate to tea production.

3) Survey management practices, attitudes and perceptions of tea growers toward sustainable tea production and to identify socio-economic indicators that relate to sustainable tea cultivation.

Description of the Study

The study consisted of two separate but inter-related sections. The first involved the evaluation of tea soil quality and the second is the study of socio-economic conditions and farmer attitudes towards sustainable tea production.

The first section focuses on evaluating changes in soil properties following forest clearance under long-term tea cultivation, and the identification of soil quality indicators. The fields selected represent a wide range in terms of production, topography and farming practices. This section has three components:

1) Pedological characteristics and inherent properties of the soils in the study area.
2) Evaluation of dynamic soil properties following long-term tea cultivation.
3) Identification of indicators of soil quality and their critical levels with regard to sustainable tea cultivation.

The objectives of the second section were to understand the socio-economic conditions in the study area, and to document farmers' knowledge and perceptions toward sustainable tea production.

2. Literature Review

2.1 Agricultural and Socio-Economic Conditions in Vietnam and the Mountainous Zones of Vietnam

2.1.1 Background

Vietnam is an agricultural country with nearly 60 million people (more than 70% of the total population) living in rural areas. Wet rice growing accounts for nearly 60% of agricultural land use. Other annual crops account for nearly 20%, perennial crops 15%, and pasture for livestock less than 5% of the agricultural land in the country. Since 1989, Vietnam has progressed from a near famine country to the third largest rice exporter in the world. Food production has risen from 21 M.T. (Million Tonnes) in 1990 to 32 M.T. in 1998 (Anonymous, 1998). The major export products of agriculture in Vietnam are rice, coffee and tea.

The recent history of development of agriculture in Vietnam involves two periods. Before 1986, the people and government focused only on self-sufficiency in agriculture. This led to serious destruction of natural resources and soil degradation. During this time, under the policies of central planning, all lands belonged to the government. Farmers worked in cooperatives or state farms, where all lands were designated as public properties. Although working on the land, the farmers did not have land use rights. They were workers providing labor in exchange for income. There were few reasons for them to pay attention to soil and resource conservation. Consequently, crop yields were very low and the soil became increasingly degraded. During this time, degradation of soils and natural resources was not evaluated due to lack of capital for research.

Since 1986, a central planned economy has gradually been replaced by more flexible policies including an open market and private economic sectors. This is considered a large step in the economic renovation of Vietnam. Along with other factors, such as improved technology and availability of inputs, the rapid change in government policy, often known as "doi moi" (renovation) contributed to the big leap in agriculture (Vo, 1995). The changes in policy included 'privatization' of agriculture, flexibility in land tenure, opening of foreign trade, and setting a comparative exchange rate for currency. The main focus of production in agriculture was to replace the cooperatives and state farms with individual farming households. Under these new incentive policies, farmers were able to lease land from the government for periods of up to 25 years. Consequently, all agricultural lands and some forest lands have been gradually allocated to farmers who are responsible for their use and management.

Recently, agriculture in Vietnam accounted for a quarter of the country's gross domestic product (GDP), and its average annual growth is about 4.5% (Statistical Handbook, 1998). Agriculture and the rural economy are recognized as one of the first-ranked priorities of the government. The household economy is promoted and the scale of production has expanded, together with a larger application of modern technology. The importance of sustainable development, including environmental protection is well recognized. It is also recognized that exports of agricultural products have become an important component of the country's economy. Although the income from agricultural exports may not add enough foreign currency to support the various economic reconstruction programs needed following a long period of war, a net surplus of food grain and of other agricultural products certainly maintains the social stability of the country (Nguyen et al., 1996).

However, there are many challenges facing agricultural development in Vietnam. The average yield of many crops is still low compared to the average of other countries in the region. More integration of crop production and processing are required, and quality standards of agricultural products must be improved to meet export requirements. The increasing shortage of natural resources along with surplus of labor in agriculture has become a burden for the government (Nguyen et al., 1996). In addition, the best strategy for maximizing the contribution of the rural economy to overall economic growth is still not clear. Land management under new incentive policies still has many challenges for consolidated and sustainable farming. In particular, small farm sizes with scattered holdings, a common scene in many parts of the country, are difficult to manage properly for agricultural development (Vo, 1995).

Overall strategies for agricultural development in Vietnam include more appropriate use of land and water resources, and improved farming systems and associated technologies (Nguyen, 1996).

2.1.2 Agricultural and Socio-economic Conditions of the Mountainous Zones of Vietnam

Upland areas in Vietnam cover three-fourths of the national territory. These areas comprise an important component of the human-ecological system because they provide livelihoods for 28 million habitants (one third of the nation's population). There are 54 ethnic groups living in these regions, of which 53 are ethnic minorities (Nguyen and Thai, 1999). These regions have many favorable physical conditions for the expansion of high value crops such as tea, coffee, fruit trees and the development of food processing industries. However, the ecosystem in upland areas is very diverse in terms of geography, climate and soil type, forming various sub-ecosystems. Most agricultural lands in the upland areas have slopes of 14 to 27 degrees. In some places farmers practice agriculture in very steep areas with slopes of 40 degrees or higher. Under high rainfall and steep slope conditions, soil degradation resulting from erosion is a special concern of agriculture in the mountainous regions (Nguyen et al., 1996).

Although Vietnam is a rice exporting country, many people in the mountainous areas still face a food shortage problem due to constraints of natural resources and socio-economic difficulties (Vo, 1995). Most people living in the mountainous area are poor and their living standard is lower than that of rural people living in the lowland areas. Incomes of the ethnic minorities are among the lowest, and socio-economic conditions (e.g. education) and infrastructures in the mountainous regions are worse than in any other part of the country. Traditional farming such as shifting cultivation, monocropping without any consideration of soil conservation are common practices throughout the mountainous regions. In addition, due to increasing population pressures and demands for food for survival, people have destroyed many forests for timber or for agricultural purposes. Many forestlands have been converted into agricultural land, increasing problems for soil and the environment (Nguyen et al. 1996). Although a number of soil conservation programs have been developed for the mountainous regions, soil degradation is still a major problem in the uplands (Nguyen and Thai, 1999). Integrated measures to assess soil quality are necessary for assuring the sustainability of agriculture in these upland areas.

2.2 Tea Production

2.2.1 Introduction

Tea has its origin in Southern China, Burma and Assam of India. At present, tea is grown in many countries around the world from Georgia of the former Soviet Union (43°N latitude) to Corrientes (Argentina) (27°S latitude), the altitude varying from sea level to about 2300 m above sea level (Ranganathan and Natesan, 1985). Tea drinking is a custom found in almost all nations of the world. Some cultures consider tea to be a means of easing thirst; others use tea as a medicinal herb or a beverage. In Vietnam, tea has been grown for centuries and Vietnamese throughout the country drink tea. Indeed, tea drinking has become an art and an elegant way to enjoy life (Do, 1980).

Tea in Vietnam is usually planted either from seed or through vegetative propagation. Recently, cloning has been quite popular in the selection and propagation of high-yielding varieties. Most tea fields are on upland areas where tea is often planted in rows along the contour lines, with densities ranging from 14,000-15,000 plants/ha (Do and Nguyen, 1997). The first commercial harvest is often in the 4th year after planting, and the highest yields are often in 10-25 year-old tea fields (Do and Le, 2000). An important operation in tea culture is the harvesting of the most succulent shoots, often with only one bud together with 2 or 3 young leaves, for the manufacture of commercial tea. The harvesting season is from March to November, which corresponds with the rainy season. During the dry season, pruning is an important operation in commercial tea cultivation. Pruning is important to improving the tea harvest, a result of various physiological processes (Ranganathan and Natesan, 1985).

2.2.2 Important Characteristics of Tea Soils

Tea grows well in many of the acidic soils found in the tropics. An important soil condition for tea growth is moderate to low pH (ranging from 3 to 6). The optimum pH for good growth and optimum nutrient utilization (especially N) is between 4 and 5 (Ranganathan and Natesan, 1985). Soil pH is considered a critical factor for tea plant growth. The lowest limits of pH for nitrification were determined in acid tea soils of Japan. Nitrification activity was positively correlated with soil pH, in which the lowest limit of pH was approximately 2 (Hayatsu, 1993a). Tea is a crop that takes up large quantities of Al^{3+} (Foy et al., 1978); thus, requiring an adequate supply of exchangeable Al and Fe. Liang et al. (1995) indicated that a high pH and low content of exchangeable Al, Zn, and Fe in soils caused high mortality and stunted the growth of the tea plant.

Phosphate deficiency is a concern, and a problem, in most tea soils. Research shows that over 70% of tea soils are P deficient (Lin et al., 1991). Inorganic P is the major constituent of phosphate in soil. Most of this is occluded P in aluminum- and iron-bound forms. Adjusting the soil pH and adding organic matter (OM) are the most common methods of decreasing P deficiencies in tea soils (Zhang et al., 1997).

Soil conditions necessary for attaining optimum yields in the uplands of Vietnam include a surface thickness of 60- to100-cm, a range of pH from 4.0 to 5.5 and an OM content higher than 2% (Do and Le, 2000).

2.2.3 Effects of Management on Tea Soil

Nutrient requirements of commercial tea crops. Tea, like any crop, requires many nutrients for its growth. Nutrient requirements for commercial tea production are particularly high because the harvestable portions of tea are succulent shoots, which contain the largest percentage of nutrients in the plant. According to Ranganathan and Natesan (1985), N is the most important nutrient element for tea cultivation because it is required in large quantities, accounting for approximately 4 to 5% of the dry weight of the harvested shoots. Potassium and P are possibly the next most important nutrients after N, accounting for 2% and 0.5%, respectively, of the dry weight of the tea harvest.

Nutrient recycling. Nutrient recycling and mineral balance are important factors affecting nutrient budgets in soil. The nutrient budget includes processes such as plant uptake, removal by harvesting, accumulation or storage in the standing plant, and recycling through litter fall, throughfall and stem flow (Larcher, 1980; Marschner, 1995; Archibold, 1995). Both biotic and abiotic factors affect nutrient cycling within the biosphere. The biotic factors are litter production, organic accumulation and degradation, and microbial biomass, whereas abiotic factors include climate and other environmental conditions (Barbour et al., 1987). Fertilization is an important approach to balancing nutrient cycling. Applications of fertilizer to improve plant growth and crop yield have long been a common practice for perennial crops (Kramer and Kozlowski, 1979). Use of fertilizers also helps to maintain soil quality by compensating for nutrient losses in cropped soils.

An understanding of the nutrient cycle is a prerequisite to gaining a more complete understanding of the cultivation. One study in China considered characteristics of the nutrient budget in the soil-tea plant system (Wang et al., 1997). Elements enriched in tea trees were, in descending order P > Ca > K > Mn > Mg > Zn > Al > Fe. Elements returned through recycling of the tea litter were Ca > Mn > P > Zn > Mg > K > Al > Fe.

Annual pruning for commercial tea cultivation is a major source of nutrient recycling and contributes to the mineral balance of the soil-plant system. Tissues removed by pruning are recycled, resulting in annual additions of organic matter and nutrients to the soil. In India, total biomass returned to the soil by annual pruning was 18.96 ton ha^{-1} (dry weight basis), equivalent to 317 kg N, 56 kg P, and 77 kg K (Raganathan, 1972).

The effects of fertilizers and crop management on pH, Fe and Al in tea soils. Fertilizers and soil management have profound impacts on soil quality and particularly on pH, Al and Fe status in many tea soils (Coonjan, 1986). Research on a Russian soil in tea plantations that were established in 1929, and which received 50- to 300-kg ammonium sulfate annually for 35 years, showed that soil pH decreased while the content of mobile Fe increased with increasing fertilizer rates; the Al was highest at the 150 kg ha^{-1} fertilizer rate (Gabisoniya et al., 1973). In Japan, on both volcanic and non-volcanic ash soils, 21 years of tea cropping resulted in soil pH values that gradually decreased from the original value (near neutral or mildly acid pH) to strongly acidic values of 4 or lower (Pansombat et al., 1997). In Acrisols of Vietnam, 10 years of continuous application of nitrogen fertilizers for tea crop produced increases in both H^+ and Al^{3+} concentrations in the soil while Ca^{2+} and Mg^{2+} concentrations have decreased (Do et al., 1980).

The magnitude of any change in soil pH and exchangeable Al and Fe in the soil, however, varies depending on management practices. The effect of high rates of application and splitting of annual applications of N fertilizers on some soil chemical properties were studied in Kenya. The results showed that soil pH and extractable nutrients such as P and K gradually decreased with increasing rates of N fertilizer application, but splitting the applications had little or no significant effect on soil pH or extractable nutrients (Dogo et al., 1994).

Decreases in soil pH and increases in exchangeable Al and Fe have a significant influence on soil quality and productivity. One study on former tea lands of Sri Lanka indicated that Al^{3+} occupies a larger part of the exchange complex and accounts for more soil acidity than H^+. Consequently, Al toxicity is a major factor affecting the growth of other crops in area formerly devoted to tea production (Johannes et al., 1998). Other soils under old, moribund tea plants at Kericho (Kenya) have become very acidic following years of mono-cropping with tea (Owino and Othieno, 1991). These soils were chemically analyzed to determine the possible soil chemical factors responsible for a decline in yield of tea. Exchangeable base concentrations and percent base saturation were low, whereas exchange acidity and exchangeable Al^{3+} concentration and percent Al saturation were high.

Soil pH has a profound influence on soil microbial biomass and other soil quality indicators. Soil acidification reduces the populations of microbes in the soil, as demonstrated by work in Japan. The nitrification activity of tea soil was highly and positively correlated with soil pH; indeed soil acidification inhibited nitrification, cellulose production and the growth of microorganisms (Hayatsu, 1991 and 1993b). Moreover, the increased acidity of tea soil was correlated with a deficient alkaline component and available phosphorus (Hasegawa, 1993). These results suggested that soil acidity should be considered a causative factor in the degradation of soil quality.

Dynamics of organic matter in tea soils. Soil organic matter is an important indicator of soil quality under tea. It is particularly important in the tropics where soils are often highly leached and of very poor quality for crop production. One study in China (Li and Ding, 1992) indicated that dead branches and fallen leaves produce 2375 kg organic substance per ha each year in productive tea gardens. However, erosion causes a loss of 188 kg and mineralization causes a loss of 1687 kg ha^{-1} of organic substances. Organic fertilizers are thus recommended to maintain the balance of OM in these soils (Li and Ding, 1992). The dynamics of organic matter in tea soils are variable, depending on the age of the plantation and management practice. The amount of plant residues returned to the soil are lower in very young and very old tea fields than in the more productive tea gardens (Li and Ding,1992).

One study in Japan showed that long-term tea cultivation practices resulted in increases in the total C and N contents in the surface layers (0- to 20-cm), while the contents remained stable in the subsurface layer (20- to 40-cm) (Pansombat et al., 1997). The increase in OM content was presumably due to the accumulation of fallen leaves and microbial residues. This result was supported by Wang et al. (1997) in China, who indicated that soil OM increased under tea cultivation.

The effects of management on chemical and physical properties of tea soils. Because tea is a perennial crop, soils under tea have different characteristics from layer to layer. Hayatsu and Kosuge (1989) studied variations in nitrification activity, soil pH and inorganic nitrogen content at different depths and distances from a tea stem. They reported that nitrification activity was highest at a depth of 0- to 10-cm in the space between hedges and that this site also showed a high concentration of inorganic N and the highest level of acidification.

Soil tests from 67 tea plantations in Hunan, China showed that many soils were deficient in P, K and Mg. To obtain high tea yields, the total P in the top soil should be at least 1.2%; available N, P and K should be maintained at minimum levels of 149, 32 and 110 mg kg^{-1} soil, respectively (Zhang et al., 1997). Wang et al. (1997) showed that in the nutrient budget of the soil-tea system, P and K were often in deficit and that Al, Fe and Mn were often in surplus. Long-term cultivation of tea also causes sulfur deficiency, particularly in coarse textured and intensively cultivated soils (Takkar, 1986). Phosphorus deficiency becomes severe after long-term cultivation when high amounts of Al and Fe are present in soil. Lin et al. (1991) investigated phosphorus status, phosphate adsorption, fixation and release of tea soils from seven provinces in China. The P content of tea soils in this region ranged from trace levels to 188 mg kg^{-1}, with over 70% of the soil considered to be P deficient even though high levels of total P were present.

There is little research available regarding physical soil quality. However, Ananthacumaraswamy et al. (1988) studied some soil properties in a 25-yr-old field experiment with tea in Sri Lanka and found that the soil cropped to tea alone had a greater bulk density and much lower air-filled porosity and water retention capacity than soils planted to tea inter-planted with other crops. Regarding water erosion of tea soils, Othieno (1975) indicated that the amounts of water run-off and soil erosion were both greatest in the first few years when ground cover by the tea canopy was between 1 and 30%, but were reduced to very small amounts in the third year when the ground cover was greater than 60%.

2.3 Soil Quality

Soil quality has been defined in several different ways, all of which relate to the capacity of a soil to support and maintain plant life. Power and Myers (1989) defined soil quality as the ability of soil to support crop growth, reflecting factors such as degree of tilth, aggregation, organic matter content, soil depth, water holding capacity, infiltration rate, pH, and nutrient supplying capacity. A more general concept of soil quality, adapted from Leopold (1949) by Anderson and Gregorich (1984), defines soil quality as the ability of soil to sustain, accept, store and recycle nutrients, water and energy.

Soil quality must recognize the capacity of a soil to support crop growth and simultaneously maintain the integrity of the environment within and beyond any boundary of the ecosystem in which it occurs (Larson and Pierce, 1994). This capacity depends on two important and distinct components (Doran and Parkin, 1994). The inherent soil quality relates to the natural characteristics of the soil, which is a function of parent material and various state factors (i.e., the distribution of soil over the landscape). Dynamic soil quality relates to properties of the soil that can be influenced by land use and management.

From the perspective of sustainable agriculture and crop production, soil quality can be considered to be the capacity of soil to support crop growth without resulting in soil degradation or being harmful to the environment (Acton and Gregorich, 1995a). Similarly, in an agricultural context soil quality is usually defined in terms of soil productivity and its capacity to sustain plant growth (Carter et al., 1997).

Soil quality is important not only for sustainable agriculture, but also for human health. Indeed, soil quality may be defined as the capacity of a soil to function in a productive and sustained manner while maintaining or improving the resource base, environment, and plant, animal and human health (NCR-59 meeting, 1992). Parr et al. (1992) also defined soil quality from a health perspective, stating that it is the capacity of soil to produce safe and nutritious crops in a sustained manner; it enhances human and animal health, without impairing the natural resource base or harming the environment.

Doran and Parkin (1994) defined three important aspects of soil quality. First is sustainable production, which defines the ability of soil to enhance plant and biological productivity. Second is environmental quality; the ability of soil to absorb and degrade environmental contaminants, pathogens and reduce offsite damage. The third is the relationship between soil quality and plant, animal and human health. These broad definitions recognize the importance of soil quality in sustainable agriculture, in which the soil functions not only as a medium for plant growth, but also to regulate and partition water flow through the environment and filter undesirable substances from the air and water (Larson and Pierce, 1991). The concept of soil quality is very closely related to that of soil health, which is mainly concerned with the balance and availability of plant nutrients and freedom from pests and diseases (Carter et al., 1997). In other words, soil health is a composite picture of the state of the soil's physical, chemical and biological properties. The term "soil quality" is more favored by scientists, whereas "soil health" is a term favored by farmers (Garlynd et al., 1994).

The concept of soil quality also can be broadened to develop the concept of land quality. Land is a term that reflects the natural integration of soil, water, climate, landscape and vegetation (Pettapiece and Acton, 1995; Pieri et al., 1995). Therefore, land quality is a broader concept than soil quality (Carter et al., 1997). Land quality refers to the conditions or health of a parcel of land and its capacity for sustainable use and management (Pieri et al., 1995).

2.4 Assessment of Soil Quality

2.4.1 Common Approaches to Soil Quality Assessment

There are two common approaches to assessing soil quality: qualitative and quantitative. Harris and Bezdicek (1994) defined qualitative and quantitative assessment based on characteristics of the diagnostic properties of soil quality such as descriptive and analytical. Descriptive properties use words as descriptors, and hence, are inherently qualitative or subjective. In contrast, analytical properties use units as descriptors and, as such, are quantitative. Both the qualitative and the quantitative approaches have been widely discussed in evaluating soil quality.

Qualitative assessment. In qualitative assessments, soil quality indicators are often described and recorded through direct soil observation. The use of indigenous knowledge and the experience of farmers is a simple approach to diagnose the status and change in soil quality in terms of qualitative assessment (Romig et al., 1995). Farmers' indigenous knowledge, which develops from their practical experience, could be used to calibrate measured values, providing a more meaningful description of soil quality (Harris and Bezdicek, 1994). Farmers usually describe soil properties based on look, smell, feel and taste (Harris and Bezdicek, 1994; Garlynd et al., 1994).

In qualitative assessments, descriptive data are considered "soft", thus many natural scientists view this type of data as being of only limited value (Harris and Bezdicek, 1994). Nevertheless, this approach has been widely used to evaluate soil quality (Pawluk et al.,1992; Harris and Bezdicek, 1994). Acton and Gregorich (1995b) indicated that a qualitative approach was useful in identifying the resistance of soil due to tillage and the presence of earthworm responses to land use and management in Canada. In the Wisconsin Soil Quality / Heath program of the U.S., the farmers' knowledge and perceptions were used effectively to categorize the level of residue decomposition, soil aggregation dynamics, and earthworm activity in response to management (Harris and Bezdicek, 1994; Garlynd et al., 1994; Romig et al., 1995).

Quantitative assessment. Quantitative assessments are more sophisticated procedures involving analytical data. Harris and Bezdicek (1994) indicated that analytical data are considered "hard". As such they are attractive to researchers as a means of identifying and measuring diagnostic soil properties. Several techniques or methods have been developed to quantify soil quality indicators, such as the comparative approach (Pierce and Larson, 1994), dynamic approach using statistical quality control procedures (Pierce and Larson, 1994; Pierce and Gilliand, 1997), computer models (Pierce et al., 1983; Larson and Pierce, 1994; Burger and Kelting, 1998), multi-scale approach (Karlen et al., 1997) and performance-based scale index (Doran and Parkin, 1994). The following discussion highlights the importance of these methods.

The comparative approach assesses the performance of one system relative to that of another (Larson and Pierce, 1994), then, based on the differences in the measured parameters, a decision is made on the relative sustainability of each system. This is a simple approach for quantitative assessment, but it provides little information about the processes involved in soil quality change. In contrast, dynamic assessment methods have been developed to assess management systems in terms of their actual performance over time. A common way of assessing changes in soil quality over time in the dynamic method is the use of a statistical quality control procedure. This method uses the mean variance obtained from past performance to assess changes in soil quality over time. Larson and Pierce (1994) considered this method for assessing the performance of a given management system as better than comparing it to other systems.

Computer modeling is used to determine how changes in soil indicators impact the important functions of the soil (Pierce et al., 1983; Larson and Pierce, 1994; Burger and Kelting, 1998). In this method, a soil productivity index is calculated to compare soil quality in different soils or units of the same soil that are under different land use or management. There are two forms of the soil productivity index model, the multiplicative model and additive model, both intended for soil quality assessment. However, the multiplicative approach is considered a better model than the additive model because it accounts for the possibility of interactions among the components (Gale et al., 1991).

The performance-based index approach is another quantitative approach used to assess soil quality. A guiding principle of this method is that the index used in the assessment must consider the major issues related to soil quality, including sustainable production, environmental quality and human and animal health (Doran and Parkin, 1994). Such an index of soil quality is considered to be a function of all soil quality components such as food and fiber production, erosivity, groundwater quality, surface water quality, air quality and food quality. Specifically, the evaluation framework of this approach indicates flexibility, in that the precise functional relationship for a given area is determined by the intended use of that area regarding the pedological, geographical and climatic conditions, as well as socio-economic concerns (Singh et al., 1990; Doran and Parkin, 1994). Therefore, this approach is often used in assessing functions of a soil based on the specific criteria established for each element in a given ecosystem.

2.4.2 Assessment of Soil Quality at Different Spatial Scales

Assessments of soil quality are dependent on spatial scale such as the pedon, landscape and region. At the pedon scale, the soil and biological processes affecting a pedon are largely controlled by hydrological and microclimatic differences. These hydrological and microclimatic differences may cause different pedogenic processes to occur within the landscape, and thus create distinctive soil properties (Pennock et al., 1994; Pennock, 1997). Therefore, when comparing pedons, pedogenic regimes within landscapes should be taken into account in the research design. At the landscape scale, association of microclimate, topography and land use create the differences in soil. For example, with regard to soil redistribution, the highest soil losses under water erosion occur in convex profile curvature slope segments, while the highest soil gains are often found in the catchment areas (Pennock, 1997). These redistribution differences may create differences in the soils within the landscape, both vertically and horizontally (Florinsky and Arlashina, 1997). At regional and higher scales, assessment of soil quality should cover all of the physical, agronomic, economic and social aspects. Such assessments are generally regarded as land quality assessments (Neave et al., 1995).

According to Kalent et al. (1997), the multi-scale approach is often used to evaluate soil quality, especially land quality, at the different hierarchical levels. They suggest five scales for soil quality assessment, including point, plot, field, farm and region or nation. The assessment at the field, farm and region scales are often used to evaluate dynamics of soil quality, while those at the lower scales (i.e., point and plot) are used to identify the processes affecting the changes in soil quality (Kalent et al., 1997). At the regional or higher levels, many researchers have used a mapping method to present soil quality status (Anonymous, 1990). For example, global assessments and soil degradation mapping were carried out by World Reference Based and United

Nation Environmental Program (Anonymous, 1990). Soil degradation mapping also was applied to many places in China (Wang and Gong, 1988). Geographic information systems provide a useful tool for developing spatial assessments (Carter et al., 1997; Wang and Gong, 1998).

2.5 Soil Quality Indicators

It is apparent that soil quality is a critical component of sustainable agriculture and has a profound impact on the productivity of a given ecosystem and the environmental integrity of this ecosystem. However, soil quality is not easy to measure and quantify unless its basic indicators are identified. Basic soil quality indicators must meet minimum suitability criteria such as:

> "1) Encompass ecosystem processes and relate to process-oriented modeling. 2) Integrate soil physical, chemical, and biological properties and process. 3) Be accessible to many users and applicable to field conditions. 4) Be sensitive to various management systems and climates. 5) Where possible, be components of existing soil data bases" (Doran and Parkin, 1994).

Larson and Pierce (1994) established minimum data sets (MDS) to assess soil quality. They provide an important practical assessment of one or several soil processes for a specific soil function. Ideally, the properties should be easy to measure. Where the properties are difficult to measure, a pedotransfer function may be used as an alternative estimate (Larson and Pierce, 1991). According to Anderson and Boehm (1995), several soil properties, such as soil thickness, organic carbon content, bulk density, electrical conductivity (EC), pH, microbial respiration and available N and P can be used as indicators of soil quality change among farming systems in prairie agro-ecosystems of Canada. Other soil properties such as water retention, porosity and soil biomass, which are difficult to measure, can be estimated using mathematical models, pedotransfer functions or predicted from relative values.

The complex nature of soil quality leads to variability in time and space of soil properties (Karlen and Scott, 1994). Therefore, indicators that are used to measure soil quality, must be clearly defined. Knowledge regarding pedogenesis, the environment and dynamic processes within a soil are necessary for selecting good soil quality indicators (Karlent et al., 1997). According to Doran and Parkin (1994), indicators of soil quality include many chemical, physical and biological characteristics.

2.5.1 Soil Chemical Indicators

Soil chemical properties influence the availability of nutrients and water, which, in turn, influence microbial populations and plant species able to survive in the soil. Soil chemical properties that are commonly used to describe soil quality in agricultural soils include OM, pH, CEC (cation exchange capacity) and mineralogy (Heil and Sposito, 1997). Doran and Parkin (1994) included total C and N, pH, EC, mineral N (NH_4 and NO_3), P and K as chemical indicators. In the tropical soils of Taiwan, important soil chemical indicators for assessing soil quality are pH, EC, OM, total and available N, P and K , available Cd, Pb, Cu, and Zn. The OM, N, P and K represent the major nutrient elements, whereas Cd, Pb, Cu and Zn reflect potentially toxic elements for plant growth and crop quality (Hseu et al., 1999). It is known that these chemical indicators are generally sensitive to soil management and are often included as part of a minimum data set (Chen, 1999).

2.5.2 Soil Physical Indicators

Crop production and ecosystem health are strongly affected by soil physical quality (Topp et al., 1997). Soil physical parameters such as the structure of the surface soil, soil depth and porosity influence important processes such as water infiltration, aggregation, and root growth (Cameron et al., 1998). Texture, soil bulk density and infiltration, water holding capacity, and water content are important physical properties that must be included in a discussion of soil quality indicators (Doran and Parkin, 1994).

Cameron et al. (1998) and Chen (1999) suggested that visual assessment of the soil profile is an additional way of assessing the physical condition of the soil, in particular where soils require reclamation or remediation. Measuring bulk density, soil texture and resistance can provide useful indices of the state of soil compaction, the retention and translocation of water, and air and root transmission. Measuring aggregate stability gives valuable data about soil structural degradation or improvement, relating to soil erosion resistance and organic matter content. Among soil physical indicators, bulk density, porosity, aggregation, and water retention easily change in response to management and a particular loss of organic matter (Chen, 1999).

2.5.3 Soil Biota

Biological attributes of soil quality involve both living organisms and material derived from living agents in the soil. Living organisms in soils include microfauna (e.g., bacteria and fungi), mesofauna (e.g. mites, spiders, ants) and macrofauna (e.g., earthworm) (Linden et al., 1994). The important biological attributes of soil quality include the many soil components and processes related to organic matter cycling, such as OC, N, microbial biomass, mineralizable carbon and nitrogen (Gregorich et al., 1997). Soil biota, particularly the microbial biomass, influence soil quality directly, provide an integrative measure of the health of the soil environment, and may minimize the number of indicator measurements needed to predict changes in soil quality (Fauci and Dick, 1994).

Earthworms are often observed in agricultural soils and provide a useful indication of soil quality (Linden et al., 1994). Earthworm activities affect the soil environment through burrowing, fecal excretion, feeding and digestion of organic materials (Logsdon and Linden, 1992). Burrowing by earthworms results in increased infiltration capacity and better aeration status of a soil. Earthworm burrows also provide pathways for root exploration into the bulk soil. Another important contribution of earthworms is the conversion of plant residues into various organic forms. Earthworms have an important role in the cycling of organic materials and nutrients in the soil environment. Most farmers want to promote earthworms in their soil as they believe that earthworms are beneficial for their soils. Furthermore, as with other bio-indicators, earthworm populations can provide early evidence of a change in soil quality long before it can be accurately measured (Powlson et al., 1987; Turco et al., 1994). Scientists and farmers consider earthworms an important indicator of soil fertility or soil health. However, caution may be needed when using earthworms as bio-indicators of soil quality. That is, whereas earthworms are often present in highly productive soils, they may not be a cause of high productivity. Indeed, large quantities of food resources in the soil may result in an abundance of earthworms rather than the reverse (Lavell, 1998). In some cases where the soil is highly productive, there are very few earthworms present because of unfavorable environmental conditions such as low moisture content, high physical stress (i.e., high bulk density) or high levels of contaminants (Linden et al., 1994).

2.5.4 Plant Growth and Crop Yield as an Indicator of Soil Quality

The relationship between plant growth and soil quality is well documented. Plants are useful indicators of site quality since they are generally in direct contact with the soil and atmosphere. Plants, in particular agricultural crops, also may be used as an indicator of performance of soil quality because of their response to soil conditions (Gregorich et al., 1997). Any change of soil properties generally leads to a change in yield. Maddonni et al. (1999) suggested that measuring plant response provides an efficient method of assessing soil quality with respect to crop production. Finlay and Wilkinson (1963) have developed a method using grain yield as a measure of the quality of environment in cereal crop production without establishing which factor or factors are yield limiting. Moss (1972) used long-term crop yields as a useful tool in developing a system of rating soils in Saskatchewan, Canada. He believed that long-term yields could indicate the past performance of the soil under specific conditions. However, as the crop is a part of the soil-plant-environment continuum, it is difficult to separate the effects of soil and non-soil factors on crop growth (Gregorich et al., 1997; Maddonni et al., 1999).

2.6 Critical Levels of Soil Quality

2.6.1 Definitions

Assessing soil quality requires that the indicators of soil quality be quantifiable and that critical levels for these indicators can be established. Critical levels, also called threshold values or standards of soil quality, indicate the point at which further alteration of soil attributes would significantly change the capacity of the soil to support plant growth and other soil functions (Pierce and Larson, 1994). With regard to sustainability, the critical level of a soil quality indicator is defined as the value beyond which the system is no longer considered sustainable (Neave et al., 1995). In other words, the critical levels should represent the values within which soil quality must be maintained for sustainable soil management (Chen, 1999). Critical levels have been used to evaluate changes in soil quality over long periods of time (Bauer and Black, 1981). Such critical levels also provide a useful measure for comparing different soils, or units of the same soil under different land use and management (Pierce and Larson, 1994).

In the Guidelines of the International Standardization for Soil Quality Measurement (Hortensius and Welling, 1997), there are two types of soil quality standards. At the international level, standards developed by bodies such as the ISO (International Organization for Standardization) are standard methods. This type of standard is developed by Technical Committees in the ISO and is useful in standardizing methodologies and procedures used in soil quality assessment. The second kind of standard, which is developed by each government or at local levels, refers to threshold values of soil quality indicators for the specific research sites and crops.

Threshold values of soil quality vary from soil to soil, from place to place and from crop system to crop system (Meeussen et al., 1993; Eswaran and Venugopal, 1993; Kawamura, 1995; Neave et al., 1995). Every country needs its own indicators and standards as physical and socio-economic conditions vary (Eswaran and Venugopal, 1993). However, whereas threshold values of soil quality can not be developed, referenced threshold values from other countries or places may be applied in assessing soil quality. For example, national governments who lack their own threshold values for toxic levels of heavy metals, have used or modified the Dutch threshold values in assessing their contaminated soils (Chen, 1999).

2.6.2 Development of Critical Levels

The development of critical levels for soil quality indicators is difficult (Haigh, 1998). The critical levels represent the desired level and define the limits within which soil quality is acceptable (Pierce and Larson, 1994). Some researchers prefer the concept of "quality of performance" to that of a standard (Pierce and Larson, 1994; Pierce and Gilliland, 1997; Chen, 1999). A specific statistical tool used in this approach is the statistical soil quality control also called "control chart", in which the upper and lower control limits are calculated from values of means and standard deviation. Whereas control charts are useful in detecting changes in soil quality, they provide little information about the processes that produced the change (Pierce and Gilliland, 1997). Thus, although this approach seems to be good conceptually, it may not be useful as a tool to measure critical levels of soil quality indicators.

Pennock and van Kessel (1997) modified the control chart method for use in measuring forest soil quality. The level of change in soil quality between undisturbed and disturbed forest soils was determined by comparing median values of soil quality at two sites. If the median values of soil properties in disturbed forest soils were outside the range defined by the lowest and highest median values in the natural site, the ecological significance of the change in these soil properties was considered 'major'. If they were inside the range, the change was considered 'minor'. This is a simple method for detecting changes in soil quality across the landscape.

Some researchers have used plant productivity as an index for soil quality performance (Larson and Pierce, 1994; Burger and Kelting, 1998). Based on this concept, Cox (1996) developed a linear response and plateau model to depict the relationship between crop yield and soil test level. In order to define the critical levels of soil quality, both the crop yield and the net profit (calculated as the sum of the gross income minus production costs) were correlated with corresponding soil test levels. The soil test level at which the maximum yield and profit occur is defined as the upper critical level recommended for fertilization. Cox (1996) suggested that use of this method would benefit farming by increasing yields, providing higher economic returns and minimizing over-fertilization.

Mausbach and Seybold (1998) suggested a method adapted from Gomez et al. (1996) for measuring the sustainability of cropping systems at the farm level. The critical level for a given indicator was set at a value equal to the average value calculated from all fields in the region or at a value 20% above the average. However, this approach is of limited use in identifying factors that affect a change in crop productivity. Similar to the control chart method, this method may not be particularly useful for measuring the critical level of an indicator of soil quality.

In assessing the economic aspects of sustainability, Neave et al. (1995) determined that the critical level of a soil quality indicator can be identified as the value occurring at the gross margin point equal zero benefit. If the gross margin of a system is below this value, the farm is unprofitable and the system is unstable. If above this value, the farm is profitable and the system is considered stable. They suggested that a determination of sustainability or un-sustainability can be made when the trend of a system, observed over time, is above or below the critical value.

2.7 Soil Quality and Long-term Cropping

2.7.1 Methods for Evaluating Soil Quality Changes Over Time

Several methods have been developed for evaluating soil quality changes in response to long-term management. Traditional methods involve long-term experiments to monitor soil quality over time. Monitoring is carried out periodically and directly on-farm or at experiment plots (Wang et al.,1995; Gregorich et al.,1996; Schmidt et al., 1996). This method has the advantage of providing an increased understanding of the mechanisms and processes responsible for changes to soil quality (Wang and Gong, 1998). However, the requirement of experimentation is a serious disadvantage in terms of time and cost (Dyck and Cole, 1994).

Chronosequence studies provide alternative methods to evaluating changes in soil quality over time (Dyck and Cole, 1994). A chronosequence represents an ecological time series of soil where the differences in age or time are selected but not differences in environmental conditions. This method is often used to define the degree of soil degradation or improvement by comparing soil properties under the same or different land use patterns but having different land use periods (Hu et al., 1993). An advantage of this method is it allows the researcher to assess ecosystem changes over time without having to wait for the changes to take place (Dyck and Cole, 1994). One can use chronosequences as an economical and rapid method of assessing soil quality changes over time. However, because different researchers use different benchmark soils, it is difficult to make comparisons between studies (Wang and Gong, 1998). To increase precision for this research, the most important assumptions which must be met for a chronosequence study include the following: all points within the study experienced similar climatic conditions; biotic factors not included in the experimental design (i.e., previous pathogens or insects) have not selectively affected sub-plots within the chronosequence; ecosystem properties such as soil type, topography and vegetation of each site within the sequence were reasonably similar to each other at time zero; and the sites represent the entire time span of the chronosequence (Dyck and Cole, 1994).

Retrospective research provides a third approach for studying long-term changes in soil quality. This is accomplished by analyzing information from areas previously receiving different management practices to understand whether these practices have affected on the present situation (Dyck and Cole, 1994). It is similar to a chronosequence study, as it allows an investigator to assess the long-term changes of soil in the different management practices without waiting for the change to take place.

2.7.2 Dynamic Soil Properties Under Long-term Cropping

Soil organic C. The lessons learned from long-term continuous cropping experiments indicate that soil C is one the most important indicators of soil quality and agronomic sustainability because of its impact on other physical, chemical and biological properties of soil (Reeves et al., 1997). Organic matter and nutrients may build up or be depleted in soil depending on farming practices (Stevenson, 1982). The amount and quality of soil organic matter in a soil are controlled by various physical, chemical, biological, and human-induced factors (Anderson, 1979; Wood et al., 1990).

There is a large volume of research indicating that continuous cropping for extended periods results in a decline in soil organic C (OC). Cultivation of soils in the prairies of North America has resulted in substantial decreases in organic matter (20-50%), within relatively short time-periods (Tiessen et al., 1982; Gregorich and Anderson, 1985). Eck and Stewart (1998) studied the effects of long-term cropping on soil quality in Oklahoma (USA) and found that OC decreased over time. Since initial cultivation, the Grant silt loam lost 45% of its surface OC in 23 years and 59% in 92 years of cultivation.

The loss of OC occurs regardless at soil type or soil structure. This is a very common observation in the lighter-textured soils at long-term experiments such as the Morrow Plots of North America and a Swedish long-term experiment on clay loam (Christensen and Johnston, 1997).

Any loss in OC is considered to represent a deterioration of soil quality. It occurs because after breaking the land, a new environment is created from the soil surface to the depth of cultivation. The OC becomes more accessible to microbial attack, and oxidation and decomposition occur at faster rates (Zentner et al., 1990). In conclusion, losses of OC and nutrients derived from organic matter, gradually result in a reduction in overall soil fertility (Verity and Anderson, 1990; Geng and Coote, 1991).

Soil organic matter (OM) under a particular crop rotation system will reach a dynamic equilibrium, which will vary depending on crop sequence (Unger, 1968). Soil OM and soil N content can be expected to decline rapidly in the first few years or decades after a change in land cover or land management. It then stabilizes and remains relatively constant as cultivation continues (Freyman et al. 1982; Pennock et al., 1994; Acton and Gregorich, 1995b; Gregorich et al., 1995; Li et al., 1997).

Management practices such as crop rotation, fertilization, and residue management affect the OM, N content and microbial population of soils (Janzen, 1987). Conservation tillage techniques can sustain or, in some case, increase OM when coupled with intensive cropping systems (Campbell and Zentner, 1993; Beare et al., 1994; Gregorich et al., 1995). These researchers indicated that increased OM was attributable to reduced erosion, resulting in higher yields and more crop residues being added to the soil surface. Also contributing to these trends are differences in the assimilation and decomposition of soil organic matter. Attributes of soil quality such as total OM, light fraction OM, microbial biomass, C and N mineralization, specific respiratory activity, and soil aggregation are important component of a minimum data set. The change in quantity and quality of soil OM are related to residue inputs and conditions governing residue decomposition (Campbell et al., 1997).

Soil chemical and physical properties. Acidification of the soil is an important process in many long-term cropping systems. Soil acidification is a natural process, but it is greatly affected by environmental factors and agricultural practices (Adriano et al., 1988). Soils can become acidic from long-term applications of N fertilizer, which undergoes nitrification, and the microbial decomposition of organic matter which produces organic acids (Stevenson, 1982). Tabatabai et al. (1992) suggested that the continuous application of ammonium or urea could result in enhanced rates of nitrification, which, in turn, can increase soil acidification as H^+ is released. One study of temperate soils showed that improved crop rotations and fertilizer use can improve soil quality by increasing the amount of organic matter in the soil (Janzen, 1987). Nevertheless, after 18 years of N fertilizer application, soil pH decreased from 7.2 to 6.9. Although a decrease of this magnitude may not affect these soils significantly, it indicates a possible problem where high rates of fertilizer are being used on already acidic soils such as in the tropics (Janzen, 1987). A change in soil pH affects other soil quality properties such as microbial population. Fauci and Dick (1994) found that in residue utilization plots, N treatment increased straw-C input by 26% in the field but had effect on the microbial biomass, relative to the control. This may be attributed to the decrease in soil pH, which, in turn reduces microbial population in the long-term N treatment.

A study in the Dark Brown soil zone of the Canadian prairies demonstrated that significant changes can occur in both the chemical and physical properties of soil as result at cropping and management. Longer periods of continuous cropping, coupled with decreases in the frequency of summer fallow and increased use of fertilizer inputs, produced increases in soil thickness, OC, infiltration, size and stability of aggregates, microbial population, bioavailable N and P (Boehm and Anderson, 1997). Conversely, bulk density, pH and the occurrence of salinity were reported to decrease.

Tiessen et al. (1983) examined changes in organic and inorganic P composition of two grassland soils following 60- to 90-yr of cultivation. They reported that all P losses were due to Po (organic P) losses, alone, and labile P fractions were greatly reduced during cultivation. The loss of P from the Po fraction was much higher than from the Pi (inorganic P) fraction (Hedley et al., 1982) and the reduction in P fertility was closely tied to soil organic matter losses (Tiessen et al., 1983; Nziguheba et al., 1999). In two tropical soils, a study of soil P fractions in unfertilized fallow-maize systems indicated that land-use systems had no effect on the extractable inorganic P fraction in both Oxisol and Alfisol soils, except for P resin (available P extracted by resin) in the Oxisols (Maroko et al., 1999). Losses of P due to erosion and leaching are generally very low, hence the main source of P loss from agriculture is attributable to removal through harvested products (Morel et al., 1994; Selles et al., 1995). According to Selles et al. (1995), grain export depletes both the fertilizer P and soil P, whereas residual P reacts with the soils. The difference between P fertilizer additions and its removal by the crop can provide an indication of the degree to which farming practices have increased or depleted soil P.

Fertilization is important for maintaining soil nutrients under long-term cultivation. A long-term experiment with P and K fertilizers in a corn–wheat system suggested that average levels of applied P and K increased soil test P and maintained the soil test K level over 50 years, even in a soil with low CEC (Cope, 1981). This result is consistent with the results reported by Hetrick and Schwab (1990).

Physical soil quality indicators, such as soil aggregation, bulk density and porosity, plant available water holding capacity, soil thickness and rooting depth, and infiltration are often considered the best indicators for long-term soil quality studies (Larson and Pierce, 1991). A long-term cropping practice, coupled with residue management, affects aggregation which, in turn, affects susceptibility to soil erosion and long-term crop production potential (Larson et al., 1983). Changes in soil structure may be a result of fluctuations in the level of organic stabilizing constituents in the soil (Hillel, 1998; Angers and Mehuys, 1989; Chenu et al., 2000).

Soil bulk density and total porosity are sensitive to management effects. Farming systems can reduce aggregation and pore space, and increase soil bulk density as a result of a decrease in soil organic matter (Blank and Forberg, 1989). The level of change of soil bulk density and total porosity also are influenced by factors such as soil texture, aggregation and tillage methods. Increased soil bulk density and decreased total porosity in cultivated soils may indicate a trend toward lower soil quality (Bauer and Black, 1981; Pierce et al., 1983; Karlen et al., 1990).

As with many other soil physical properties, the plant available water holding capacity of the soil is also sensitive to management. For example, in minimum- and zero-tillage systems, the water retention capacity of soil can increase significantly compared to that of conventional farming systems (Tracy et al., 1990; Dao, 1993). Changes in plant available water holding capacity are highly correlated with the change in soil organic matter, clay content and soil structure (Bauer and Black, 1981; Emerson et al., 1986).

When forest soils are converted to agricultural use, many soil properties necessary for plant growth change. Larson and Pierce (1994) showed that soil bulk density was higher and plant available water capacity was lower in cropped soils compared to those in native soils. Many major nutrient elements such as C, N, P and K in soil are subject to change under crop cultivation following forest clearance (Jordan, 1985).

2.8 Socio-Economic Perspectives

2.8.1 Socio-Economics and Sustainable Agriculture

Sustainability has become a worldwide concept used in discussions of agriculture and the environment. A number of different terms are used interchangeably to describe sustainable agriculture: alternative, low-input, organic, regenerative, conservation, ecological and so on (van Kooten, 1993). Like the concept of sustainable development, various definitions have been proposed for sustainable agriculture. Heliman (1990) based his definition of sustainability on the aims of agriculture, namely, adequate productivity and profitability, conservation of resources, protection of the environment and assured food safety. In another definition, the emphasis is placed on the balance of natural resources and utility. Such sustainable agriculture should evolve indefinitely toward greater human utility, greater efficiency of resource use and a balance with the environment favorable to both human and most other species (Harwood, 1990). In the agro-ecosystem perspective of sustainability, sustainable agriculture is considered as a philosophy and system of farming. It involves design and management procedures that work with natural processes to conserve all resources, promote agro-ecosystem resilience and self-regulation, minimize environmental impacts, and maintain or improve profitability. This concept has values that reflect a state of empowerment and awareness of ecological and social realities (MacRae et al., 1990).

Lal (1998a) indicated that sustainable agriculture refers to the ability of a system to maintain productivity, efficiently and indefinitely. It implies trends in agricultural production over time. There are three important aspects to the sustainability of a system: space, time and dimension (Herdt and Steiner, 1995). The space (or spatial) aspect refers to the scale of assessment of a system such as crop, farming, or regional system. Time reflects the dynamic aspect of a system because agricultural production systems change over time. The dimension aspect includes biophysical, economic and social aspects, all at which are interaction. The biophysical dimension may change in response to changing soil quality over time. The economic dimension changes as a function of its dependence on biophysical outputs. The social dimension may also change in response to economic changes and changes in food habit and standard of living. Maintaining high soil quality is an important strategy for attaining economic progress and thus improves standards of living, which in turn affect soil quality through the application of new technologies and improved inputs for production. Sustainability must be assessed in relation to all these dimensions (Herdt and Steiner, 1995; Lal, 1998a).

2.8.2 Socio-Economic Evaluation of Sustainable Agriculture

Agriculture is seen as a complex social process in which resources and inputs are managed in a socio-political, economic and biophysical context. These inter-relationships influence farming processes and sustainability. Therefore, soil conservation should be considered from both the socio-economic and the technological points of view (Gameda and Dumanski, 1995).

In a comparison of the socio-economic and technological aspects of sustainability, it is much more difficult to understanding the role of people and society in the adoption of conservation technologies than in providing technological solutions (Swader, 1994). Understanding the role of people and society is critical to the success of a conservation program, as suggested by Lynam and Herdt (1992):

> "Sustainability of common systems necessarily incorporates value judgments on multiple criteria over how the community wishes to utilize the resource; moreover, sustainability of the system will depend more on social institutions controlling access and use than on production technologies".

In most agricultural systems, farmers play an important role in decision making and are main actors in societies. Lal (1987) agreed that failure to consider the socioeconomic conditions of farmers often resulted in poor adoption rates for new technologies. Sustainable land use practices are successfully introduced if they respond to farmers' concerns and the needs of the rural community, and are adaptable to local social, cultural, economic and political conditions. It is suggested that sustainable agriculture must address both socioeconomic concerns and environmental principles. They are integrated into new policies, technologies and activities designed to improve agricultural systems (Dumanski and Smyth, 1993).

As profitability is one of most important factors controlling farming practices, farmers often focus on achieving the highest economic benefit without considering soil conservation (Cary, 1994). Many farmers do not lack information about the benefit of soil conservation technologies but they may not be willing to change their farming practices because these technologies only relate to maintaining soil quality and have no economic and social sustainability (Bradsen, 1994; Napier at al., 1994). Practices that are not economically beneficial or do not conform to social or culture requirements by farmers may not be adopted (Smyth and Dumanski, 1995). Therefore, profitability is possibly one of the most important factors controlling the adoption of soil conservation practices (Boehm and Burton, 1997). Farmers can accept conservation practices only when the costs of these technologies do not exceed the short-term, and possibly the long-term benefits (Cambomi and Napier, 1994).

Economic analysis of soil conservation suggests that the degradation of soils caused by erosion results in two types of costs: on-farm costs and off-farm costs (external costs) (van Kooten, 1993). On-farm costs are measured in terms of the loss of farm income, while off-farm costs are the external or off-site costs which account for environmental damages from the erosion such as air and water pollution, biodiversity changes and so on. The on-farm and off-farm costs together constitute the social costs of soil erosion. Economic research indicates that on-farm costs are often small and negligible compared to off-farm costs. However, because farmers are not directly and immediately affected by the off-farm costs, they lack incentive to change their cultivation behavior.

Another concern in addressing sustainable agriculture is the investment costs that are used to maintain a stable system. Economists suggest that there are two values of land: the Ricardian and the capital component (van Kooten, 1993). The Ricardian component is a function of state factors such as land location, climate, topography and parent material. This component is similar to the inherent quality described by soil scientists. The other component is the capital component, which consists of three sub-components. The first is “expendable surplus” that is seen as free goods, such as nutrients that are readily available in the soil when it is first cropped. The second sub-component, called the "revolving fund" involves nutrient stocks balanced by fertilization during cultivation. Finally, the "conservable flow" refers to the costs due to soil losses that can not be replaced by fertilizers. Increased bulk density and decreased water retention in the soil as a result of the loss of soil carbon, which can not be compensated for by fertilizers, is an example of the third sub-component (van Kooten and Furtan, 1987). Farmers are usually unable to distinguish between the revolving fund and the conservable flow. They believe that applying fertilizers is enough to offset those losses that occur from the soil during cultivation. However, because this compensation is only sufficient for the revolving fund, the sustainability of the system may be compromised (van Kooten and Furtan, 1987).

2.8.3 Applications of Indigenous Knowledge and Farmers' Perceptions to Soil Quality Research

It is good for land management if one can understand what has been happening on the land. Farmers, who have been working and living on the land for a long time, usually understand their land well. They can perceive how their land has changed since it has been in crop production. Chamber (1983) stated that farmers' knowledge about the specific conditions in which they produce may be more exact than and often superior to that of researchers who are outsiders. Through the practice of farming, farmers also respond to varying personal, social, economic and environmental conditions (Eyzaguirre, 1988). Thus, it is important to gain an understanding of soil quality from the farmer's perspective (McCallister and Norwark, 1999).

Farmers' knowledge is sometimes referred to indigenous knowledge or rural people's knowledge. Eyzaguirre (1988) defined indigenous knowledge (here referring to indigenous technical knowledge) as a body of information applied to the management of natural resources and labor at a specific place. Scoones and Thompson (1994) considered farmers' knowledge to be highly specific and contextually bound knowledge emerging from localized and practical experience. In contrast to farmers' knowledge, scientific knowledge (the formalized system of knowledge in agriculture) is seen as theoretically based and providing objectives (Kloppenburg, 1991). Farmers' knowledge and scientific knowledge usually complement each other in sustainable programs as they are both general and specific, theoretical and practical (Scoones and Thompson, 1994). Chamber (1983) suggests indigenous knowledge and modern scientific knowledge are complementary in their strengths and weaknesses so that when combined, they can achieve what neither could alone.

Eyzaguirre (1988) suggested that the use of indigenous technical knowledge would be useful in adapting new technologies. Farmers in many developing countries have a great potential to identify new crops and technologies that can provide the basis of more specialized, non-traditional and high-value exports. For example, in the rice farming system in Asia, rice researchers tried to incorporate farmers' perspectives into identification of research issues and setting research priorities. The concept "farmer-back-to-farmer", "farmer-first", or "farmer-based experimentation" was successfully applied in such research (Fujisake, 1992).

The indigenous approach has been applied to identifying indicators of soil quality. In efforts to investigate sustainable agriculture in Washington and Idaho (in the United States), researchers interviewed groups of farmers who were selected on the basis of their reputed use of alternative farming practices. Most farmers responded that building a healthy soil was one of the keys to sustainable agriculture. They recognized soil organic mater as a key ingredient of soil quality because, based on their observations, soil organic matter improved soil moisture storage, reduced erosion and made tillage easier. Many farmers believe that improving soil tilth, enhancing the microbiological health of soil, and increasing soil organic matter are primary goals for sustainable production (Harris and Bezdicek, 1994). In Southeast Asia, Lefroy et al. (2000) used farmers' knowledge and an on-farm research approach to identify the key indicators for sustainable land management programs suitable to different regions or countries. Because the farmers participated in the on-farm research, various indicators of sustainable land management were rapidly assessed.

Applications of socio-economics have become a worldwide approach for studying soil quality and sustainability. Boehm and Burton (1997) presented two case studies in Canada and Nepal, one country developed and the other developing. Although these two countries have many differences in physical conditions, traditional farming practices and socio-economic status, they share many reasons for unsuccessful adoption of soil conservation technologies. Farmers, in both countries, who did not apply soil conservation practices were those who had economic difficulties. They also indicated that the levels of inputs, capital, labor force and profitability were determinant to successful soil conservation practices. Gana (2000) used the results from a farmer survey to study the effects of agriculture on soil quality in Ghana. Farmers' indigenous knowledge and perceptions were considered useful to understanding problems in land use and management of soils in Ghana. Similarly, Beckie (2001), used knowledge of farmers to study two agricultural systems, zero tillage and organic farming, in Saskatchewan, Canada. In this latter study, the role of informal and formal knowledge systems were examined in the development of sustainable agriculture in the Prairie region.

2.8.4 Government Policy and Market Access in Relation to Soil Conservation Programs

Government policies and market access have a major influence on the development of agriculture, as they predetermine the social and political economy. Policies and market access have affected soil conservation programs both directly and indirectly (Rosaasen et al., 1990). Some of these programs have provided incentives to reduce or prevent degradation of soil quality, including technical support and funding for research and training related to sustainable land management. In contrast, many other government programs have focused on improving land policies, socio-economic situations and market access. These efforts are believed to have a great influence on soil conservation and sustainability. However, it is important to carefully consider all the government policies in terms of their effects on land use practices and market distortion (Rosaasen et al., 1990). In addition, policies must be integrated and conservation-oriented and meet the needs of agriculture without causing environmental harm (Boehm, 1995).

2.9 Physical Conditions of the Study Sites

2.9.1 Site Selection

This research was conducted at the Song Cau tea enterprise of Thai Nguyen Province, Northern Mountainous Zone of Vietnam, where tea is one of most important crops and occupies a large area. The study site was located at 105°E longitude and 22°N latitude, about 15 km east of the city of Thai Nguyen. To the east of the country is the South China Sea, to the north and west is China, and about 110 km to the south is Hanoi, the capital city of Vietnam (Fig.2.1).

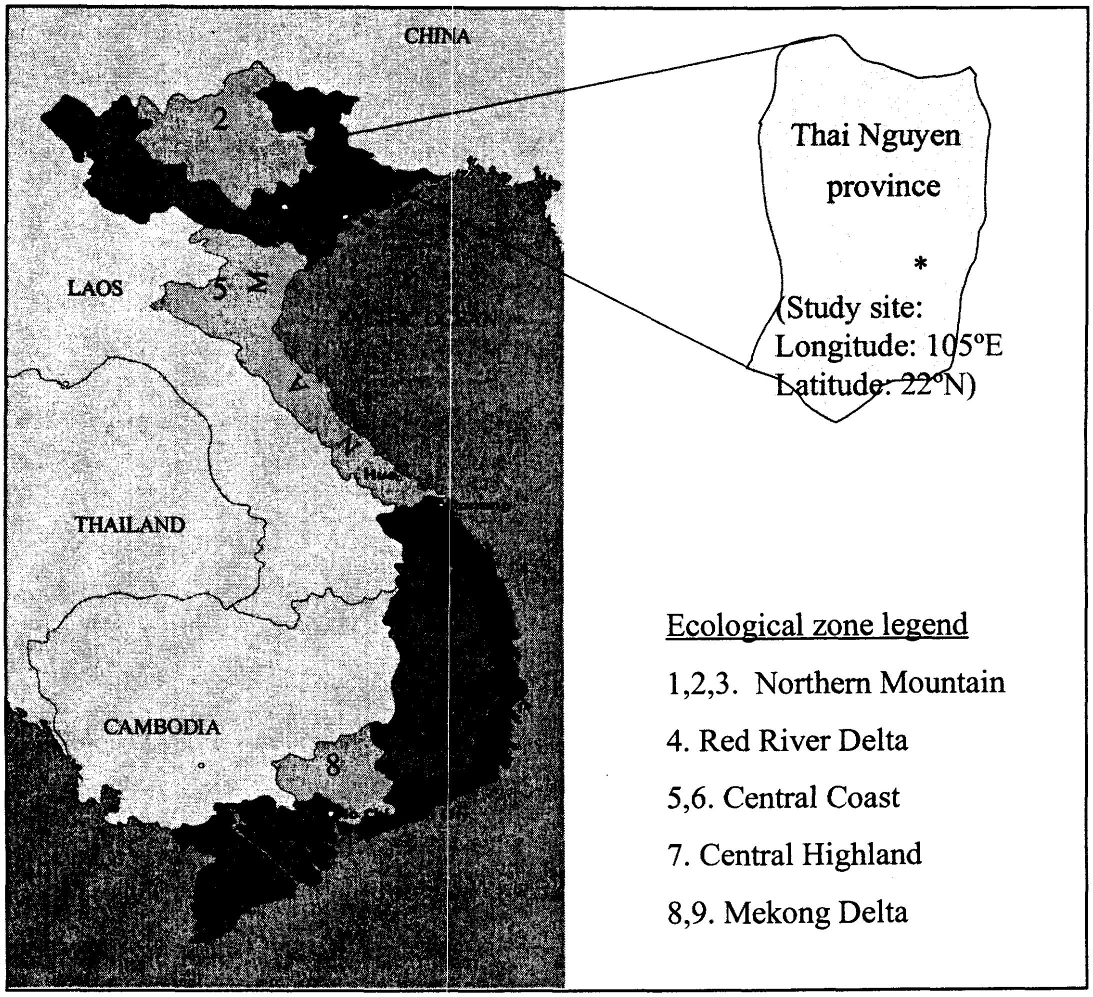


Figure 2.1. Map of Thai Nguyen Province in relation to the ecological regions of Vietnam.

2.9.2 Geomorphology

The topography of the study site is characterized by undulating hills with narrow valleys. This area lies at an elevation ranging from 180 to 240 meters above sea level. Slope steepness of the hills ranges from 10 to 45 degrees. The length of slope is generally variable and it is about hundred meters.

2.9.3 General Geology

Northern Mountainous Vietnam is characterized by undulating hills and high mountains, representing an ancient, weathered landscape from igneous, sedimentary, and metamorphic rocks (Nguyen and Thai, 1999). The igneous and metamorphic rocks occur mainly in the Northwest Regions and comprise both ortho- and para-gneiss. Sedimentary formations consisting mainly of shale, sandstone and limestone (probably Paleozoic in age) are predominant in the Northeast Mountainous Zones, Thai Nguyen province is located in the Northeast Region, and its geological conditions are similar to those throughout the region. Weathering products from sedimentary rocks, particularly shale materials, are predominant parent materials identified in the study area (Vietnamese Soil Map, 1996).

2.9.4 Climate

Vietnam is located on the east side of the Indochinese peninsula in Southeast Asia. It lies completely in the tropical zone so that a humid tropical climate is an important characteristic of the country. The country is very long and narrow, and consists of many physiographical regions: coastal, plains, undulating midlands, low mountains and high mountains (Fig. 2.1). Climatic conditions vary greatly from region to region, as well as within regions.

The climate of the study area is monsoonal with one dry and one wet season. Generally, the climate is hot and moist from April to September, and cool and dry from October to March (Fig. 2.2). The cool season consists of two periods: October to January is cold and dry while February to March is cold and humid. The mean annual temperature is 23°C with a maximum in the summer season (July) of 34°C and a minimum in the winter season (January) of 8°C. Annual average rainfall ranges from 1660- to 2200-mm, more than 80 percent of which falls from April to September. Because the monsoon climate has a mean temperature of 23°C with one rainy season of seven months and one dry period of more than three months (from November to early February), the soil moisture regime is considered to be *ustic* (Soil Survey Staff, 1975). The *ustic* moisture regime (intermediate between udic and aridic regimes) is common in regions of the tropics and subtropics where a monsoon climate has either one or two dry seasons and where annual rainfall ranges from 1125- to 3750-mm (Sanchez 1976).

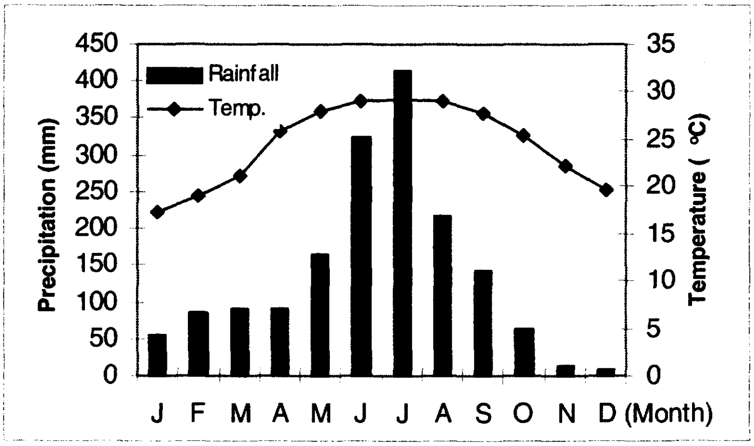


Figure 2.2. Mean monthly temperature and precipitation at Thai Nguyen for the period 1969-1998. (Source: Thai Nguyen Meteorology Station. 1998).

2.9.5 Soil

The soils in the study site have characteristic red-yellow color, and are acidic; they also have a low content of organic C, high decomposition rates of plant material, low CEC and base saturation, and strong accumulation of mobile Fe and Al (Vietnamese Soil Map, 1996).

2.9.6 Forest Vegetation

Tropical rainforest is the most common vegetation community in this study area. These are mixed forests, with deep-rooted trees and some bamboo species. The predominant families in the eco-region are *Fabaceae* and *Lauraceae* (Nguyen and Thai, 1999). Many species are found in both the understory and the overstory, suggesting that the vegetation is still in a successional stage. Due to increasing food demand in the region, most forest soils have been converted to agricultural crop production. Forests slashed and burned, and the lands planted to crops such as upland rice, cassava, tea and fruit trees. Shifting cultivation has been a common practice in the past, resulting in increasing soil degradation due to water erosion. Only limited areas of primary forest are currently present in this region. Many are secondary forests, because most old growth forests were cleared for timber or agricultural purposes during the period from 1960 -1965.

3. 'Pedological Characteristics' and 'Inherent Properties' of Tea Soils in the Northern Mountainous Zone of Vietnam

3.1 Introduction

Soil quality is composed two distinct components (i) inherent and (ii) dynamic soil quality (Doran and Parkin, 1994). Inherent soil quality reflects the natural composition of the soil, which is a function of parent material and various state factors (such as topography) that are essentially static, exhibiting little change over time (Carter et al., 1997). These properties impart important characteristics to the soil, such as buffering capacity, storage of organic matter and nutrients, and resilience (Warkentin, 1995). These soil functions vary from soil to soil because of differences in basic properties. For example, the capacity for buffering, water storage and resiliency of clay soils (Vertisol) are much greater than those of sandy soils. Quantitatively, most inherent soil properties are often resistant to change over the short term (e.g., years to decades). Nevertheless, some inherent properties of a soil may change due to management effects. For example, soil texture may change in response to different tillage systems (e.g., tillage vs. no till), possibly as a consequence of gradual erosive losses of fine (clay and silt) particles in the former (Lal, 1998b). Measuring inherent properties, on the other hand, can allow the classification of the soils (Hughes, 1981), and the separation of natural variability from management-induced variability.

Tea is a perennial crop in Vietnam and most tea crops are planted in upland areas where the soils are variable. The complex nature of these soils often results in increased variability in the measured properties of the soils. Therefore, it is essential to determine the uniformity of the soil, in terms of soil type and classification, when evaluating soil quality under tea cultivation systems.

The objectives of the study were to 1) characterize the inherent properties of "tea soils" in the Northern Mountainous Zone of Vietnam; 2) assess natural variability associated with inherent soil quality; and 3) classify these soils based on Soil Taxonomy (Soil Taxonomy, 1998).

3.2 Material and Methods

3.2.1 Soil Sampling.

The soils for this study were chosen from the native forest, and from 10-, 25-, and 40-yr-old tea plantations in the Northern Mountainous Zone of Vietnam. Each age class was replicated three to six times. Field sampling was carried out during the winter growing season in 1999 and 2000 (winter season was selected because no fertilizers were being applied at this time). Two slope positions, upper slope and lower back slope, were sampled at each field. Three sub-samples representative of each slope position were collected from within three grids (10-m x 7-m) at each position. At each grid, the bulk soil samples were taken at three incremental depths (0- to 10-, 10- to 20-, and 20- to 40-cm) and five soil cores were composited to provide the bulk sample.

A single soil pit was excavated at the upper and lower back slope positions of all fields, except the 10-yr-old tea plantations. Soil profiles were described and samples from the 40- to 60- and 60- to 80-cm depths were collected from these soil pits. Munsell color charts and dry samples were utilized to identify colors of the soil profiles. All the soil samples were crushed to pass an 8-mm sieve, and crop residues, roots and stones were removed. The soil samples were then air dried and brought to the University of Saskatchewan for chemical and physical analyses.

3.2.2 Laboratory Methods

Inherent properties of the soils were analyzed, including particle size distribution, clay mineralogy and Al and Fe oxide content. Particle size distribution was determined by using the pipette method described by Kalra and Maynard (1991). Because the soils were acidic, the use of HCl to remove carbonates was not necessary.

Bulk soil was sieved to obtain the ≤ 2 mm fraction and a 10 g sub-sample transferred a 500 mL flask. Organic matter was removed by treating with H_2O_2 (30 mL for surface samples and 20 mL for subsoils) and placing the samples on a hot plate at 85°C for 5 h. Samples were then removed from the hot plate, cooled to room temperature and the volume brought to 350 mL by adding water. Five milliliters of Calgon (sodium hexametaphosphate) was added as a dispersing agent. The sample was then mixed by hand, followed by shaking slowly on an end-over-end shaker for 16 h. The sand fraction (> 50 μm) was separated by wet sieving the dispersed sample through a 300-mesh sieve with water into a 1000 mL cylinder. A sub-sample of the silt plus clay fraction was removed from the suspension immediately after stirring. The clay fraction was sampled at 10-cm below the solution surface after a settling period of seven hours. The silt fraction was calculated as difference between the silt + clay and clay fractions.

Clay minerals were determined by x-ray diffraction (Jackson, 1969). Free iron was removed by the dithionite-citrate-bicarbonate method. To identify the clay minerals, sub-samples were then prepared with four different treatments: Mg saturation, Mg saturation plus glycerol, K saturation, and K saturation plus heating at 550°C for two hours. Analyses of the clay fractions were carried out using oriented samples and a Phillips X-ray diffractometer. Because clay minerals change little over a decadal time scale (Hughes, 1981), the clay fractions of only the native forest and the 40-yr-old soils were analyzed.

Dithionite citrate bicarbonate (DCB) extractable Al and Fe was extracted by the method of Mehra and Jackson (1960). The DCB extraction were used to remove finely divided hematite and goethite, amorphous inorganic Al and Fe oxides and organically complexed Al and Fe. It is an estimate of free Fe and Al oxides in the soils. A 0.5 g soil sample was placed in 25 mL of 0.68M sodium citrate solution to which 0.4 g of dithionite was added. This was shaken on an end-over-end shaker for 16 h, followed by centrifuging for 20 min at 510 x g. Oxalate-extractable Al and Fe were extracted by a procedure described by McKeague and Day (1966), revised by Schwertmann (1973) and McKeague (1981), in which acid ammonium oxalate dissolves mostly amorphous inorganic Fe and Al from soils. A 0.25 g soil sample was shaken in 20 mL of 0.2M acid oxalate in the dark for 4 h on an end-over-end shaker, followed by centrifugation at 510 x g for 20 min. Concentrations of Al and Fe in the DCB and oxalate solutions were measured by an atomic adsorption spectrophotometer (AAS).

3.2.3 Statistical Analysis

Data processing and statistical analysis were performed using SPSS software (Norusis, 2000). Means comparisons were carried out using the F-test, with a level of probability of 5%. The coefficient of variation (CV) was selected to evaluate soil variability of because it is a dimensionless parameter and allows for comparison of magnitudes of the variability of different properties, regardless of the units used for the measurement.

3.3 Results and Discussion

3.3.1 Profile Description

Soils in the study area were moderately deep, with a low content of rock fragments, and lacked distinct horizons. Soil horizons were identified based mainly on differences in color, texture and structure.

Soil color in both the forest and cropped profiles was generally dominated by pale brown to yellowish brown hues (Munsell color), except for the Ah horizon in the forested soils and Ap horizon in the cropped soils, which were slightly darker (Table 3.1 and 3.2), an indication of having a higher OM content. The LFH layers in the forest soils were relatively thin, a probable consequence of the rapid decomposition of the organic materials in soil under warm and moist conditions. In the subsoil layers (i.e., at the 40- to 60- and 60- to 80-cm depths), reddish yellow and yellowish red colors (7.5 YR hue) were dominant. The reddish yellow and red colors generally indicate oxidizing conditions of iron oxide minerals such as hematite or goethite, and are an indication of good drainage in the uplands (Birkeland, 1999). The sub-soil colors in the upper and the lower back slope positions were similar (data not shown).

Soil structure was mostly granular and medium subangular blocky in the surface horizons, becoming weak subangular blocky with depth. The granular structures were finer in the surface horizons of the cropped sites than in the forest soil. Small animal channels and many medium pores were common in the surface layer of the forest soils, but less prominent in the cropped soils, suggesting possible differences in soil bulk density, total porosity and fauna between the native and the cropped soils.

Table 3.1. A description of a representative forest soil profile.

Horizon designation	Depth (cm)	Description
LFH (0-2 cm) and Ah	0-12	Dark brown (10YR 7.5/5 dry); slightly decomposed organic matter at surface; clay; moist; granular structure; many fine roots throughout; some small animal channels; many medium pores; no clay skins; clear boundary.
A and AB	12-22	Brownish yellow (10YR 7/5 dry); clay; weak medium sub-angular blocky and granular structure; many fine and medium roots; many medium pores; slightly moist; gradual smooth boundary.
	22-42	Yellowish brown (7.5YR 6/8 dry); clay; fine granular structure with sub-angular blocky to angular blocky; some clay skins cover on small gravels; moist; some medium and big roots; medium pores; clear smooth boundary.
Bt	42-62	Reddish yellow (7.5YR 6/6 dry); clay; moist; fine structure; slightly firm; some patchy clay skins on ped faces; few fine and medium pores and fewer roots than above horizons; smooth boundary.
	62-82	Yellowish red (7.5 YR 5/6 dry) ; clay; slightly moist; some weathering shales with purple colour; some red and reddish yellow mottles; firm and hard when dry; clay skins on some small gravel and rock fragments diameter with different colour and waxy.

Clay content increased with depth in all soils (Table 3.3 and Fig. 3.1). The soil layer from 42- to 82-cm in the forested soils and 40- to 80-cm in the cropped soils had a higher clay content (55-60%) than the A horizons, and was designated a Bt horizon (Dang and Anderson, 2000). Clay skins were evident in the Bt, indicating clay illuviation. A dense, clay-enriched Bt horizon, a diagnostic horizon for the Ultisol Order in Soil Taxonomy, may limit root growth (Buol et al., 1997). Tea roots were found mainly in the surface layer from 0- to 40-cm, with fewer roots below the 40-cm depth, corresponding to the Bt horizon (Table 3.2).

Table 3.2. A description of a representative 40-yr-old tea soil profile.

Horizon designation	Depth (cm)	Description
Ap	0-10	Brown and brownish yellow (10YR 7/5 dry); clay; slightly moist; granular structure; few fine roots throughout, very few animal channels; fine and medium pores; gradual smooth boundary.
A and AB	10-20	Brownish yellow and yellowish brown (10YR 6.5/5); clay; weak medium sub-angular blocky and granular structure; fine and medium roots; fine pores; slightly moist; smooth boundary.
	20-40	Yellowish brown (7.5YR 6/8 dry); clay; fine granular structure with sub-angular blocky to angular blocky; some clay skins cover on small gravels; moist; medium and larger roots; fine pores; clear smooth boundary.
Bt	40-60	Reddish yellow (7.5YR 6/6 dry); clay; moist; fine structure; slightly firm; some patchy clay skins on ped faces; fine pores and fewer roots; clear smooth boundary.
	60-80	Yellowish red (7.5 YR 5/6 dry); clay; slightly moist; weathering shales with purple colour; few red and reddish yellow mottles; firm and hard when dry; clay skins on some small gravel and rock fragments with different colour and waxy.

3.3.2 Soil Texture

Clay content of the soils ranged from 42% to 49% at depths from 0- to 40-cm, thus, they were classed as clay soils. High clay contents suggest that these soils have a high capacity for buffering, storage of organic C and nutrients, and resiliency. The clay, silt and sand contents at the 0- to 10-cm, 10- to 20-cm and 20- to 40-cm depths were not significantly different between the forested and the cropped soils and among the cropped soils (Table 3.3). The fairly uniform texture among the tea fields suggested that change in texture due to erosion was negligible, even for the soils cropped for 40 years.

Table 3.3. Sand, silt and clay content (%) of representative soils from all sites.

Particle size	Forest	10-yr	25-yr	40-yr	P>F[1]
---0- to 10-cm depth---					
Sand	21	30	30	26	0.28
Silt	33	28	27	31	0.08
Clay	46	42	43	43	0.72
Textural class	clay	clay	clay	clay	
---10- to 20-cm depth---					
Sand	20	28	27	24	0.36
Silt	33	25	24	30	0.06
Clay	47	47	49	46	0.90
Textural class	clay	clay	clay	clay	
---20- to 40-cm depth---					
Sand	20	28	27	24	0.27
Silt	33	25	24	30	0.29
Clay	47	47	49	46	0.51
Textural class	clay	clay	clay	clay	

Note: [1] P>F values show statistically significant differences of means among the forest, 10-, 25- and 40-yr-old soils.

Clay content increased gradually with depth in both the forest and cropped soils (Fig. 3.1). This indicates the uniformity of soils in the study area with regard to soil development, suggesting that further comparison of the soils be warranted.

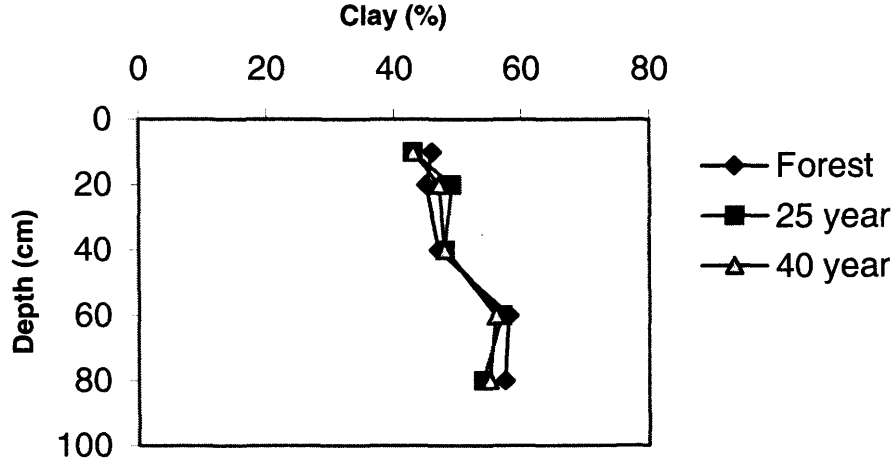


Figure 3.1. Distribution of clay with depth in the soils of the forest, 25- and 40-yr-old sites.

3.3.3 Clay Mineralogy

The X-ray diffraction analysis included both Mg- and K-saturated treatments, and showed that the predominant clay minerals were kaolinite, associated with hydroxy-interlayered 2:1 minerals, mostly vermiculite and mica (Fig. 3.2). Kaolinite was the dominant clay mineral and estimated from 42 to 64% of total clay minerals (Nguyen and Thai, 1999). Comparing the forest soils and the cropped soils, the clay minerals were similar, an indication of no change in clay mineralogy during 40-yr of tea cropping.

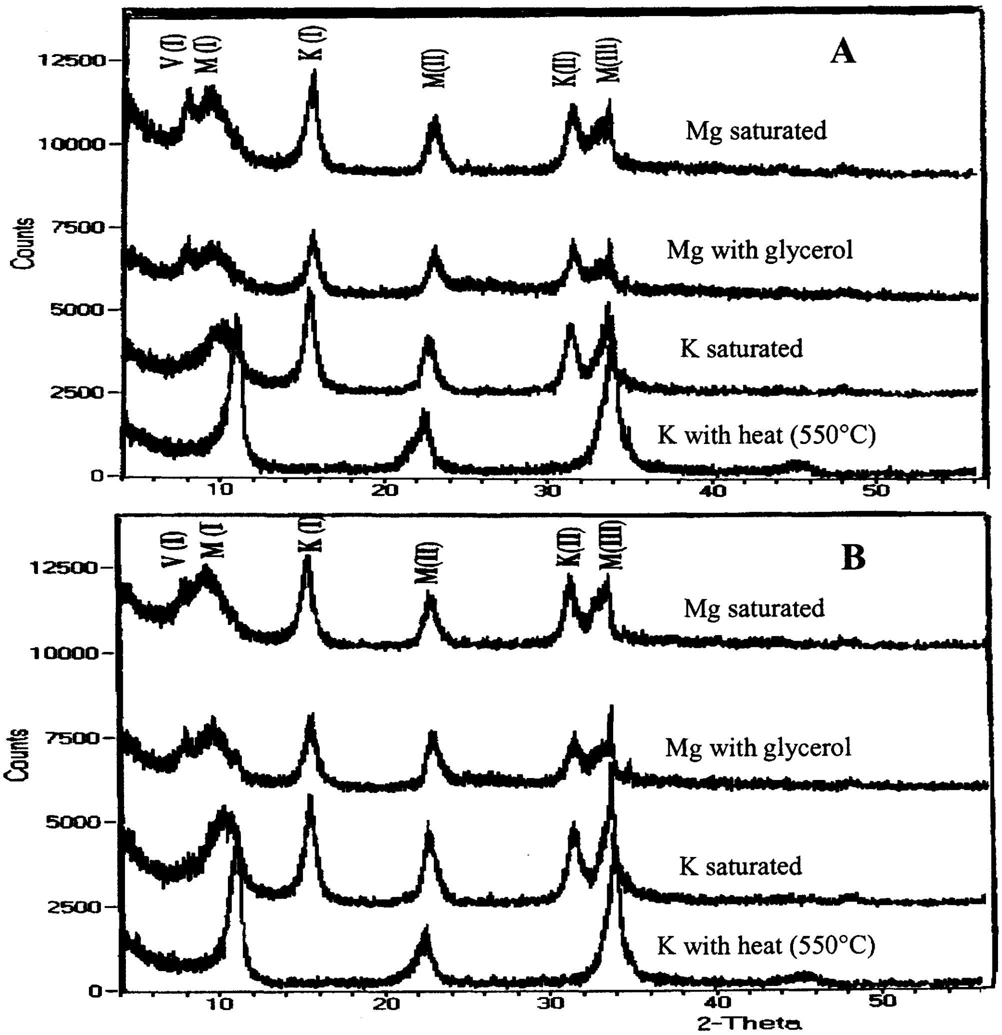


Figure 3.2. X-ray diffractograms of DCB-treated fractions of clay in the surface layer (0- to 40-cm) of the forest (A) and the 40-yr-old tea soils (B).

Note: K-kaolinite, M-mica (illite), V- vermiculite. I, II and III in parentheses indicate the first, second and third order of the mineral.

3.3.4 Aluminum and Iron Oxides

Aluminum and Fe oxides may be either crystalline or non-crystalline (amorphous), the latter probably forming as a result of very rapid precipitation reactions (Hausenbuiller, 1978). Amorphous Al and Fe oxides are the most important form as they influence soil properties such as increased surface charge, specific surface area and soil aggregation (Huang and Wang, 1997; Birkeland, 1999). In this study, the respective crystalline and non-crystalline forms of Al and Fe oxides were extracted using dithionite-citrate-bicarbonate (DCB) and oxalic acid (Ox), respectively. Extractable Al and Fe by DCB in both the forested and the cropped soils were higher than those extracted by Ox (Table 3.4), indicating that crystalline Al- and Fe-oxides were dominant. This is consistent with reports that relatively small amounts of the amorphous compounds compared to the total amounts of Al and Fe oxides are common in most Ultisols and other tropical soils (Juo, 1981). High temperature and the fluctuation of the wet and dry seasons cause poorly crystalline Fe to lose water of hydration and develop greater crystallinity (Juo et al., 1974).

Formation of crystalline or amorphous forms of Al and Fe oxides also could have been influenced by the type of parent rocks from which the soil materials developed (Juo, 1981) as well as the OM content present in the soils (Huang and Wang, 1997). Low OM content in these tropical soils could have resulted in the lower content of the amorphous Al and Fe oxides compared to the corresponding crystalline forms, because there was lack of bonding between the amorphous materials and OM (Shang and Tiessen, 1998).

The total extractable Al and Fe oxides increased with increasing soil depth, in both the forested and cropped soils (Table 3.4). The constant increase of Al and Fe oxides associated with increasing clay content with depth suggests downward co-migration of these oxides and clay (Juo, 1981). This perhaps results in clay coating the sesqui-oxides during transportation.

Table 3.4. Content of aluminium and iron oxides of the soils at all sites.

Depth (cm)	Forest	10-yr	25-yr	40-yr	P>F[1]
---------- % Al extracted by DCB (Al_d) ----------					
0-10	0.78	0.72	0.83	0.86	0.12
10-20	0.82	0.69	0.86	0.88	0.09
20-40	0.84	0.72	0.88	0.89	0.17
---------- % Al extracted by oxalate acid (Al_{ox}) ----------					
0-10	0.46	0.43	0.47	0.46	0.55
10-20	0.44	0.41	0.46	0.43	0.19
20-40	0.42	0.38	0.42	0.39	0.28
---------- % Fe extracted by DCB (Fe_d) ----------					
0-10	4.10	3.93	4.20	4.59	0.34
10-20	4.32a	4.01a	4.65ab	4.98b	0.04
20-40	4.73	4.00	4.88	5.17	0.11
---------- % Fe extracted by oxalate acid (Fe_o) ----------					
0-10	0.59	0.60	0.64	0.60	0.75
10-20	0.51	0.55	0.60	0.58	0.26
20-40	0.46	0.47	0.48	0.46	0.94
---------- Fe_o/Fe_d ----------					
0-10	0.15	0.15	0.15	0.14	0.60
10-20	0.12	0.13	0.13	0.12	0.26
20-40	0.10	0.12	0.10	0.09	0.31

Note: [1] P>F values show the statistically significant difference of means.

Formation of Al and Fe oxides is influenced by various factors such as occurrence of inorganic and organic ligands, and fluctuation of temperature and moisture in soils (Huang, 1988). Farming practices are thought to influence the weathering of Al- and Fe-bearing materials in cropped soils over the long term. Fe_d and to some degree Al_d were somewhat higher in soils cropped for longer periods, although only Fe_d for the 10- to 20-cm depth was different statistically, suggesting that these changes were minor. There was possibly not enough time for the changes to take place, since the time required for soil formation can extend perhaps over a period of centuries (Huang, 1988).

The Fe_o/ Fe_d ratio is a measure of the proportion of the total pedogenic Fe that is amorphous plus ferrihydrite (Birkeland, 1999), and is also called the active Fe ratio (Blume and Schwertmann, 1969). The Fe_o/ Fe_d ratio at all depths was generally similar in the forest and the cropped soils (Table 3.4). In addition, the Fe_o/ Fe_d ratio in all soils decreased gradually with depth. According to Huang and Wang (1997), the Fe_0 / Fe_d ratio is higher in soils or horizons that are rich in OM. Thus, a lower active Fe ratio with depth corresponded to a lower OM content with depth.

3.3.5 Spatial Variability of the Soil Properties

Soil variability at the landscape level can be "management-induced" or "natural". Management induced-variability often refers to trend changes in a predictable way (Arnold et al., 1990; Boehm, 1998), such as a decline in soil organic carbon and nutrient status generally resulting from land use and management. In contrast, natural variability represents random and cyclic changes, which may be unavoidable and often unpredictable due to the nature of soils, depending on the many combinations of the soil forming factors (Arnold et al., 1990; Boehm, 1998). Spatial variability must be considered in an evaluation of the effects of management on soil quality in order to distinguish between random variability and those due to management (Larson and Pierce, 1991). Inherent soil properties are considered to be good indicators for assessing natural variability, since they are static and change little over time (Carter et al., 1997). Wilding (1988) recommends the coefficient of variation (CV) as a good statistical measure to express soil variability; with low variability associated with CVs less than 16%, moderate variability associated with CVs ranging from 16% to 35%, and high variability associated with CVs ranging from 36% to 70%.

For each horizon, CVs were calculated using the measured values for all samples within each tea plantation age class. The CVs for the soil particle size distributions of the whole study soils (Table 3.5) were low to moderate, as defined by Wilding (1998). Thus, the variability of the study soils sampled was identified as moderate. The clay fraction was less variable than the silt and sand fractions, particularly in the surface horizons. Because the clay was a binding agent of soil aggregates (Hillel, 1998), it probably was less influenced by water erosion than the sand fraction. The content and CV of clay were similar with depth for all soils, suggesting the development of these soils was consistent in parent material and soil formation.

Table 3.5. Coefficients of variation (%) of the textural components of soils.

Particle size	Forest	10-yr	25-yr	40-yr
----0- to10-cm depth----				
Sand	40	38	22	43
Silt	13	28	16	20
Clay	15	12	10	21
----10- to 20-cm depth----				
Sand	32	39	24	50
Silt	11	36	38	18
Clay	13	12	24	18
----20- to 40-cm depth----				
Sand	35	41	25	51
Silt	13	34	18	19
Clay	15	9	14	17

Coefficients of variation for the Al and Fe oxides were between 13 and 40% (Table 3.6), indicating that the variability of these soil components is moderate. The greatest CVs were associated with the DCB extractable Fe and Al in the surface horizon of the 25- and 40-yr-old soils, which may reflect a change in mineral composition in response to increased exposure to air and moisture as a result of cultivation.

Table 3.6. Coefficients of variation (%) of free aluminium and iron content of soils.

Depth (cm)	Forest	10-yr	25-yr	40-yr
---- Al extracted by DCB ----				
0-10	13	15	20	38
10-20	15	13	19	30
20-40	13	14	19	37
---- Al extracted by oxalate acid ----				
0-10	22	14	13	24
10-20	18	24	13	19
20-40	21	13	17	21
---- Fe extracted by DCB ----				
0-10	17	16	31	40
10-20	15	18	24	23
20-40	15	18	28	33
---- Fe extracted by oxalate acid ----				
0-10	25	32	23	28
10-20	31	22	25	29
20-40	18	21	21	30

3.3.6 Classification of the Study Soils

The soils were classified based on the intrinsic properties of the soil such as clay mineralogy, soil texture, and soil morphology, as well as environmental factors such as soil temperature and moisture (Soil Taxonomy, 1998). Variations in texture, particularly clay content, from horizon to horizon can be used to depict the pedogenic and geological history of a soil and associated geomorphic surface (Birkeland, 1999). In all soils, the clay content increased with depth and was 1.2 times higher at 40- to 80-cm than in the upper layers (Table 3.3, and Figure 3.1). Although no clear evidence of an E (eluviated clay) horizon was observed, there were some patchy clay films on ped faces and on gravel at depth, both in the forested and cropped soils. Based on criteria from Soil Taxonomy, the 40- to 80-cm depth in the cropped soils and the 42- to 82-cm depth in the forested soils were designated as argillic horizons. The presence of an argillic horizon with low base saturation indicated that the soils were Ultisols (Soil Survey Staff, 1975).

A "kandic" horizon is defined as a subsurface with at least 1.2 times the clay of the overlying horizon (within a vertical distance of 15 cm) and well developed subangular blocky structure, which often occurs in Ultisols (Buol et al., 1997). Kandic often refers to soil that has a regular decrease in organic carbon and an apparent low activity clay (LAC) defined as soil material with a cation exchange capacity (CEC) equal to or less than 16 cmol kg^{-1} and effective cation exchange capacity (ECEC) less than 12 cmol kg^{-1} (Soil Taxonomy, 1998). Kandic horizons in the study soils (resembled with argillic horizons) because as mentioned in the next chapter these soils had regular decreases of organic carbon with depth, and their ECEC and particular CEC were low and met the charge requirements of LAC (Dang and Anderson, 2000).

It is necessary to verify this soil classification with an examination of the criteria for Oxisols, since the Ultisols are very close to the Oxisols in terms of soil forming processes (Birkeland, 1999). The soils were developed from acidic parent materials, with a mineralogy that is predominantly kaolinite, associated with hydroxy-interlayered 2:1 minerals such as mica and vermiculite as shown earlier. The clay minerals were either inherited from the parent materials or the product of weathering (Birkeland, 1999). The study area was characterized by undulating hills, representing a weathered landscape from sedimentary materials (Nguyen and Thai, 1999). Clay minerals as vermiculite and mica were attributed to the weathering products of micaceous materials in the shale parent material. The continuous weathering of clay minerals might begin with illite (mica) to form biotite and muscovite. Biotite is then possibly altered to vermiculite or other minerals, depending upon conditions of alteration. At the same time, the combined depotassication and desilication of illite may yield kaolinite (Keller, 1964). The mixture of 1:1 clay minerals with some 2:1 clay minerals associated with the gradual increase in clay content with depth indicated that there was no oxic horizon in these soils. Hence, the tea soils were not classified as Oxisols; instead, they were classified as less weathered Ultisols (Soil Taxonomy, 1998).

The study area has an ustic soil moisture regime with one pronounced rainy season (March to November), and a dry period of more than 90 days. This places the soils in the suborder Ustult. Ustult soils have a clay decrease of approximately 20% from maximum clay content with increasing depth and do not have more skeletant (silt coatings) in that layer. Therefore, the great group is Kanhaplustult (Soil Taxonomy 1998).

3.4 Synthesis and Discussion

Soil profile descriptions indicate that the study soils are moderately deep with little mixing of stones in the surface horizons. The granular to medium sub-angular blocky structure is favorable for tea crops (Do, 1980). The surface soil structure was finer in the cropped soils than in the forested soils. The number of small animal channels and medium pores by visual observation were less in the cropped soils, suggesting the effects of cultivation on these soils. The reddish yellow soil color indicated oxidizing conditions of iron oxide minerals, a rich mineral in these soils. The iron and aluminum oxides are the most abundant metallic oxides in the earth's surface, particularly in tropical soils. They play a vital role in soil formation, and dynamics or fates of nutrients in the soil environment (Huang and Wang, 1997). The most important influence of Fe and Al oxides in soils is increased P and micronutrient adsorption capacity, resulting in decreased nutrient availability by plants (Juo, 1981; Tiessen et al., 1993b; Birkeland, 1999). They also influence soil physical properties by stabilizing soil aggregates, in which the stable aggregates are heavily coated with Al and Fe oxides (Huang, 1988).

The soils are clayey, with clay contents as high as 42% to 46% in the surface layer and increasing with depth. The presence of a Bt horizon, with very high clay contents at depth (40- to 90-cm), may limit root growth into the sub-soil layer. Thus, although tea is perennial crop with a tap root system (Do, 1980), the active root zone area was defined as the surface 0- to 40-cm. In general, soils containing large amounts of fine clay have more chemical activity because of their high surface area (Huang, 1990). Many other soil properties such as OM, nutrient content and degree of aeration are also closely related to soil texture (Birkeland, 1999).

The particle distribution and Al and Fe oxides were not statistically different between the forest and cropped soils or among the cropped soils. The particle size distribution was uniform with depth and there was no difference among the soils, suggesting that there was no change in texture due to erosion. Similarly, the change of Al and Fe in the soils was minor, perhaps due to the short time frame. In addition, similar inherent properties in the forest and the cropped soils suggest these soils have undergone similar development.

Ultisols with a kaolintic mineralogy are relatively infertile, with a low CEC, and a high content of Al and Fe oxides (Juo, 1981; Hughes, 1981). All soil have a kandic horizon, which resembled with argillic horizon, at 40- to 80-cm depth, with up to 60% clay, limiting root growth in this layer. All soils are considered to be Kanhaplustults, and are reasonably uniform in the forest and cropped sites. Major differences in dynamic properties such as organic matter and nutrient content can be attributed to cultivation.

4. Dynamic Soil Properties Under Long-term Tea Cultivation Systems in the Northern Mountainous Zone of Vietnam

4.1 Introduction

An important component in evaluating soil quality, and the resulting sustainability of agricultural systems is the monitoring of a soil's dynamic properties (Larson and Pierce, 1994). This reflects the fact that dynamic properties are always in a state of flux, responding to environmental and management forces. The concept of "dynamic soil quality" makes clear that soil properties are subject to change with time, and that change is governed mainly by land use, management practice and soil type (Wang and Gong, 1989). Changes in soil quality occur over both the short- and long-term, depending on which soil property is being assessed. For example, changes in total soil organic matter (OM) may be observed during a period of years to decades, whereas a change in soil pH, nutrient mineralization or labile OM may require a period of only months to years (Carter et al., 1997).

Efforts to identify the minimum data set that can be used to evaluate changes in soil quality require an assessment of the soil's dynamic properties integrating soil physical, chemical and biological properties (Doran and Parkin, 1994; Larson and Pierce, 1994). Whereas both qualitative and quantitative aspects of dynamic soil properties may be assessed (Larson and Pierce, 1991; Harris and Bezdicek, 1994), quantitative measures are more critical to a soil quality assessment than are qualitative estimates of soil quality (Larson and Pierce, 1991).

Tea is a perennial crop in the tropics, with tea plantations remaining productive for several decades. Thus, cultivation-induced changes in soil quality can be assessed by examining changes in the soil's dynamic properties under long-term cultivation. Long-term tea cultivation influences soil chemical properties such as pH, Al^{3+}, OM and nutrient supplying power (e.g., N, P, K and Mg) (Do et al., 1980; Li and Ding, 1992; Wang et al., 1997). As most tea soils are characterized by low pH and high Al^{3+} (Ranganatan and Natesan, 1985), P fixation has resulted in P deficiencies becoming a world-wide problem for tea cultivation (Lin et al., 1991; Wang et al., 1997). One consequence of a change in soil chemical properties is a change in biological properties such as population and growth of soil organisms (Hayatsu, 1993b). Long-term tea cultivation also influences soil physical properties such as bulk density, air-filled porosity and water retention (Othieno, 1975; Ananthacumaraswamy et al., 1988).

Most tea fields in Vietnam are located on upland areas with slopes ranging from 15- to 25-degrees. The initial change in land use from forested to cropped soils is reflected in a change in the more dynamic soil properties (Jordan, 1985). In addition, changes in dynamic soil properties also reflect the various management practices that farmers have adopted.

It is hypothesized that long-term cultivation of tea degrades soil quality, thereby reducing both the productivity and sustainability of tea production. The major objectives of this study were to: 1) quantify changes in dynamic soil properties resulting from forest clearance and long-term tea cultivation; and 2) identify external factors affecting the change in soil properties, such as landscape position and management.

4.2 Materials and Methods

4.2.1 Research Design and Soil Sampling

A series of tea plantations ranging from 1- to 40-years old, with native forest as the control, were sampled during the winter growing season in 1999 and 2000. There was a minimum of three randomly selected replicate fields for each age class.

Representative upper and lower back slope position (n = 3) were sampled at each field site. At each landscape position within a field, a grid (10-m x 7-m) was established and five sub-samples were collected at depths of 0- to 10-cm, 10- to 20-cm, and 20- to 40-cm. The sub-samples were then combined to form a composite sample for each depth increment. In addition, soil pits were dug in the upper and lower landscape positions at each field site (except at the 1- and 10-yr-old tea plantations) and additional samples collected from the 40- to 60-cm and 60- to 80-cm depths. All soil samples were air-dried, passed through a 0.14-mm sieve, and shipped to the Department of Soil Science, University of Saskatchewan for further analyses. Soils were analyses for organic C (OC), total N, S, P, K and Cd, available K, P fractionation, and exchangeable cations as described in the following sections.

Core samples collected from each landscape position (at depths of 0- to 10-cm and 10- to 20-cm) were used to determine the bulk density and plant available water capacity (PAWC) of the soils. Separate core samples were collected at a depth of 0- to 20-cm for soil aggregate analysis and the determination of the mean weight diameter (MWD). To avoid problems associated with compaction, shattering and puddling of the soils, these samples were collected when the soil was moist and were kept intact until they were analysed in the laboratory at the National Institute of Soils and Fertilizers in Hanoi, Vietnam.

4.2.2 Plant Sampling and Plant Measurement *in situ*

Plant tissue sampling. Plant tissues (i.e., young leaves, mature leaves, branches and stems) were collected in October 2000. Tissues samples were collected from randomly placed subplots (1 m^2, n = 5) in each field and combined to form a composite sample for each tissue type. Plant tissue samples were then dried immediately at 60°C (Anderson and Ingram, 1993).

Crop yield. Yield data were obtained monthly in 2000 with the assistance of technicians from the Agriculture and Forestry College of Thai Nguyen University in Vietnam. Yield samples (n = 5) were collected from randomly placed sub-plots (1 m^2) in each field, weighed and dried. Yield data were based on oven dry weights and expressed as Mg ha^{-1}.

Measurement of pruning and above ground stand biomass. Pruning biomass samples (n = 5, 1 m^2 each) were collected immediately after the tea plantations were pruned (once per year). Above-ground biomass was determined on three trees in each field after pruning, with the plants cut and partitioned into three components: leaves, stems, and branches. All plant samples were weighed immediately after cutting and a sub-sample oven-dried to estimate dry weight.

4.2.3 Earthworm Population Sampling

Earthworm populations were monitored monthly using a hand sorting method (Anderson and Ingram, 1993; Baker and Lee, 1993). Five random 25-cm x 25-cm blocks from two depths (0- to 10-cm and 10- to 20-cm) of soil in each field were collected. The soils were then passed through a 10-mm sieve, the earthworms removed by hand and counted.

4.2.4 Laboratory Methods

Soil analyses

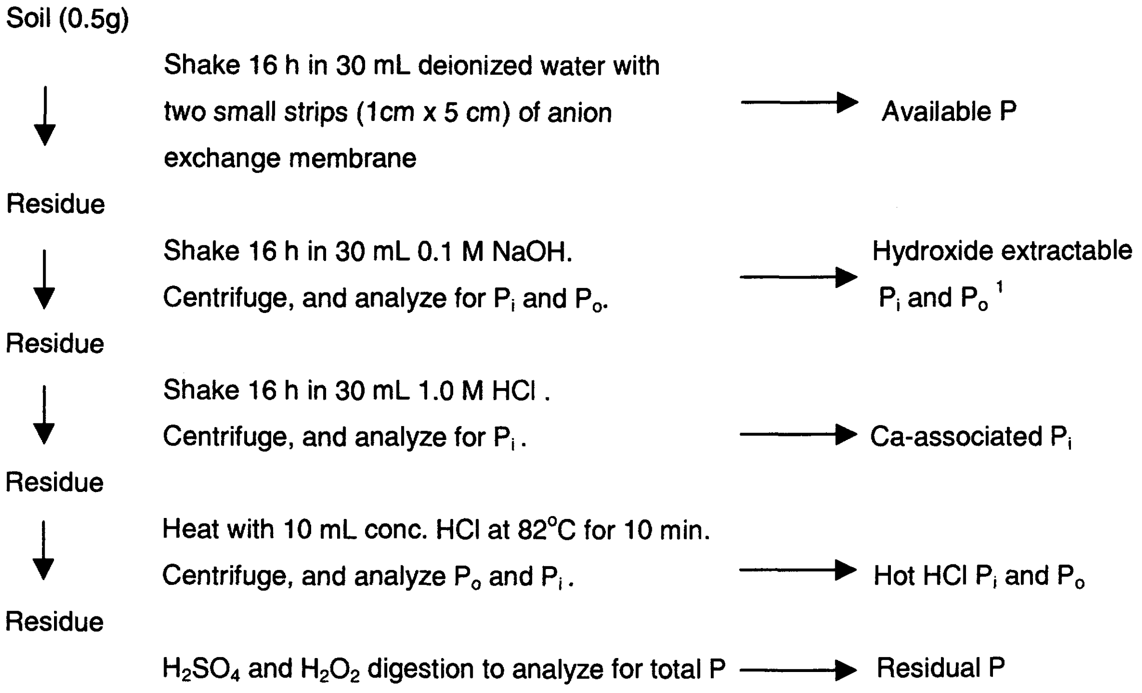
Chemical analyses. Soil pH was measured on 1:1 soil:water suspensions, which were stirred and allowed to settle for 30 minutes, and then measured by using a Radiometer PHM82 pH meter.

Soil organic C and total N and S were measured using the CNS combustion method and a LECO CNS-2000. The furnace temperature was set to 1350°C for total C, N, and S analysis from 0.25 g soil samples.

Total P and K were extracted using 0.25 g soil samples digested with concentrated H_2SO_4 and H_2O_2 (Thomas et al., 1967). Phosphate in the digests was then measured using a Technicon autoanalyser. Potassium was determined using atomic emission spectrometry (AES). Total Cd was determined using atomic absorption spectrophotometer (AAS) following digestion with concentrated HNO_3, $HClO_4$ and HF (Sheldrick, 1984).

Available K was extracted by using the cation membrane method described by Qian et al. (1992), followed by analysis using AES.

Phosphate fractions were extracted using a fractionation scheme adapted from Hedley et al. (1982) and Tiessen and Moir (1993) (Fig.4.1). The $NaHCO_3$-extractable P fraction was not determined based on knowledge that resin P in tropical soils includes most of the available P (Maroko et al., 1999).



[1] Pi - inorganic P, and Po – organic P

Figure 4.1. Flow chart of sequential extraction procedure for phosphorus.

Exchangeable cations were extracted using 0.1 M $BaCl_2$ (Hendershot and Duquette, 1983; Hendershort et al., 1993). Soil samples (3 g) were shaken on an end-over-end shaker for 2 h with 30 mL of 0.1 M $BaCl_2$, followed by centrifugation (700 x g) for 15 minutes. Cations in the supernatant were measured using AAS, except for Na and K which were determined using AES. The summation of Ca, Mg, K, Na and Al was termed the effective cation exchange capacity (ECEC). Base saturation was defined as the % ECEC occupied by the sum of the Ca + Mg + K + Na. Aluminum saturation was defined as the % ECEC occupied by exchangeable Al (Tisdale and Nelson 1975).

Physical analyses. Bulk density was estimated using a core method (Kalra and Maynard, 1991) in which an undisturbed soil core was collected by means of a metal cylinder of known volume. Soil samples were weighed and subsamples oven dried to calculate the soil moisture content and oven dry weight. Total porosity was calculated from bulk density and the particle density (assumed to be 2.65 Mg m^{-3} for most mineral soils) (Hillel, 1998). Field capacity and the permanent wilting point were determined at 0.033 and 1.5 Mpa, respectively (Anderson and Ingram, 1993). Plant available water capacity (PAWC) was estimated from the difference between the field capacity and the permanent wilting point.

Mean weight diameter (MWD) of aggregates was measured using a modified wet sieving method (Angers and Mehuys, 1993). Fifty grams of air dry soil that had passed through an 8-mm sieve was placed in the upper sieve of a nest of sieves with openings of 5-, 3-, 1-, and 0.2-mm. The sieves were lowered into water until the top sieve was level with the surface. The soils were allowed to wet for about 10 minutes, after which the sieves were moved upward and downward 50 times by hand. Each size fraction was then collected and oven dried. The MWD was then calculated as the sum of the products of the mean diameter of each size fraction and the proportion of the total sample weight occurring in the corresponding size fraction, which can be expressed as:

$$MWD = \sum_{i=1}^{n} XiWi$$

where Xi is the mean diameter of the size class i, and Wi is the proportion of the sample's weight found in size class i.

Mechanical resistance was measured by using a base surface cone penetrometer (Davison, 1965). The penetrometer was held in a vertical position and the cone point was forced slowly downward into the soil at a uniform rate. At each tea field, three test grids (10-m x 7-m) at each slope position, were examined. Five random zigzag penetrations were repeated in each testing grid and the readings were averaged.

Plant analyses

Dry plant samples were ground to ≤ 2 mm. Total C, N and S were measured on 0.25 g samples with a LECO CNS-2000 and a furnace temperature at 1350°C. Total P, K, Ca, Mg, Fe, and Al were extracted by H_2SO_4-H_2O_2 digestion method for 0.25 g plant samples (Thomas et al., 1967). Phosphate in the digestion solution was measured by a Technicon autoanalyser. The total K in the solution was determined using AES. Total Ca, Mg, Fe and Al were measured by AAS.

4.2.5 Statistical Analysis

The SPSS software program (Norusis, 2000) was used for the data processing and analysis. Means comparisons were carried out using the F- and T-statistics, with a level of probability of 5%. Pearson correlation analysis was applied to identify the relationships among soil properties.

4.3 Results and Discussions

4.3.1 Soil Quality–Time and -Landscape Relationships

Based on an F-test for a two factorial treatment model, statistically significant differences in soil chemical and physical properties were found only for the time factor (Table 4.1). Similar results also were found for the other soil depths (i.e., 10- to 20-cm and 20- to 40-cm) (data not shown). That there were no differences in soil properties between the upper and lower slope positions suggested that the soil erosion was not serious in the tea fields, possibly because tea rows were planted along the contour and at a high plant density. These row contour lines have been shown to be highly effective at preventing soil erosion as the tea crop matures (Dau et al., 1998). This suggests that changes in soil properties, in response to long-term tea cultivation, are mostly due to management factors, rather than the effects of landscape position.

Table 4.1. Statistically significant difference (P>F) of time and slope factors and their interaction (at 0- to 10-cm depth).

Properties	Slope factor	Time factor	Interaction
Total C (mg g^{-1})	0.77	0.03	0.52
Total N (mg g^{-1})	0.32	0.05	0.69
Total P (μg g^{-1})	0.29	0.01	0.83
Total K (mg g^{-1})	0.45	0.03	0.96
Total S (mg g^{-1})	0.42	0.08	0.09
Total Cd (μg g^{-1})	0.56	0.16	0.70
Available P (μg g^{-1})	0.34	0.02	0.92
Available K (μg g^{-1})	0.56	0.00	0.32
pH	0.56	0.00	0.72
Bulk density (Mg m^{-3})	0.69	0.00	0.96
Porosity (%)	0.69	0.00	0.96
PAWC[1] (% Vol.)	0.41	0.00	0.53
MWD[1] (mm)	0.73	0.02	0.44
Mechanical resistance (MPa)	0.18	0.03	0.67

[1] PAWC: Plant available water capacity; MWD- Mean weight diameter of aggregates.

4.3.2 Dynamic Soil Properties

Organic carbon and total N. In general, the organic carbon (OC) content of the soils decreased as a result of cultivation (Fig. 4.2). This was especially apparent in the upper 40 cm of the soil profile, where the OC content exhibited a significant ($P \leq 0.05$) decrease during the first ten years of cultivation. Changes in soil OC content during the next 30 years of tea production, however, were minimal, suggesting that the soil OC had reached a steady state (or equilibrium) condition. That is, the rapid decline in soil OC during the first decade of tea production most likely reflects an increase in the rate of decomposition of the organic matter (OM), as well as a decrease in the amount of organic matter being returned to the soil as fallen leaves and plant debris (Li and Deng, 1992). As the age of the tea plantations increased, the rates of OM decomposition and organic matter renewal from fallen leaves, plant prunings, and decaying roots eventually reached an equilibrium, with little or no net change in soil OC. Similar trends have been observed in both temperate and tropical agricultural systems (Uexkull, 1984; Pennock et al., 1994; Acton and Gregorich, 1995b).

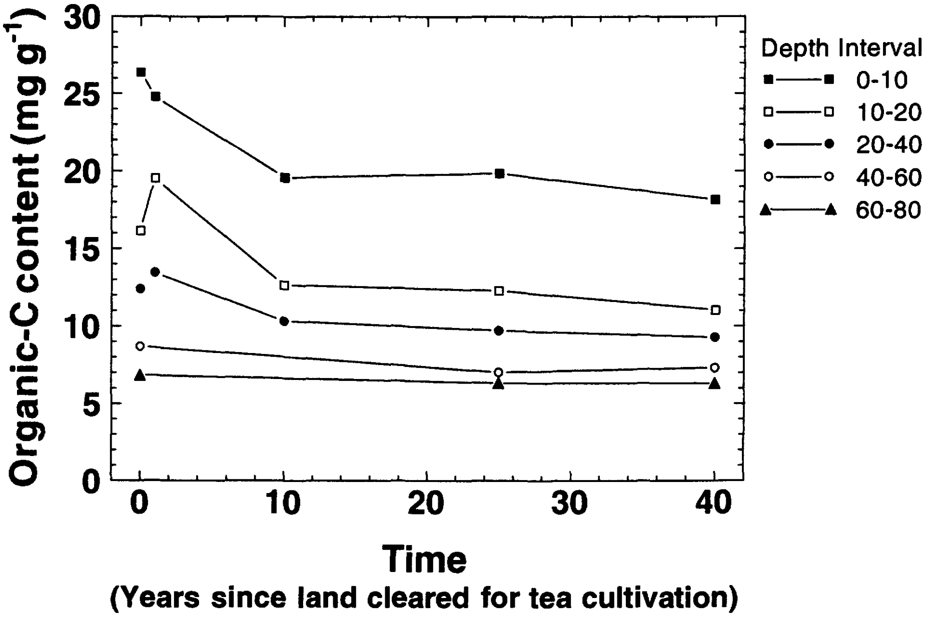


Figure 4.2. Effect of long-term cultivation and tea production on soil organic C.

Whereas there was a small decrease in the OC content in the surface soil (0- to 10-cm) during the first year following clearing and burning of the native forest (Fig. 4.2), the soil OC content of the 10- to 20-cm sample exhibited a significant ($P \leq 0.05$) increase during the same period. Presumably, this reflects a degree of vertical mixing of the OM at the time the land was broken for cultivation as well as some downward movement of soluble and colloidal organic matter during the ensuing year. A similar (though not significant) change was observed at the 20- to 40-cm depth.

The change in soil OC content in the subsurface soils (40- to 80-cm) exhibited a trend similar to that of the surface soils (Fig. 4.2). In the subsurface soils, however, changes in soil OC with 40 years of cultivation (ΔOC_{40}) were generally much smaller than those in the surface soils and were not significant ($P \leq 0.05$). These results indicate that tillage operations have a significant impact on soil OC content, and that changes in soil OC below the plow layer (i.e., below the zone of active cultivation) occur only very slowly. Consequently, soil OC should be viewed as a 'dynamic soil property' only as it relates to the surface horizons.

It should be noted that OC contents reported on a weight basis (as in Fig. 4.2) fail to take into account the fact that the bulk density of the soil tends to increase as the age of the tea plantations increases. Changes in bulk density can be accounted for, however, by expressing the soil OC content on a volume basis (e.g., as kg m^{-3}). Indeed, transforming the soil data to a volume basis resulted in much larger OC values in the surface soils collected from older tea plantations. However, expressing the soil OC on a volume basis had no significant effect on the overall trend observed (data not shown). That is, soil OC decreased significantly ($P \leq 0.05$) during the first 10 years of cultivation, but exhibited little change thereafter at all depths.

Like OC, the total N content of the soils tended to decrease with time following clearing of the native forest (Fig. 4.3). Moreover, the decrease in total N (at the 0- to 10-cm, 10- to 20-cm, and 20- to 40-cm depths) was greatest during the first 10 years of cultivation, reaching a steady state after 10- to 25-yr of continuous tea production. Data analysis (Appendix 3) revealed a strong correlation between total N and soil OC ($r = 0.88^{**}$), suggesting that the decrease in total N with time reflects a concomitant decrease in soil organic matter. As with the soil OC, total N in the 40- to 60-cm and 60- to 80-cm samples exhibited no significant change during 40 years of cultivation and tea production.

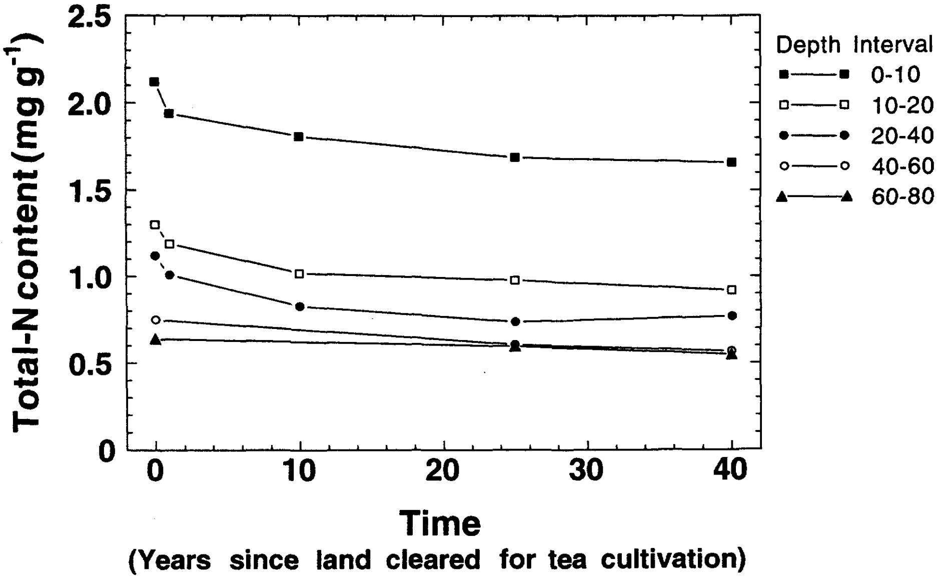


Figure 4.3. Effect of long-term cultivation and tea production on total soil N.

Carbon:nitrogen (C:N) ratios in the forest soil ranged from 10.2 to 12.4 and, as in most soils, decreased with increasing depth (Table 4.2). In the cultivated soils, C:N ratios ranged from about 10.6 to 16.4 and were generally higher following short-term (1-yr) cultivation than long-term cultivation. Whereas this is primarily a reflection of the greater soil OC content of the 1-yr cultivated soil (Fig. 4.2), it may also reflect the effects of increased microbial activity in the newly cleared and cultivated soil. However, following long-term cultivation and tea production, C:N ratios in the surface (0- to10-cm) soil were generally lower than those in the forest soil. Whereas this undoubtedly reflects the addition of fertilizer N to the cropped soils, it may also reflect the recycling of N in fallen leaves and plant prunings. Indeed, it is reasonable to assume that the type (quality) of organic matter being returned to the soil was different in the cropped systems than in the forest. On the other hand, at depths greater than 20 cm, the C:N ratios of the cultivated soils were generally greater than those of the forest soil, reflecting the fact that cultivation-induced decreases total-N were generally smaller than the concomitant decreases in OC (see Figs. 4.2 and 4.3). Increased C:N ratios at depth in the cultivated soils may also reflect the effects of N uptake by the tea plants. Moreover, these results demonstrate that the C:N ratio of the below-ground biomass is significantly different from that of the above-ground biomass.

Table 4.2. Effect of long-term cultivation and tea production on C:N ratios.

Depth (cm)	Forest	1-yr	10-yr	25-yr	40-yr
0–10	12.44	12.77	10.82	11.75	10.95
10–20	12.42	16.40	12.40	12.54	12.02
20–40	11.08	13.33	12.45	13.15	12.08
40–60	10.22	NA[1]	NA	11.52	12.86
60–80	10.70	NA	NA	10.57	11.53

[1] NA: not available.

Total sulfur. Sulfur (S) deficiencies in intensively cultivated tea soils have been reported in India, Sri Lanka, Bangladesh, and China (Takkar, 1986; Verma et al., 1993; Yong and Ye, 1992), but have not been reported for tea soils in Vietnam. Relative to the native forest soil, there was an increase in the total S content of the 1-yr cultivated tea soils (Fig. 4.4), which presumably reflects the addition of S in ash from the burned forest vegetation. Total S concentrations in the 10- and 25-yr-old tea soils also were increased relative to the forest soil, though these increases could be attributed to sulfate (SO_4^{2-}) additions during the application of potassium (K_2SO_4) and ammonium [$(NH_4)_2SO_4$] fertilizers. On the other hand, the 40-yr-old tea soils received fewer fertilizer inputs, resulting in total S contents that were not significantly different from those in the native forest and 1-yr-old tea soils.

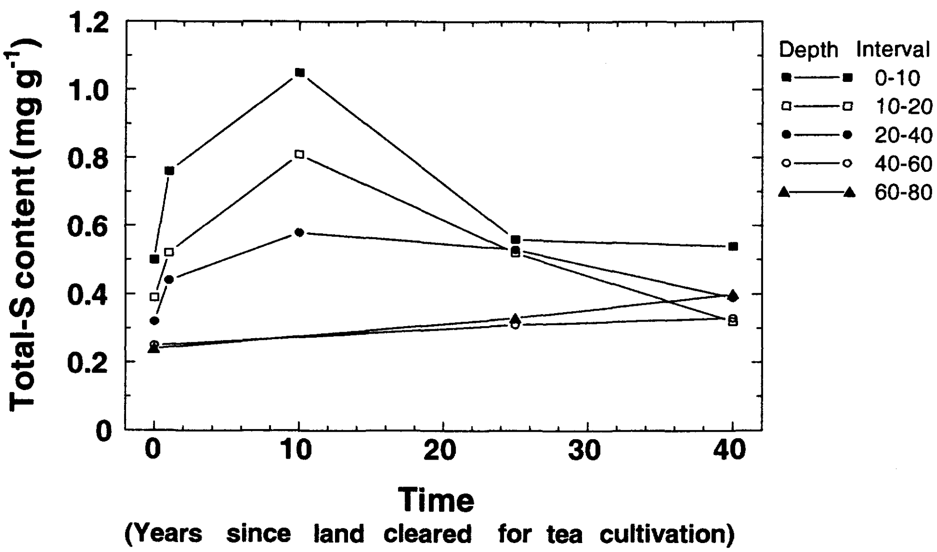


Figure 4.4. Effect of long-term cultivation and tea production on total soil S.

The trend in total S content versus time exhibited the same pattern at all three sampling depths in the top 40 cm of soil. However, total S concentrations in the 0- to10-cm samples were characterized by an extremely high degree of variability (CVs = 20% to 63%); consequently, no significant differences were detected. Conversely, total S concentrations in the 10- to 20-cm and 20- to 40-cm samples were characterized by much lower degrees of variability (CVs = 16 to 40%) and significant ($P \leq 0.05$) differences were detected in the 10- and 25-yr-old tea soils.

Total and available potassium. Total K concentrations in the native forest soil were generally greater than those in the cultivated soils (Fig. 4.5). Plant available K, on the other hand, was generally greater in the cultivated soils than in the forest soil (Fig. 4.6).

Moreover, there was a significant ($P \leq 0.05$) increase in the available K content of the surface (0- to 10-cm) soil during the first year of cultivation. Whereas this increase could be attributed to nutrient deposition in the ash produced by burning the original forest vegetation (Jordan, 1985), the relative increases observed after 10 and 25 years of cultivation reflect the addition of fertilizer K and, most likely, the release of nonexchangeable K from clay minerals. Indeed, the decrease in total K observed in the 10-yr-old tea soils presumably reflects the release, and subsequent plant uptake (perhaps even including luxury consumption of K by the tea plants) of nonexchangeable K. Thereafter, any excess K added to the soil as fertilizer (i.e., K exceeding the plant requirement) would most likely be bound to the clays in nonexchangeable forms, thus increasing the amount of total K in the soil. As with total S, however, the 40-yr-old tea soils received fewer fertilizer inputs, again resulting in a decrease in both the total and available soil K.

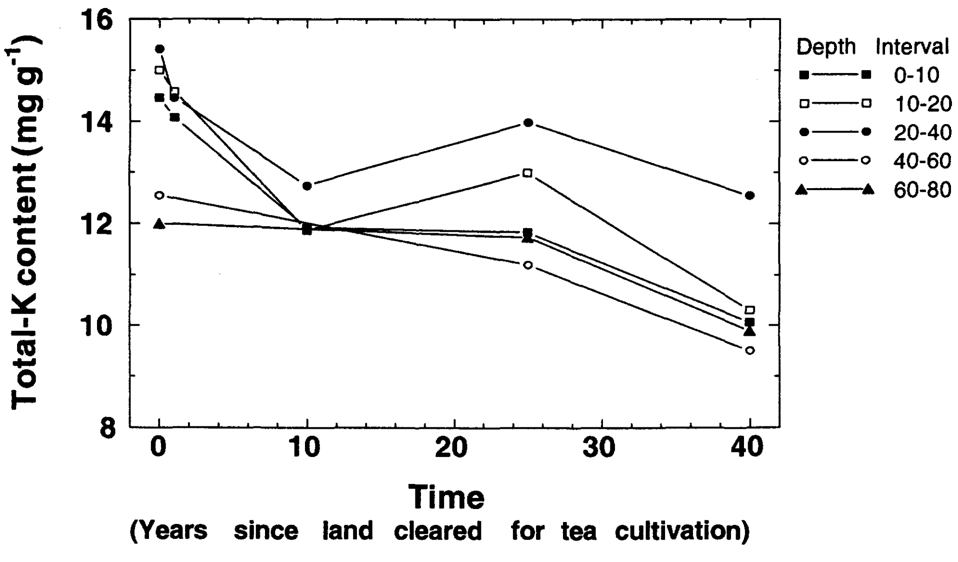


Figure 4.5. Effect of long-term cultivation and tea production on total soil K.

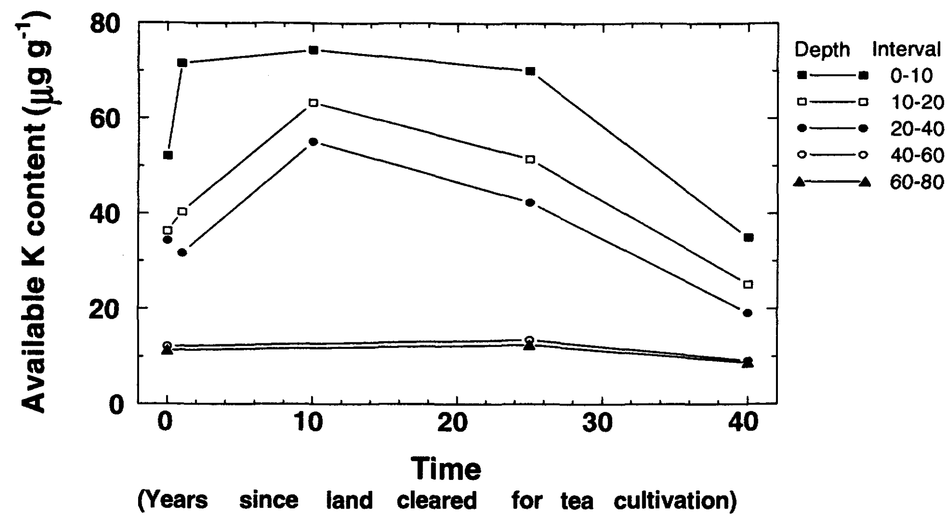


Figure 4.6. Effect of long-term cultivation and tea production on available soil K.

Total phosphorus. With the exception of the surface (0- to 10-cm) soil, total P concentrations in the forest soil were generally the same as those in the cultivated soils (Fig. 4.7). That is, there were no significant differences between tea soil age classes. On the other hand, the amount of total P in the surface layer of tea soils cultivated for 10- to 40-yr was significantly ($P \leq 0.05$) greater than that in the forest soils. This reflects the fact that the soils of the Northern Mountainous Zone of Vietnam have a high potential to fix added P. Thus, P being the most limiting plant nutrient, large amounts of P added as fertilizer were 'fixed' by the soil, resulting in the observed increase in total soil P.

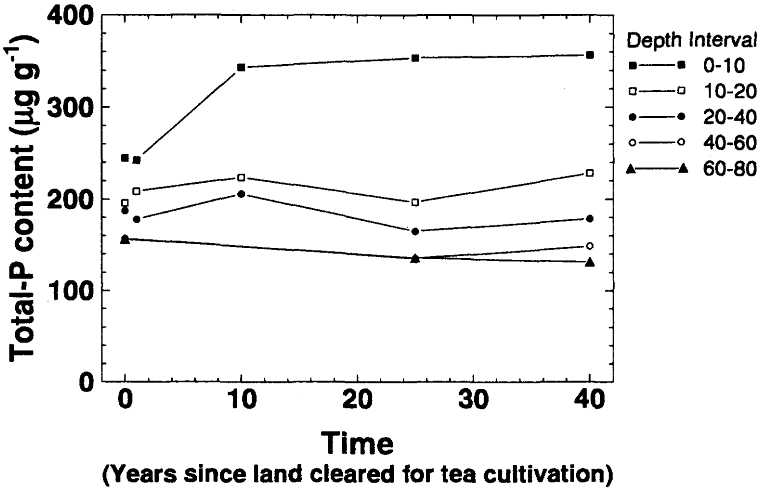


Figure 4.7. Effect of long-term cultivation and tea production on total soil P.

Phosphorus fractionation. Sequential fractionation of P separates the various forms of P into biologically meaningful fractions. Resin P is defined as the freely exchangeable inorganic P (Pi) fraction and, in tropical soils, includes most of the plant available P. Not surprisingly, plant available P in the tea soils (Table 4.3) exhibited a pattern similar to that of total P; i.e., soils receiving significant amounts of P fertilizer (the 10- and 25-yr old tea soils) exhibited greater available P concentrations ($P \leq 0.05$) than the forest, 1- and 40-yr-old tea soils. The sharp decrease in available P in the 40-yr-old tea soils was attributed to the combined effect of low P fertilizer inputs coupled with a high capacity for P fixation.

Inorganic P extracted with NaOH is considered to represent secondary P minerals associated with amorphous and crystalline Fe and Al (Williams et al., 1980). Given that the tea soils contain significant amounts of amorphous and crystalline Fe and Al oxides (see Chapter 3), which have a large capacity to fix P, it follows that much of the Pi added as PO_4-fertilizer would be bound in OH-extractable forms. Indeed, the amount OH extractable Pi in the surface layer of the cultivated soils (which accounted for 26% to 30% of the total P) was about three times that in the forest soil (Table 4.3). Moreover, the amount of OH extractable Pi in the 40-yr-old tea soil was little different from that in either the 10- or 25-yr-old tea soils, indicating that this fixed P was essentially bound in forms unavailable to the tea plants (Wagar et al., 1986). The dilute HCl extractable Pi represents the P in close association with Ca (Tiessen and Moir, 1993). Increased Ca-Pi in the cropped soils ($P \leq 0.05$; Table 4.3) was attributed, in part, to the use of superphosphate fertilizers (Wagar et al., 1986). However, as with most tropical soils, the tea soils of the Northern Mountainous Zone of Vietnam are acidic and, hence, are frequently limed for tea production. In turn, chemical reactions between the lime and superphosphate fertilizers would lead to the formation of Ca phosphates.

Table 4.3. Phosphate fractionation[1] of forest and soils under long-term tea cultivation.

Depth (cm)	0 (Forest)	1-yr	10-yr	25-yr	40-yr
Available P (μg g^{-1})					
0-10	7.97a[2]	8.61a	31.52b	20.26c	9.38a
10-20	2.93a	4.45a	9.38b	3.70a	2.66a
20-40	1.93a	1.75a	2.70a	1.35a	1.10a
Hydroxide-Pi (μg g^{-1})					
0-10	33.39a	NA[3]	94.73b	93.29b	105.37c
10-20	22.89a	NA	33.51a	28.16a	38.64a
20-40	20.03a	NA	26.32a	19.61a	24.47a
Ca-P (μg g^{-1})					
0-10	1.46a	NA	14.06b	22.87b	13.23b
10-20	1.42a	NA	5.86a	2.38a	2.16a
20-40	1.41a	NA	2.99a	1.67a	1.21a
Total Po (μg g^{-1})					
0-10	79.35a	NA	79.09a	89.40a	88.89a
10-20	57.97a	NA	50.58a	57.52a	66.66a
20-40	50.86a	NA	48.89a	38.38a	49.31a
Resistant P (μg g^{-1})					
0-10	114.60a	NA	129.29a	128.12a	140.93a
10-20	102.80a	NA	111.89a	93.15a	117.62a
20-40	112.12a	NA	108.71a	101.63a	115.04a
C/Po					
0-10	331a	NA	260a	236a	268a
10-20	279a	NA	257ab	239bc	198c
20-40	234a	NA	219a	258a	214a

[1] Available P is extracted by resin, Ca-Pi is inorganic P extracted by 1M HCL, Hydroxide Pi is inorganic P extracted by NaOH, Total Po is sum of organic fractions extracted by hot HCL and NaOH, Resistant P is an inorganic fraction extracted by hot HCL plus residue fraction extracted by H_2SO_4.

[2] Means in the same row followed by the same script do not differ significantly at 5% probability.

[3] NA- not available.

Total organic P (Po) contents were greatest in the surface horizon, accounting for 32% of the total P in the forest soil and 23% to 25% of the total P in the cropped soils, though there were no significant differences among the tea soil age classes (Table 4.3). Over the long-term, the dynamics of Po in soils is closely linked to that of the soil OC (Stewart and Tiessen, 1987) and fertilizer use (Beck and Sanchez, 1996). Dalal

(1977) suggested that the ratio of total OC to Po (C:Po) can be used to estimate the mineralization potential of Po in soils, with C:Po ratios greater than 200:1 indicating low mineralization potential. The C:Po ratios of the soils included in this study ranged from about 330 for the forest soil to 255 (± 14) for the cropped soils (Table 4.3). Thus, the soils have little potential for the mineralization of Po, suggesting that the Po is tightly bound in organo-mineral complexes associated with strongly humified organic matter (Lekwa and Whiteside, 1986).

The bulk of the soil P was present as recalcitrant (resistant) P (Table 4.3). That is, about 47% of the P in the forest soil and 38% of the P in the cropped soils was present in the residue remaining after the sequential extractions had been completed (Table 4.3). As with the Po, this residual P was not available for plant uptake and was essentially unaffected by cultivation history.

Soil pH and exchangeable cation composition. As expected, all the soils included in this study were acidic (Table 4.4) with pH values ranging from 4.2 to 4.4 in the forest and newly cleared (1-yr-old) soils to about 4.0 in the cropped soils. The lower pHs in the cropped soils ($P \leq 0.05$) were attributed to the cumulative effect of long-term fertilizer additions (i.e., the fertilizers used in tea production are acidic) and the release of organic acids during decomposition of the plant litter incorporated into the soil on an annual basis (Stevenson, 1982; Tabatabai et al., 1992). Given the low pH of the soils, it was to be expected that the effective cation exchange capacity (ECEC) of the soils would be dominated by Al^{3+}. Indeed, the soil exchange complex had an Al saturation index of 88% to 91%, with no significant differences among tea soil age classes. Whereas exchangeable Al concentrations as high as those reported here are generally considered toxic to most plant species, tea is well know for its ability to thrive in soils high in exchangeable Al (Liang et al., 1995; Johannes et al., 1998).

All base cations (i.e., K^+, Na^+, Ca^{2+}, and Mg^{2+}) were present at low concentrations, with only small differences (and no predictable pattern) among the various tea soil age classes. The small, but significant ($P \leq 0.05$) increase in exchangeable K^+ in the 10- and 25-yr-old tea soils, mirrors that of the plant available K observed earlier (see Fig. 4.6) and presumably reflects the impact of fertilizer additions.

Table 4.4. Weighted mean (0- to 40-cm) of pH and exchangeable cations of forest and soils under long-term tea cultivation.

Property	Forest	1-yr	10-yr	25-yr	40-yr
pH	4.20a[1]	4.40b	3.90c	3.94c	4.05d
K (Cmol kg^{-1})	0.10a	0.09a	0.15b	0.14b	0.08a
Na (Cmol kg^{-1})	0.06a	0.12b	0.04c	0.05c	0.04c
Mg (Cmol kg^{-1})	0.1a	0.15b	0.08a	0.05c	0.05c
Ca (Cmol kg^{-1})	0.23a	0.24a	0.24a	0.26a	0.27a
Al (Cmol kg^{-1})	4.53a	4.51a	4.73a	5.16a	4.76a
ECEC (Cmol kg^{-1})	5.02a	5.13a	5.26a	5.67a	5.11a
Base saturation (%)	10a	12a	11a	9a	9a
Al saturation(%)	90a	88a	89a	91a	91a

[1] Means in the same row followed by the same script do not differ significantly at 5% level of probability.

Soil bulk density and total porosity. Bulk densities in both the surface and subsurface layers of the cropped soils were generally greater than those in the forest and newly cultivated (1-yr-old) soils (Table 4.5). Cultivation-induced increases in bulk density ($P \leq 0.05$) were primarily attributed compaction resulting from the human and animal traffic associated with cultivation of the tea soils, as well as to the loss of soil organic matter accompanying cultivation (see Fig. 4.2). As a result of increased bulk densities in the cropped soils, there was a concomitant decrease ($P \leq 0.05$) in total soil porosity. This reduction in porosity could be expected to have negative impacts on the soil's capacity to store water, solutes (nutrients), and gases (Topp et al., 1997).

Table 4.5. Bulk density and total porosity of the forest and cultivated soils.

Depth (cm)	Forest	1-yr	10-yr	25-yr	40-yr
---------- Bulk density (Mg m^{-3}) ----------					
0-10	1.02a[1]	0.97a	1.15b	1.21c	1.22c
10-20	1.18a	1.13a	1.20b	1.28b	1.33c
---------- Total porosity (%) ----------					
0-10	63a	64a	57b	54c	54bc
10-20	56a	58a	53b	52b	50c

[1] Means in the same row followed by the same script do not differ significantly at 5% level of probability.

Soil mechanical resistance. Penetration resistance, as measured with a cone penetrometer, is considered to be a good measure of a soil's strength (Hillel, 1998). In general, mechanical resistance increased with depth, reflecting the increased clay content and bulk density of the subsurface soils (Table 4.6). In addition, mechanical resistance values were significantly ($P \leq 0.05$) greater in soils cropped for 25- or 40-yr than in the forest or 10-yr cropped soils. As with bulk density, greater mechanical resistance in the long-term cropped soils can most likely be attributed to the cumulative effect of animal and foot traffic on soil compaction.

Table 4.6. Soil resistance (MPa) of forest and soils under long-term tea cultivation.

Depth (cm)	Forest	10-yr	25-yr	40-yr
3	0.30a[1]	0.39ab	0.63bc	0.66c
5	0.81a	1.00a	1.23b	1.26c
10	1.54a	1.60a	1.99b	2.09b
15	2.23a	2.19a	2.60b	2.77b
20	2.77a	2.81ab	3.19bc	3.48c
25	3.40a	3.39a	3.81ab	4.09b
30	3.99a	3.91a	4.36ab	4.64b
35	4.48a	4.40a	4.71a	4.76a
40	4.88a	4.81a	4.95a	4.99a

[1] Means in the same row followed by the same script do not differ significantly at 5% level of probability.

Soil water holding capacity. The plant available water-holding capacity (PAWC) of a soil is calculated as the difference between field capacity (FC; water held in the at a matric potential of 0.033 MPa) and the permanent wilting point (PWP; water held in the soil at a matric potential of 1.5 MPa). The PAWC of the 25- and 40-yr-old tea soils, at both the 0- to 10- and 10- to 20-cm depths, was significantly ($P \leq 0.05$) lower than that of the forest, 1- and 10-yr-old soils (Table 4.7). Whereas cultivation had no significant effect on the PWP of the soils, long-term cultivation resulted in significant ($P \leq 0.05$) decreases in FC. These results are consistent with previous findings indicating that FC is more responsive to changes in soil porosity and organic matter content than is the PWP (Topp et al., 1997).

Table 4.7. Plant available water capacity (volumetric %) of forest and soils under long-term tea cultivation.

Parameter	Forest	1-yr	10-yr	25-yr	40-yr
---------- 0- to10-cm depth ----------					
FC[1]	40.03a[2]	41.26a	39.42a	37.53b	38.45b
PWP	26.85a	28.39a	27.19a	28.79a	28.87a
PAWC	13.18a	12.87ab	12.23b	8.74c	9.52c
---------- 10- to 20-cm depth ----------					
FC	43.71a	42.92a	41.78b	41.39b	39.40c
PWP	30.12a	29.09a	28.81a	29.52a	30.12a
PAWC	13.59a	13.83a	12.96b	11.86b	9.27c

[1] FC: field capacity; PWP: permanent wilting point; and PAWC: plant available water capacity.

[2] Means in the same row followed by the same script do not differ significantly at 5% level of probability.

Aggregate size distribution. The most important physical changes occurring in the soil as a result of management practice are structural in nature and often involve changes in soil aggregation. Consequently, aggregate analysis can be used as an indicator of soil structure. The mean weight diameter (MWD) of aggregates was lowest in the 10-yr soils, and somewhat higher in the 25- and 40-yr-old tea soils (Fig. 4.8). The MWD in the 25- and 40-yr soils suggests a highly resilient soil. Presumably, this reflects the fact that the soils contain a high content of clays and sesqui-oxides, which can act as cementing agents for stabilized aggregates (Hillel, 1998).

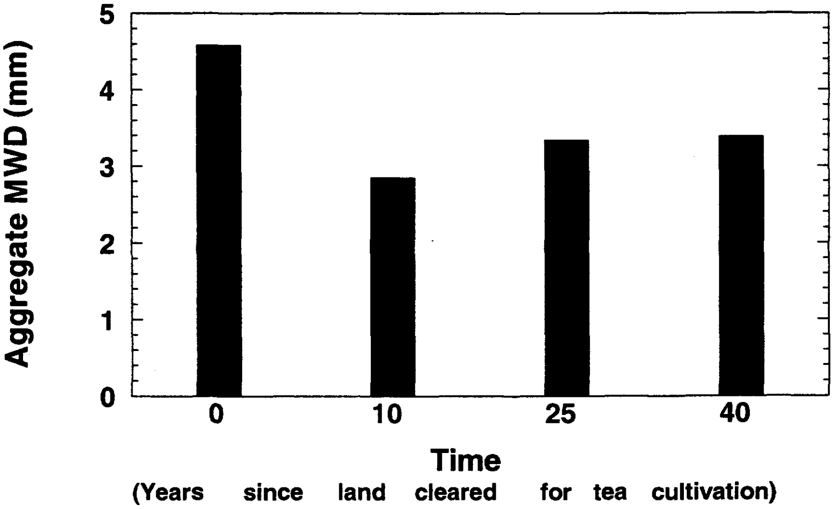


Figure 4.8. Aggregate distribution of forest and long-term cultivated soils.

Earthworm populations. Long-term cultivation had a significant ($P \leq 0.05$) negative impact on earthworm populations in both the surface (0- to 10-cm) and upper subsurface (10- to 20-cm) layers (Fig. 4.9). In addition, earthworm populations in the surface layer of the cultivated soils were significantly ($P \leq 0.05$) greater during the wet season (April to October) than during the dry season (November to March). On the other hand, earthworm populations in the subsurface layer were generally the same during the wet and dry seasons, the lone exception being the 25- and 40-yr-old tea soils, which yielded more earthworms in the dry season than the wet season.

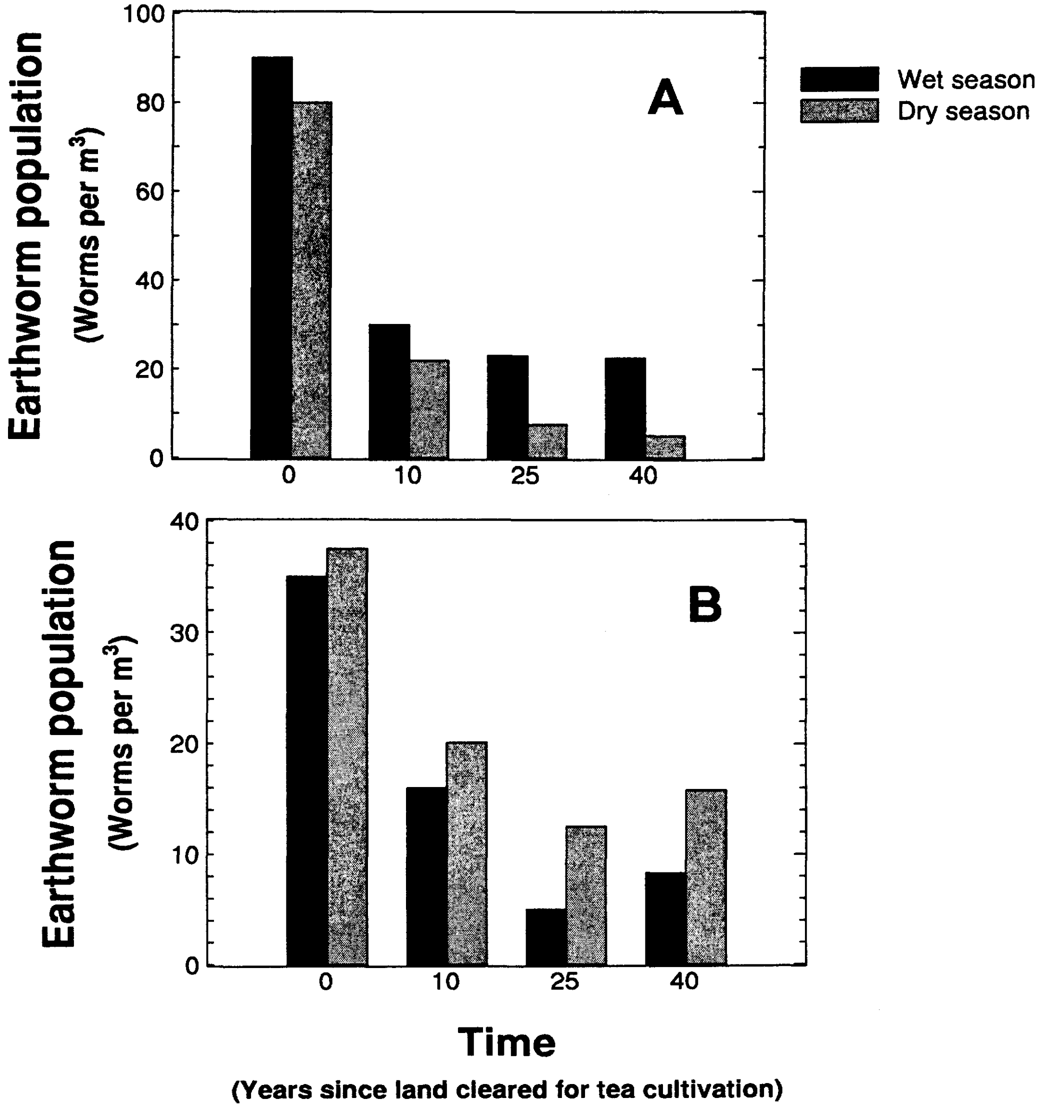


Figure 4.9. Effect of long-term cultivation on earthworm populations in the 0- to 10-cm (A) and 10- to 20-cm (B) depth increments.

Reduced earthworm populations in the cultivated soils most likely reflect changes in the quality and availability of food sources (i.e., soil organic matter) as well as changes in soil chemical and physical properties. For example, Linden et al. (1994) reported that cultivation-induced changes in soil physical (increased bulk density and mechanical resistance) and chemical properties (increased acidity and the accumulation of pesticide residues) could negatively impact earthworm populations. In turn, cultivation-induced decreases in earthworm population and activity could significantly impact the fertility status of the tea soils (Lodsdon and Linden, 1992). A reduction in the number of earthworms will result in decreased burrowing activity and organic matter turnover (ingestion, digestion, and excretion of the soil organic matter), producing a soil that is rather poorly aerated and has lower nutrient content and a decreased water holding capacity.

4.3.3 Management Factors Affecting the Change in Soil Properties

Plant biomass. Whereas continuous cropping had no significant effect on tea yields during the first 25-yr of cultivation, yields were decreased significantly ($P \leq 0.05$) in the 40-yr-old tea plantations (Table 4.8). Likewise, the total amount of plant material (leaves and branches) added to the soil in the form of prunings was the same in the 10- and 25-yr-old tea plantations, but was reduced significantly ($P \leq 0.05$) in the 40-yr-old tea plantations. Conversely, the above-ground biomass remaining after pruning increased in the order: 10-yr-old tea plants < 25-yr-old tea plants < 40-yr-old tea plants. This increase in total (post-pruning) stand biomass reflects the continuous accumulation of dry matter in the primary stems of the tea plants (Lodhiyal and Lodhiyal, 1997).

Table 4.8. Dry plant biomass and productivity of tea plantations.

Tea age	Tea yield (Mg ha^{-1} yr^{-1})	Plant prunings (Mg ha^{-1} yr^{-1}) Leaves	Branches	Standing state[1] (Mg ha^{-1}) Leaves	Stems
10-yr	3.06a[2]	2.17a	3.25a	1.99a	20.54a
25-yr	3.02a	2.06a	3.09a	1.86a	27.73b
40-yr	2.30b	1.66b	2.48b	2.08a	34.60c

[1] Measurement of the plant biomass after pruning;

[2] Means in the same column followed by the same script do not differ significantly at 5% level of probability.

The organic C and nutrients stored in the standing biomass represent a loss from the soil (though they will eventually be returned to the soil when the plantation is no longer economically viable and the stands are burned or plowed under). The carbon and nutrients removed with the harvest also are considered to be lost from the soil. Only the carbon and nutrients in the prunings are returned to the soil and, together with fertilizer additions, are essential to maintaining the fertility status of the soil and, in turn, tea productivity.

Plant nutrient uptake. Plant tissue analysis provides a means of assessing the plant uptake, and removal from the soil, of essential nutrient elements such as N, P, K, S, Ca, and Mg. Plant tissue nutrient concentrations also reflect the availability of soil nutrients and, thus, are useful indicators of soil nutrient deficiency (Pearcy et al., 1989; Lodhiyal and Lodhiyal, 1997). Indeed, Epstein (1972) suggested that nutrient concentrations in mature leaves could be used as indicators for soil deficiencies of the plant-mobile nutrients, whereas young leaves could be used as indicators for soil deficiencies of the less mobile nutrients.

In general, it was determined that plant nutrient concentrations in the tea stands decreased in the order: young leaves (and buds) > mature leaves > branches > stems (standing biomass) (Table 4.9). The lone exception was Ca–plant tissue concentrations of which were greatest in the mature leaves. These differences reflect the fact that nutrient elements such as N, P, K, S, and Mg are highly mobile and are often translocated from old leaves to young leaves prior to senescence and abscission (Marschner, 1995). Moreover, these results indicate that the harvested tea, which involves mainly the young leaves and buds, represents a significant, permanent removal of nutrients from the soil.

Results from this study also show that long-term cultivation had little effect on nutrient concentrations in the tissues of the tea plants (Table 4.9). That is, age of the tea plantations had no significant effect on tissue concentrations of N, Ca, or Mg. There were, however, significant ($P \leq 0.05$) differences between tea age classes for K (in both the young and mature leaves) and for P and S (in the mature leaves). The effect of tea age on K concentrations in the leaves follows a similar pattern to that observed for plant available soil K in the rooting zone (see Fig. 4.6), and suggests that there is some potential for K deficiencies to develop in the older tea plantations. Likewise, the data for P and S suggest an increased risk of nutrient deficiencies as the age of the tea plantations increases beyond 25 years.

Table 4.9. Concentration (%) of the major nutrient elements in plant tissues.

Tea age	N	P	K	S	Ca	Mg
------------ Young leaves and buds from harvesting ------------						
10-yr	6.02a[1]	0.41a	2.36a	0.38a	0.45a	0.23a
25-yr	5.75a	0.37a	2.25a	0.33a	0.44a	0.20a
40-yr	5.70a	0.36a	2.09b	0.35a	0.47a	0.23a
------------ Mature leaves from pruning and standing crop ------------						
10-yr	3.96a	0.20a	1.61a	0.32a	0.81a	0.18a
25-yr	4.06a	0.19ab	1.56b	0.29b	0.69a	0.15a
40-yr	3.90a	0.17b	1.52b	0.29b	0.70a	0.15a
------------ Branches from pruning ------------						
10-yr	1.02a	0.06a	0.59a	0.12a	0.30a	0.05a
25-yr	0.90a	0.05a	0.62a	0.13a	0.30a	0.04a
40-yr	0.99a	0.05a	0.55a	0.10a	0.31a	0.05a
------------ Stems from standing crop ------------						
10-yr	0.90a	0.05a	0.35a	0.11a	0.31a	0.03a
25-yr	0.91a	0.04a	0.40a	0.12a	0.39a	0.04a
40-yr	0.80a	0.04a	0.32a	0.12a	0.40a	0.05a

[1] Means in the same column followed by the same script do not differ significantly at 5% level of probability.

Nutrient budgets. Nutrient budgets were calculated by multiplying the nutrient concentration in the plant tissues by the amount of plant biomass produced during the 2000 growing season. The total amount of nutrients removed with the annual harvest was generally greatest in the 10-yr-old tea plantations, intermediate in the 25-yr-old plantations, and least in the 40-yr-old plantations (Table 4.10). The same pattern was observed for the pruned materials, though the total nutrient content of the prunings was generally less than that of the harvested tea. In addition, the cumulative amount of nutrients stored in the standing crop increased with increasing age of the tea plants. Fertilizer inputs (N, P, K, and Ca) generally surpassed the amount of nutrients removed with the harvested tea (Table 4.10).

Table 4.10. Nutrient budget of plant removals, recycling, storage and additions.

Tea age	N	P	K	S	Ca	Mg
---------------------------- Removed through harvest (kg ha^{-1} yr^{-1}) ------------------------						
10-yr	184	13	69	12	14	7
25-yr	174	11	66	10	13	6
40-yr	131	9	49	8	11	5
---------------------------- Recycled through pruning (kg ha^{-1} yr^{-1}) -----------------------						
10-yr	119	6	54	11	27	6
25-yr	112	5	51	10	24	5
40-yr	89	4	37	7	19	4
-------------------- Total accumulation in the standing plants (kg ha^{-1}) [1] ----------------						
10-yr	284	14	102	29	81	10
25-yr	325	16	140	39	120	15
40-yr	340	16	146	48	153	22
------------------------------- Added as fertilizer (kg ha^{-1} yr^{-1}) -----------------------------						
10-yr	205	88	81	NA[2]	168	NA
25-yr	194	90	83	NA	175	NA
40-yr	163	64	65	NA	204	NA
---- Balance between added as fertilizer and removed through harvest (kg ha^{-1} yr^{-1}) ----						
10-yr	21	75	12	NA	154	NA
25-yr	20	79	17	NA	162	NA
40-yr	32	55	16	NA	193	NA

[1] Measurement after pruning.

[2] NA- Non available.

An estimated nutrient balance budget (inputs – outputs) was calculated by assuming that (i) over the short-term (i.e., in successive years), the amount of nutrients recycled as plant prunings is roughly the same each year and (ii) the amount of nutrients sequestered in the standing crop during any given year is generally small and decreases with age of the tea plants. Thus it appears that crop nutrient demands are generally met, or exceeded, by fertilizer inputs (Table 4.10). However, some 'nutrient pools' were unaccounted for in the overall nutrient budget; e.g., nutrients sequestered in the below-ground biomass (roots) or leached from the rooting zone (especially N, K and S) (Watabe, 1998; Gordzhomeladze, 1989). As well, the soil data indicate that a considerable amount of the added P is bound to Fe and Al oxides or present as insoluble Ca-phosphates and, hence, is not available to the tea plants. This suggests that, as the age of the tea plantations increases, the amount of fertilizer inputs required to meet crop demands should probably be increased rather than decreased (see Table 4.10), though such a scenario may be economically unsustainable.

4.4 General Discussion and Synthesis

This study was undertaken to quantify changes in dynamic soil properties under long-term tea cultivation following forest clearance. The selected dynamic soil properties included: biochemical properties (OC and total N), chemical properties (total and available P and K, total S and Cd, pH and exchangeable cations), physical properties (bulk density, porosity, MWD of aggregates, PAWC and mechanical resistance), and earthworm populations. All of these soil properties could be used to detect differences in soil quality under long-term tea cultivation, at the landscape scale (Larson and Pierce, 1991).

Comparisons between the natural forest and newly cultivated (1-yr-old) soils after burning showed that most biochemical, chemical and physical properties were similar, except for slight increases in pH, and some soluble and exchangeable cations in the newly cultivated soils, probably from nutrients in the ash. Based on that comparison, the differences in soil properties between the cropped and forest soils were considered to reflect the effects of cultivation, rather than deforestation. In addition, changes in soil properties in response to cultivation occurred mainly in the upper 40-cm of the soil.

Soil organic C contents decreased in response to cultivation, with the lowest OC contents occurring in the 40-yr-old tea soils. Likewise, nutrient supplying power, such as total N, S and K, and available K contents, decreased in the soils with longer term of tea cropping. These changes were attributed to losses from crop removal and leaching that exceeded additions in the form of fertilizers. Conversely, total P was significantly higher in the cropped soils, a result of P fertilizer accumulation. High concentrations of NaOH extractable P_i (Fe and Al phosphates), together with low concentrations of plant available P in the cultivated soils suggests the P was being fixed.

Tea cultivation also resulted in lower soil pHs. Relative to the forest soil, pH was lower in the 10-yr-old tea soils and slightly higher in the 40-yr-old soils. This probably relates to the decomposition of organic C, which occurred at a faster rate after breaking land for agricultural practice, increasing the organic acid products in these soils. Continuous application of lime during farming could sustain the pH value in 25- and 40-yr-old tea soils. Exchangeable Al accounted for the largest proportion of ECEC and was consistent in all soils. The low pH and high exchangeable Al in the soils would not be a problem for tea plant growth (Liang et al., 1995; and Johannes et al., 1998), but would increase deficiencies in plant available P (Jordan, 1985; Wolt, 1990).

Long-term tea cultivation degraded soil physical properties, in which bulk density and soil strength increased and total pore volumes decreased. An important agricultural consequence of increased soil strength and bulk density is an increase in ability of the soil to resist penetration by root crops and burrowing soil fauna (Ehler et al., 1983; Topp et al., 1997). The cultivation also decreased PAWC, indicating a reduction of soil water retention in the cropped soils. Similarly, MWD of aggregates was lower in the cropped soils than in the forested soils. Changes in these soil properties indicated a trend toward lower soil quality under long-term tea cultivation.

The population of earthworms was much lower in the cropped soils than in the forested soils. Reduction of earthworms' population was attributed to the changes of both soil physical and soil chemical properties, resulting from cultivation practices. Although earthworms may not be a causative factor to the changes of some soil properties, the change of earthworm populations provided evidence of the changes in soil environments, particularly moisture deficiency in the tea soils.

Farming practices, such as fertilization and cultivation techniques, have a great impact on soil properties. Cultivation techniques such as planting tea in rows along with the contour line resulted in limited erosion, even though the tea fields were on steeply sloping topography. Indeed, there were no statistically significant differences between soil properties in upper slope positions and those in lower slope positions. Thus, slope class was ruled out as a major factor contributing to the degradation of soil quality observed during long-term tea cultivation. On the other hand, fertilizer inputs generally only meet the crop nutrient demands (nutrient loss from harvest). However, if some other nutrient pools (e.g. nutrient leaching, storage in the plants) are accounted for the total nutrient budget, these inputs of fertilizer may not be enough to balance total nutrient losses. Adequate fertilizer application, thus, is one of most important management practices to maintain crop yields and soil quality in this tea cultivation system.

5. Identification of Important Soil Quality Indicators and Their Critical Levels for Sustainable Tea Cultivation

5.1 Introduction

Tea is an important cash crop in the Northern Mountainous Zone of Vietnam and, because of its economic value, many farmers have replaced their traditional annual and food crops with tea. Indeed, tea acreage continues to increase each year, especially in the Northern Mountainous Zone. Whereas tea plantations remain productive for long periods (20+ years), yields tend to decline in the latter years. This drop in productivity is traditionally attributed to natural aging of the plants (Do, 1980), although there is some speculation that it may also reflect a loss of soil quality. To be sure, degradation of soil quality is often associated with the intensive land use involved in tea production. Since crop growth and productivity are a reflection of soil quality, any degradation of the soil can be expected to adversely affect the stability of system.

The first step in a study such as this is defining what is meant by "soil quality", and then identifying those indicators that will be most useful in monitoring its change. We have adopted the definition of soil quality espoused by Doran and Parkin (1994); i.e., soil quality is a soil's capacity to support plant growth. To be useful, soil quality indicators must provide a sensitive and timely measure of the soil's ability to function and be able to identify whether the change in soil quality is induced by natural processes or occurs as a result of management (Doran and Parkin, 1994; Burger and Kelting, 1998). Moreover, the soil quality indicator(s) chosen must (i) have an available baseline against which to compare changes, (ii) be highly correlated to long-term response in cultivation, and (iii) be readily obtainable (not too expensive) and easy to use.

Theoretically, long-term yields are a good indicator of changes in soil quality because they reflect the crop's response to soil conditions (Gregorich et al., 1997). Thus, under specific conditions of climate and management, a reduction in yield indicates degradation in soil quality. Yields may also be an important measure of the difference in soil quality associated with different land use practices. Indeed, the use of crop yield as an important indicator of soil quality has been adopted by many researchers. Moss (1972) used long-term yields as a useful tool in developing a system of soil rating–changes in yield were often found to occur in parallel with a change in various soil properties (e.g., soil fertility and organic carbon). Similarly, Mausbach and Seybold (1988) used crop yield as an indicator of soil quality and used it to identify the "critical level" of soil quality. That is, the point at which further alteration of the soil would significantly change the productive potential of the soil (Pierce and Larson, 1993). According to Chen (1999), a production system may no longer be considered sustainable when the measured value of the soil quality indicator(s) is beyond the critical level.

Economic analysis for profitability is another useful tool, reflecting both agricultural sustainability and soil quality. Indeed, maximizing sustainable profits is one the factors that influence the adoption of soil conservation practices (Cary, 1994; Boehm and Burton, 1997). Cox (1996) used a linear response model to depict the relationship between crop yield and soil test (fertility) level. In this model, yield levels and expected profit (calculated as gross income minus total production costs) were used to determine an appropriate critical level of soil nutrient concentrations. Similarly, while assessing the economic sustainability of agricultural systems, Neave et al. (1995) considered a system's performance to be at the critical level when the "gross margin" equaled zero. They argued that farms operating below this value lose money and, hence, the system is unstable. Conversely, if the gross margin is greater than zero, the farming operation makes money and the system is sustainable.

The objectives of this study were to: 1) identify appropriate indicators for assessing the impact of long-term tea cultivation on soil quality in the Northern Mountainous Zone of Vietnam; and 2) identify the potential limiting (critical) values of those soil quality indicators having the greatest predictive value for assessing the economic sustainability of tea cultivation.

5.2 Materials and Methods

5.2.1 Soil Sampling

The study area is located in Thai Nguyen Province, a Northern Mountainous province of Vietnam. Field sites were selected based on age of the tea plantation; i.e., native forest (control), 10-, 25- and 40-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 (10-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).

5.2.2 Crop Yield and Farm Inputs

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 40-yr-old tea plantations receiving different fertilizer inputs were compared. Based on the most recent fertilizer application, the 40-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.

5.2.3 Earthworm Population

Earthworm populations were monitored monthly. Five randomly collected soil samples (25 × 25 × 20-cm) were passed through a 10-mm sieve to recover the soil fauna, and the number of earthworms counted.

5.2.4 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 H_2SO_4-H_2O_2 digestion (Thomas et al., 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 HNO_3, $HClO_4$ 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 al., 1992) and determined using AES. Exchangeable cations (i.e., Ca, Mg, K, Na, Al) were extracted using unbuffered 0.1 M $BaCl_2$ (Hendershort et al., 1993) and determined using AAS.

Soil physical properties also were determined using standard procedures (Black et al., 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) (Anderson and Ingram, 1993). 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 (Davidson, 1965).

5.2.5 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, 1966). 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 > 0.

5.3 Results and Discussion

5.3.1 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 5.1. 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 ($P \leq 0.001$) were total organic C, available K, pH, mechanical resistance, bulk density, total porosity, PWAC and earthworm population. Moderately sensitive indicators ($0.001 < P \leq 0.01$) include available P and total N, P, and K. Weaker indicators of soil quality ($0.01 < P \leq 0.05$) 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.

Table 5.1. Significance level of soil chemical, physical and biological indicators for difference of depth-weighted means among the forested, 10-, 25- and 40-yr-old tea plantations.

Soil property[1]	Depth (cm)[2]	Forest (n=4)	10-yr (n=3)	25-yr (n=4)	40-yr (n=6)	Statistical significance[3]
Soil chemical indicators						
Total C (mg g^{-1})	0-40	16.29	13.12	13.00	12.09	***
Total N (mg g^{-1})	0-40	1.41	1.12	1.03	1.03	**
Total P (μg g^{-1})	0-10	244.7	343.2	353.5	356.5	**
Total K (mg g^{-1})	0-40	15.07	12.21	13.20	10.25	**
Total S (mg g^{-1})	0-40	0.39	0.75	0.63	0.43	*
Avail. P (μg g^{-1})	0-20	5.45	20.44	11.97	6.02	**
Avail. K (μg g^{-1})	0-40	39.21	63.07	51.55	24.57	***
Soil pH	0-40	4.20	3.90	3.94	4.05	***
ECEC	0-40	4.82	5.20	5.72	5.11	ns
Fe oxides (%)	0-40	4.40	4.00	4.70	4.80	ns
Al oxides (%)	0-40	0.82	0.71	0.86	0.89	ns
Total Cd (μg g^{-1})	0-10	0.05	NA[4]	0.06	0.06	ns
Soil physical indicators						
Resistance (MPa)	0-30	3.99	3.91	4.36	4.64	***
Bulk density(Mg m^{-3})	0-20	1.08	1.21	1.26	1.29	***
Porosity (%)	0-20	60	55	53	51	***
PAWC (% Vol.)	0-20	13.50	13.34	10.30	9.43	***
MWD (mm)	0-20	4.53	2.88	3.45	3.40	*
Clay content (%)	0-20	46	45	47	46	ns
Bio-indicator						
Earthworms m^{-3}	0-20	11.8	4.5	2.4	2.5	***

[1] ECEC: effective cation exchange capacity, PAWC: plant available water capacity, and MWD: mean weight diameter of aggregates.

[2] Reported values are the weighted-averages for the composite 0- to 10-cm, 10- to 20-cm, and 20- to 40-cm depth intervals for soil chemical properties; and the 0- to 10-cm and 10- to 20-cm depth intervals for physical properties.

[3] Significant at 0.05 (*), 0.01 (**) and 0.001 (***) level of probability; ns = not significant.

[4] Not available.

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 5.2.

Table 5.2. Statistical levels (P>F) for contrasts among the study soils.

Property[1]	Effective depth (cm)	Forest vs. 10-yr	10-yr vs. 25-yr	25-yr vs. 40-yr
------ Chemical indicators ------				
Total C (mg g^{-1})	0-40	0.000	0.176	0.006
Total N (mg g^{-1})	0-40	0.004	0.097	0.368
Total P (μg g^{-1})	0-10	0.000	0.004	0.223
Total K (mg g^{-1})	0-40	0.000	0.055	0.040
Total S (mg g^{-1})	0-40	0.002	0.128	0.001
Avail. P (μg g^{-1})	0-20	0.000	0.000	0.000
Avail. K (μg g^{-1})	0-40	0.000	0.061	0.006
Soil pH	0-40	0.000	0.060	0.010
------ Physical indicators ------				
Resistance (MPa)	0-30	0.580	0.009	0.160
Bulk density(Mg m^{-3})	0-20	0.000	0.008	0.926
Porosity (%)	0-20	0.000	0.007	0.964
PAWC (% Vol.)[2]	0-20	0.000	0.008	0.049
MWD (mm)[2]	0-20	0.002	0.204	0.740
------ Bio-indicators ------				
Earthworms m^{-3}	0-20	0.000	0.003	0.604

[1] Only dynamic soil properties were selected.

[2] PAWC: plant available water capacity, MWD: mean weight diameter of aggregates.

Results of the contrast analysis, including the direction of change, also were expressed in qualitative terms; i.e., ↑ = significant ($P \leq 0.05$) increase in population mean, ↓ = significant ($P \leq 0.05$) decrease in population mean, and ↔ = no significant change ($P > 0.05$) in population mean (Table 5.3).

Table 5.3. Qualitative changes in soil quality indicators in response to tea cultivation[1].

Properties	Effective depth (cm)	Forest vs. 10-yr	10-yr vs. 25-yr	25-yr vs. 40-yr
Chemical indicators				
Total C (mg g^{-1})	0-40	↓	↔	↓
Total N (mg g^{-1})	0-40	↓	↔	↔
Total P (μg g^{-1})	0-10	↑	↑	↔
Total K (mg g^{-1})	0-40	↓	↔	↓
Total S (mg g^{-1})	0-40	↑	↔	↓
Avail. P (μg g^{-1})	0-20	↑	↓	↓
Avail. K (μg g^{-1})	0-40	↑	↔	↓
Soil pH	0-40	↓	↔	↑
Physical indicators				
Resistance (MPa)	0-30	↔	↑	↔
Bulk density(Mg m^{-3})	0-20	↑	↑	↔
Porosity (%)	0-20	↓	↓	↔
PAWC (% Vol.)[2]	0-20	↓	↓	↓
MWD (mm)[2]	0-20	↓	↔	↔
Bio-indicators				
Earthworms m^{-3}	0-20	↓	↓	↔

[1] ↑ = increase ($P<0.05$), ↓ = 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) following forest clearance and cultivation. During the first 10 years following cultivation, significant changes occurred in 13 of the 14 soil quality indicators (Tables 5.2 & 5.3). 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 10- to 25- to 40-years. At the period 25 to 40 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.

5.3.2 Crop Yield as an Indicator of Soil Quality

During the 2000 season, crop yields from the 10- and 25-yr-old tea plantations (3.06 and 3.02 Mg ha^{-1}, respectively) were significantly greater than those from the 40-yr-old plantations (2.30 Mg 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 (Do, 1980) 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 5.4).

Table 5.4. Comparison of tea yields and total plant biomass in 40-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 (Mg ha^{-1})	2.83	1.78	0.01
Standing crop (Mg ha^{-1})	38.54	34.83	0.00
Pruning (Mg 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^{-1} yr^{-1} of N, P and K fertilizers, respectively (note: these are the minimum fertilizer inputs recommended by local agronomists for 40-yr-old tea fields); fields receiving fewer fertilizer inputs were classified as "low fertilizer".

[2] Significance levels of t-test for difference in means.

Both total biomass production and crop yield were significantly ($P \leq 0.05$) greater in 40-yr cultivated soils receiving high rates of fertilizer than in similarly aged plantations receiving low rates of fertilizer. Moreover, the 40-yr-old tea plantations receiving high rates of fertilizer produced tea total biomass and yields that were nearly equal to those of the 25-yr-old tea plantations (i.e., total yield and pruning biomass, representative for annual plant biomass, of the 40-yr-old tea plantations was 7.92 Mg ha^{-1}, compared to 8.17 Mg ha^{-1} of the 25-yr-old tea plantation). This suggests that the 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 40 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.

5.3.3 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 al., 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 are presented in Fig. 5.1 for the soil quality indicators that were most sensitive to change ($P \leq 0.05$) in response to cultivation (Table 5.1). Regression analysis of the yield versus soil property data revealed that yield was positively correlated ($P \leq 0.05$) 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 $P \leq 0.05$) 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 (Tables 5.1 & 5.3), 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.

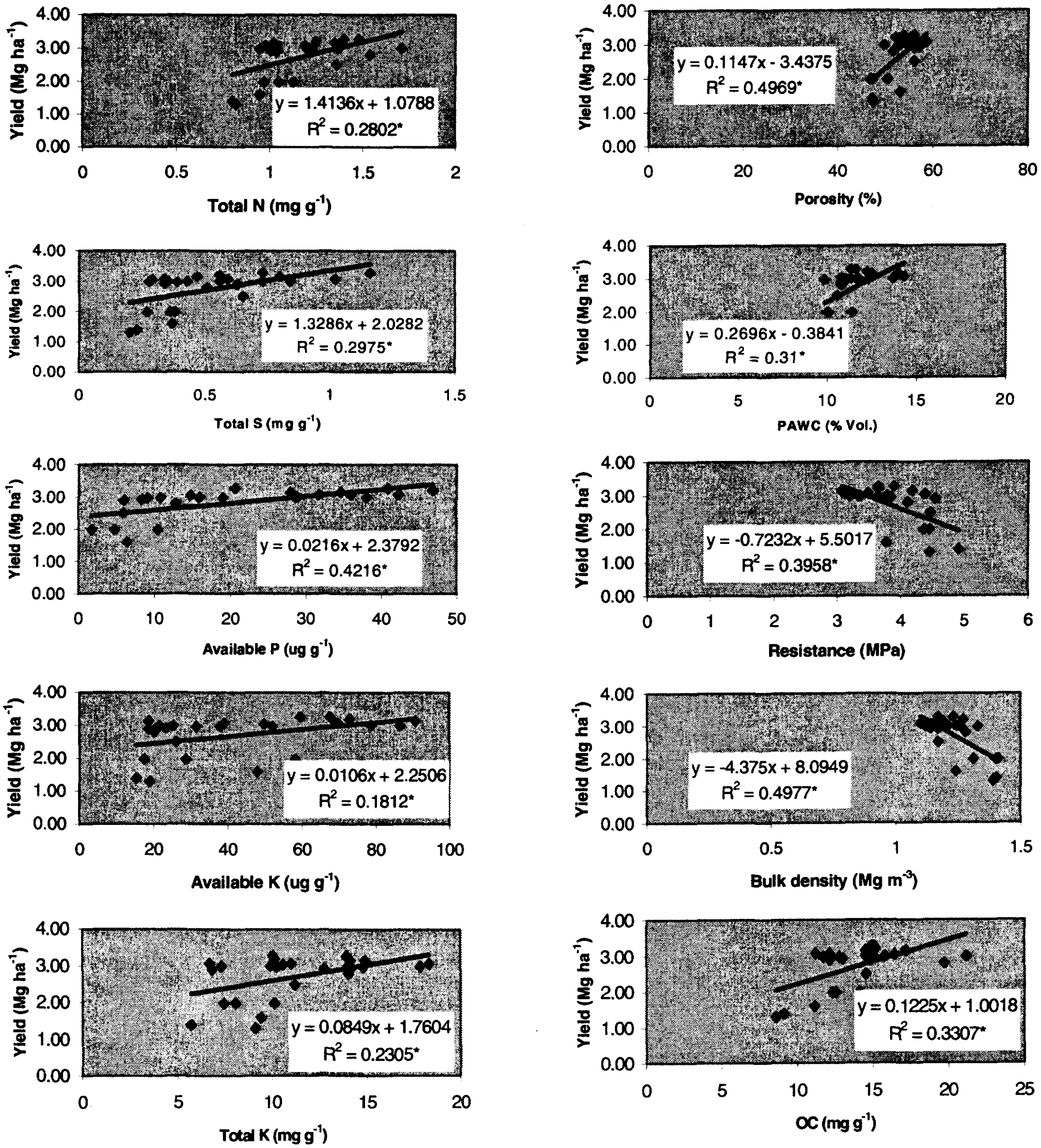


Figure 5.1. Linear correlation between tea yield and most important soil quality indicators.

* significant at 0.05 level of probability.

Soil properties that were identified as being sensitive indicators of cultivation-induced changes in soil quality (Table 5.1), as well as being significantly correlated with crop yield (Fig. 5.1), 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 5.5.

Table 5.5. 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^{-1})	0.141**	0.032
Total N (mg g^{-1})	1.387	0.138
Total K (mg g^{-1})	0.054*	0.069
Total S (mg g^{-1})	0.656	0.131
Available P (µg g^{-1})	0.018**	0.034
Available K (µg g^{-1})	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 5.5) indicated that total organic C and available P were the most highly significant variables ($P \leq 0.05$) in the predicted yield model; total K and PAWC were moderately significant variables ($P \leq 0.1$). 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 properties assessed using multiple regression analysis is presented in the following equation:

$$Y = 0.141OC^{**} + 0.018Available\text{-}P^{**} + 0.054Total\text{-}K^{*} + 0.099PAWC^{*}$$
$$R^2 = 0.764^{***}$$

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

5.3.4 "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 40-yr-old plantations (Table 5.6). 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 10-, 25- and 40-yr-old tea plantations (Table 5.6). As a result, the calculated total profit and benefit:cost ratio (BCR) for the 40-yr-old tea plantations were significantly lower than those for the 10- and 25-yr-old plantations. Indeed, whereas tea yields from the 40-yr-old plantations were only about 26% lower than those from the 10-yr-old plantations, there was a decrease of about 93% in the total net benefit associated with the 40-yr-old plantations (Table 5.7).

Table 5.6. Cost-benefit analysis of tea cultivation by age of plantations (in 2000).

Indicator	10-yr (n=3)	25-yr (n=4)	40-yr (n=6)
Yield (Mg ha^{-1})	3.06	3.02	2.30
Total benefit (cost per ha, 1000 VND)[1]	29854	29320	22368
Total inputs (cost per ha, 1000 VND)	23420	23299	21940
Net benefit (1000 VND)	6434	6021	488
Benefit:cost ratio[2]	1.27	1.26	1.02

[1] At the current rate of exchange, $1 Cdn is equivalent to 9000 VND.

[2] Benefit is calculated based on 3% discount rate per season of total gross income for tea cultivation in this area.

The low values calculated for both the BCR (1.02; see Table 5.6) and relative net benefit (7%; see Table 5.7) 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 (Neave et al., 1995). 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 (i.e., the farmer would lose money).

Table 5.7. Relative yield and net-benefit associated with long-term tea cultivation (determined relative to the yield and net benefit associated with the 10-yr-old tea plantations).

Tea age	Relative yield (%)	Relative net benefit (%)
10-yr	100	100
25-yr	98	94
40-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 40-yr-old tea soils (Table 5.8) were considered to be estimates of the critical (limiting) levels below which productivity was no longer economically sustainable.

Table 5.8. "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^{-1})	0-40	12.09
Available P (µg g^{-1})	0-20	6.02
Total K (mg g^{-1})	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 40-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 40-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 level (see Appendix 5). Moreover, the net benefit of applying adequate levels of fertilizer to the 40-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 40 years.

5.4 Synthesis

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 al., 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 al., 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 al., 1997). Bulk density and 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 Northern Mountainous Zone are predominantly clayey so that the increase in bulk density associated with long-term tea cultivation (Table 5.1) 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 40-yr-old tea plantations), the roots of several crops (i.e. pea, cotton, corn 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 fertilizer 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 al., 1995). Economic analysis of the yield and production cost data indicated that in its present state, tea cultivation in the Northern Mountainous Zone 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 of soil quality. Among the soil quality indicators identified as being sensitive to 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.

Fertilization is an important approach to maintaining soil fertility and crop yields. Thus, to some degree, the decline in soil quality (fertility) resulting from long-term tea cultivation can be compensated for by fertilizer additions. Indeed, the fact that older tea plantations (even 40-yr-old tea) which receive adequate fertilizer inputs still produce a good harvest suggests that the productive period for tea cultivation can be extended beyond 40 years.

6. Socio-Economic Analysis and Farmers' Perceptions Toward Sustainable Tea Cultivation

6.1 Introduction

Tea is a major cash crop in the humid areas of the Northern Mountainous Zone of Vietnam, with approximately 50,000 ha in tea production in 1998. Tea is the largest cash crop in the region and provides a livelihood for many ethnic minority people. The tea production system, like that of many other upland crops in Vietnam and throughout south-east Asia, is undergoing major changes in response to population pressures and improved market access. As a consequence, there has been an increase in both land-use intensity and soil degradation (Pandey, 1996). Other socio-economic problems related to agricultural development in the Northern Mountainous Zone, include low literacy rates and poor standards of living among farmers (Nguyen et al., 1996). These issues are believed to have a strong influence on the decisions farmers make regarding soil and crop management, which in turn affects agricultural sustainability (Nguyen and Thai, 1999). More importantly, the 1986 government policy known as "doi moi" (restructuring), which included privatization of agriculture, changes in land ownership, and an open market economy, has contributed to increased agricultural development. These government policies often change the behavior of farmers toward land use (Vo, 1995) and, consequently, affect soil conservation efforts and the sustainability of tea production.

The importance of socio-economic analysis in evaluating land use and the management of agricultural systems is well-recognized (Gameda and Dumanski, 1995; Lal, 1998a; Fletcher, 1986; Lovejoy and Napier, 1986). Indeed, many agricultural programs that promote the adoption of new technologies fall short of their goal because they fail to take into consideration the socio-economic issues affecting the farm community (Lal, 1987). In general, however, new soil conservation technologies are readily accepted and adopted when they are in harmony with the socio-economic conditions and cultural requirements of the farmers. Thus, sustainability of the system depends not only on production technologies but also (and perhaps more importantly) on the social institutions controlling access and use of these technologies (Lynam and Herdt, 1992).

Concern for soil conservation is of interest not only to agricultural scientists, natural resource managers and policy makers, but also to farmers (Romig et al., 1995). That is, because the soil is a nonrenewable asset for agriculture, farmers are quick to recognize the importance of soil conservation. In addition, farmers who have worked the land for a long time can provide detailed information regarding any change in soil quality that has been observed since the land has been in crop production. Therefore, if future soil conservation programs are to succeed, it is imperative that we gain a better understanding of the indigenous knowledge possessed by farmers (Douglas, 1990; McCallister and Norwark, 1999).

Identifying appropriate socio-economic indicators is an important step in developing new soil conservation programs (Nguyen and Thai, 1999). For example, to understand the key variables affecting conservation decisions made by farmers, it is necessary to analyze farm business characteristics and farm conservation factors (van Kooten, 1993). Among the socio-economic analysis approaches used to evaluate soil conservation programs, *production function analysis* is often used to assess the importance of various factors affecting the productivity of the system by quantifying relationships between productivity and a mix of economic, political and social factors (Shapley and Shubik, 1965). This approach has been used to value environmental impact (Barbier, 1994; Maler, 1992), categorize socio-economic and physical factors affecting soil productivity (Acharya, 1998), evaluate input factors affecting tea productivity (Dao and Do, 1997), and estimate the overuse of chemical fertilizers in rice and vegetable crops (Nguyen et al., 1999).

Based on the above considerations, as well as the results of previous socio-economic studies, the major objectives of this study were to: 1) document the socio-economic conditions of tea farmers with respect to sustainable tea cultivation, 2) gain a better understanding of the indigenous knowledge of the farmers, in particular, as it relates to their interests and perceptions towards soil quality in relation to tea cultivation, and 3) define important socio-economic indicators (based mainly on analysis of the factors affecting long-term tea production) for evaluating the sustainability of tea cultivation in the Northern Mountainous Zone.

6.2 Methodology

The interactive framework of the socio-economic study consisted of three parts: developing an appropriate questionnaire, interviewing farmers, and analyzing the results.

6.2.1 Questionnaire Development

The questionnaire was developed based on the minimum socio-economic survey approach described by Moran (1989) and the questionnaire guide for soil quality studies proposed by Garlynd et al. (1994). The questionnaire was used as an interview guide, in which the questions were structured in a way that was easily understood by the farmers. Both open- and closed-ended questions were used. Closed-ended questions were used when a simple "yes" or "no" answer was required; open-ended questions were employed when more detailed information was needed to satisfy the objectives of the interview.

The questionnaire was divided into five parts: demographic data, economic status, land-use pattern, soil and crop management practices and soil quality issues, and market access and government policies (see Appendix 2 for a sample questionnaire). The questionnaire guide was pre-tested on a small sampling of farmers (n = 5). Corrections were then made to ensure that questions incorporated into the final survey were understandable by the farmers and satisfied the research objectives.

6.2.2 Farmer Interviews

The survey was conducted in the Song Cau tea enterprise of Thai Nguyen Province (the same area in which the soil quality study was conducted; see Chapters 3 and 4). The preliminary survey for gathering information regarding which variables affect farmers' decisions with respect to land use and management involved interviews with key farmers, local authorities, lawmakers, and extension workers.

The final survey included 42 farmers chosen at random from the tea enterprise community. Only heads of household who were experienced in tea cultivation were interviewed; each farmer was interviewed individually, at home. To avoid bias, leading or directed questions were avoided. Ambiguous answers were checked during discussions with other family members.

6.2.3 Data Analyses

Both qualitative and quantitative information described and recorded by farmers were synthesized. The results were then presented in a cross-tabular form as means and percentages. The Cobb-Douglas production function (Cassman et al., 1995) was applied to analyze input and socio-economic factors affecting the productivity of the cropping systems.

Theory of Cobb-Douglas production function. The activity of production is defined as the process of combining materials and vector services in the creation of outputs such as goods and services. Economists perceive this transformation process through the concept of the *production function*, in which the outputs from a production activity (e.g., tea cultivation) are expressed as a function of the combined inputs in a given production period (e.g., land, labor services, machinery services, seeds, fertilizers and pesticides) (Rayner and Welham, 1995). At its simplest, the production function can be presented as:

$$Y = f(X_1, X_2, \ldots, X_n) \qquad (1)$$

where: Y is the output and X_1, X_2, and X_n are inputs *1* through *n*.

The Cobb-Douglas production function allows for substitutability between inputs and is less restrictive than other approaches (e.g., fixed proportions functions) (Cassman et al., 1995) and, hence, is a common approach. The Cobb-Douglas production function can be presented as:

$$Y = X_i^{ai} \times X_j^{aj} . \times . . X_n^{an} \tag{2}$$

which can be log-transformed to yield a linear relationship of the form:

$$\ln Y = a_i \ln X_i + a_j \ln X_j \ldots + a_n \ln X_n \tag{3}$$

where: Y is the output; a_i, a_j and a_n are 'production elasticity' coefficients calculated using regression analysis; and X_i, X_j and X_n the input quantities. In the regression analysis, qualitative variables, which usually indicate the presence or absence of a 'quality' or an attribute (e.g. education or economic status of farmers), are expressed in a terms of a 'dummy variable' (Gujarati, 1979).

Estimation procedure. For purposes of this study, it was anticipated that the production function would measure the relationships between crop yield (the output variable), management inputs (e.g. fertilizers and pesticides), and the socio-economic factors related to tea production (e.g. education, economic status). Thus, the function takes the form:

$$Y = f(N, P, K, Ca, Lbr, Mnr, Pest, Slope, FrmS, Age, Econ, Tech, Edu) \tag{3}$$

which, following log-transformation, takes the form:

$$\begin{aligned} \ln Y = I + \alpha_1 \ln N + \alpha_2 \ln P + \alpha_3 \ln K + \alpha_4 \ln Ca + \alpha_5 \ln Lbr + \alpha_6 \ln Mnr + \alpha_7 \ln Pest \\ + \alpha_8 \ln Slope + \alpha_9 \ln FrmS + \alpha_{10} \ln Age + \beta_1 Econ + \beta_2 Tech + \beta_3 Edu \end{aligned} \tag{4}$$

where the dependent (output) variable, Y, is the tea yield (Mg ha^{-1}) estimated by the farmer; I is the intercept of the regression equation; $\alpha_1, \alpha_2, \ldots, \alpha_{10}$ are regression coefficients for the 'normal' variables; and β_1, β_1, and β_3 are regression coefficients for the 'dummy' variables. The independent (input) variables are defined in Table 6.1.

Table 6.1. Input variables used to define the Cobb-Douglas production (yield) function[1].

X_i	Description
N	Nitrogen fertilizer applied (kg ha^{-1});
P	Phosphate fertilizer applied (kg ha^{-1});
K	Potassium fertilizer applied (kg ha^{-1});
Ca	Lime applied (kg ha^{-1});
Lbr	Labour (man day^{-1});
Mnr	Manure application (Kg ha^{-1});
Pest	Pesticide application (grams active gradient ha^{-1});
Slope	Slope of tea field (degree);
FrmS	Farm size (m^2);
Age	Age of the tea plantation;
Econ	Dummy economic variable: *Econ* =1 if the farmer's income was sufficient for Living while providing some savings, otherwise *Econ* = 0;
Tech	Dummy technology variable: *Tech* = 1 if soil conservation technologies were Employed by the farmer, otherwise (e.g., use of traditional farming practices) *Tech*= 0;
Edu	Dummy education variable: *Edu* = 1 if the farmer's education was equal to or Higher than a secondary education level, otherwise *Edu* = 0.

[1] Input variables selected were those available from the survey.

Development of the production (field) function was based on the following facts and assumptions: the farms surveyed included a range of operational conditions, with different size land holdings and varying levels of fertilizer inputs; all farmers within the study area had access to the same information with regard to soil conservation technologies, and had equal treatment in terms of government policies and society (Nguyen et al., 1999); and all benefits derived by the farmers were based on tea production as the output variable.

6.3 Results and Discussion

6.3.1 Socio-Economic Conditions, Land Use Systems and Government Policies Related to Tea Cultivation

Family (household) characteristics. Characteristics of the households described in the study included the number of people per household and the distribution of people by age and sex. The number of people per household ranged from 2 to 8, with 77% of households consisting of four or fewer members (Table 6.2). The relatively small size of these households reflects the 'two children per family' policy of the government. The head of the household; i.e., the person responsible in making decisions regarding farm practices, was generally a male. Occasionally, if the male was ill or worked away from home, the head of household was female.

Table 6.2. Number of people per household.

Number of people	Number of households	Percentage
2	4	10
3	4	10
4	24	57
5-8	10	23
Total	*42*	*100*

The main labour force for tea production consists of males and females between the ages of 18 and 60. In the households surveyed, this accounted for 70% of the total population (Table 6.3). The remaining 30% (of which only 3% were older than 60) were economically dependent on the family for support. The large number of people of working age is important, because tea production is labor intensive. The number of male and female labourers between the ages of 18 and 60 was nearly identical. Male workers are generally responsible for the application of fertilizers and pesticides, as well as for pruning and weeding; female workers are usually responsible for harvesting.

Table 6.3. Distribution of people by age and sex.

Age	Sex	Number of people	Percentage
< 18	Male + female	50	27
18-60	Male	66	37
18-60	Female	60	33
> 60	Male + female	6	3
Total		*182*	*100*

Education. The literacy rate for working age people in the Song Cau tea enterprise was as high as 93% (see Appendix 6). Because the tea enterprise is close to Thai Nguyen city, the education system is most likely better than that found in many other rural areas of the country (Anonymous, 1998). In particular, all heads of household had some type of formal education, with approximately 43% having completed a high school level education, 47% at a secondary school level, and 10% at a primary school level (Table 6.4). In addition, the level of education varied with the age of farmer, with younger farmers having received more formal education.

Table 6.4. Formal educational status of the heads of household (n=42).

Education level[1]	Age (years)	Number of people	Percentage
Primary school	53-60	4	10
Secondary school	30-55	20	47
High school	30-49	18	43

[1] Primary, secondary and high school correspond to grades 1 to 5, 6 to 9, and 10 to 12, respectively (in the Vietnamese educational system).

Economic status. For 64% of households, tea production provided a sufficient income for the families to maintain an adequate standard of living, including the accumulation of some savings, and reinvest in their land (Table 6.5). On the other hand, 36% of the households surveyed received only a subsistence level of income from tea production. In most cases, family income from tea production was limited primarily because there was too little agricultural land available and because tea yields were generally low. One consequence of this economic insufficiency is that investments for improved crop production (e.g., additional fertilizer or the adoption of new soil conservation technologies) were reduced. Consequently, long-term soil fertility and crop productivity are at risk.

Table 6.5. Economic status of households in terms of tea farming producing an adequate income.

Economic status	Number of surveyed households	Percentage
Insufficient[1]	15	36
Sufficient	27	64

[1] Insufficient farmers are those whose income were less than 6,000,000 VND per capita.

Farm characteristics. Individual farms in the Song Cau tea enterprise are relatively small, with most farmers having less than 1 ha of cultivated land (Table 6.6). Indeed, only 26% of farmers had more than 1 ha of cultivated land and only 5% had more than 2 ha of cultivated land. The small size of the farms is primarily the result of high population pressures in the region.

Table 6.6. Distribution of the tea households by farm size.

Farm size (ha)[1]	Number of households	Percentage
< 0.5	14	33
0.5-1.0	17	41
1.0-2.0	9	21
>2	2	5

[1] Area indicated in this table was accounted for total tea cultivated area per household.

An important characteristic of the tea farms is the fragmentation and scattering of land holdings. That is, the complex topography in the highlands makes it difficult to farm a single, large field in one place. As a result, each household generally farms two to four tea fields (varying in size from 1000 m^2 to 1 ha) which may be scattered throughout the tea enterprise. The larger tea fields are often located further from the village.

Farming practices. Most of the farming operations involved in tea production (e.g., weeding, fertilizer application and harvesting) are carried out manually and are thus labour intensive. Despite this, there were no reports of labour shortages in the tea production area. Even at the peak of the harvesting season, when more labour is required, the addition of women (and sometimes children) to the labour force meant that labour shortages were uncommon. In the study area, tea was planted primarily as a monocrop, except in some small areas near the villages where tea was intercropped with legumes or fruit trees. Farmers applied both organic and chemical fertilizers to supplement the fertility of the soil and increase yields. The use of chemical fertilizers was much greater than that of organic fertilizers (manures) because of transportation problems in the highly sloping topography, particularly when the soil surface between rows was entirely covered by the tea canopy.

In general, farmers reported that crop response to inorganic N fertilizers was greater and more rapid than the response of crops to other soil amendments. Consequently, N (150 to 200 kg N ha^{-1} yr^{-1}) was the predominant fertilizer element added to tea soils in the Song Cau region. This was reflected in the fertilizer trends reported for the past five years (Table 6.7). During this period, P-fertilizer inputs have generally remained the same or decreased (60-85 kg P ha^{-1} yr^{-1}). Potassium fertilizer usage also has been increasing, though not at the rate observed for N-fertilizer (60-90 Kg K ha^{-1} yr^{-1}).

Table 6.7. The trend in fertilizer applications to tea soils during the last five years (expressed as a percent of 42 respondents).

Direction of change	Nitrogen	Phosphate	Potassium
Increase	85	24	43
Decrease	5	24	24
No change	10	52	33

Method of application varied with the type of fertilizer. For example, N fertilizer applications were often 'split', with small amounts of N added on a monthly basis. Other fertilizers were applied only one or two times per year, generally at the beginning of, or mid-way through, the harvesting season. Whereas splitting the N fertilizer application probably contributed to a greater fertilizer use efficiency, applying large amounts of K fertilizer may have lead to decreased K use-efficiency by increasing the potential for leaching and luxury consumption by plants.

Land policies in relation to sustainable tea cultivation. Since 1986, land ownership has shifted from co-operative and state farms to individual farm households in which the farmers were able to lease land from the government for 25 to 30 years. The effects government land policy on soil quality were well recognized by the farmers. The majority of farmers interviewed reported an increase in soil fertility after land ownership was shifted from the state enterprise to individual households (Table 6.8).

Table 6.8. Farmers' perceptions about the change in soil fertility after changing land policies in 1986.

Trend of change in soil fertility	Number of respondents	Percentage
Improvement	29	69
Degradation	5	12
No change	8	19

Increases in soil quality following the change in land ownership were attributed to an increase in the amount of inputs used during tea cultivation (Table 6.9). The increased usage of chemical fertilizers also was accompanied by a dramatic increase in the use of organic fertilizers, which in the past had been applied only rarely. In addition, labour inputs increased markedly with the farmers (now the landowners) spending more time working the fields and employing more soil conservation technologies.

Market access. Most farmers reported that the cost of fertilizers and the price of tea products were particularly unstable during the past five years (Table 6.10) and that this had a major impact on the profitability of tea production. Whereas low prices for tea products most likely reflected lower market demand in recent years (Anonymous, 1998), they also reflect the government monopoly of the tea market. That is, until recently (1986) there had been only one government tea company responsible for tea processing and exporting. The new open-market system should allow for more competition and benefit the farmers (Vo, 1995).

Table 6.9. The change in inputs for tea cultivation after land policies changed in 1986 (expressed as a percent of 42 respondents).

Direction of change	Chemical fertilizer	Organic fertilizer	Labour
Increase	71	100	83
Decrease	12	0	0
No change	17	0	17

Table 6.10. Farmers' perception of how the cost of fertilizer and price of tea affected tea production during the last five years (n = 42).

Parameter	Number of respondents	Percentage
Increase in the cost of fertilizer	30	72
Fluctuation of the price of tea	42	100

3.2.2 Indigenous Knowledge and Farmer Perceptions of Soil Quality

Identification soil quality indicators by farmers. Farmers were asked to comment on any changes they had observed in any of the ten key soil quality indicators (see Table 6.11). Most recognized that organic matter content, soil fertility, soil moisture storage, soil structure, earthworm population, and weed incidence decreased over time, while soil compaction increased as a result of long-term cultivation. On the other hand, many farmers had difficulty answering questions about changes in soil properties such as acidity (pH), thickness of the topsoil, and soil erosion.

Each farmer also was asked to rank the relative importance of the various soil quality indicators to tea yield. Soil organic matter content, soil fertility and compaction were the most important soil quality indicators identified by the farmers. Soil erosion, acidity, topsoil thickness, and weed incidence were considered to be least important (Table 6.12).

Table 6.11. Farmer perceptions of the change in soil properties with tea cultivation (expressed as a percent of 42 respondents).

Indicators	No change	Increase	Decrease	No idea
Soil organic matter	12	33	55	0
Soil chemical fertility	17	29	52	2
Soil acidity	14	38	14	34
Soil compaction	29	57	12	2
Moisture in dry season	21	10	69	0
Topsoil thickness	31	12	48	9
Soil erosion	21	36	43	0
Soil structure	31	14	55	0
Earthworm numbers	7	7	86	0
Weed incidence	19	19	62	0

Table 6.12. Importance of the soil quality indicators based upon the farmers' perceptions.

Indicators	Total soil quality points[1]	Overall Rank
Soil organic matter	92	1
Soil fertility	102	2
Soil compaction	145	3
Soil structure	181	4
Moisture in dry season	191	5
Earthworm numbers	254	6
Soil erosion	288	7
Soil acidity	291	8
Topsoil thickness	302	9
Weed incidence	344	10

[1] Each farmer ranked the soil quality indicators on a scale from 1 to 10, with 1 being the most important indicator and 10 being the least important. Soil quality points for each indicator were then totaled, and an overall ranking assigned to each soil variable.

Farmer rankings of the soil quality indicators was somewhat comparable with the results obtained using more scientific approaches (see Chapters 4 and 5). For example, both the farmers and the soil tests identified soil organic matter (or soil organic C) as the most important soil quality indicator for sustainable tea production. Whereas the farmers identified 'soil fertility' as an important soil quality indicator, soil testing identified total/available S, P, and K as important chemical indicators of soil quality. Likewise, whereas the farmers identified soil compaction as an important physical indicator of soil quality, soil testing identified soil porosity and mechanical resistance as important soil properties.

The set of criteria farmers used to assess changes in soil quality are described in Table 6.13. Farmers commonly assess soil quality in terms of tactile, or visual properties of the soil, such as appearance or feel. For example, observed changes in soil color (darkness) are used by farmers to evaluate changes in organic matter content. Likewise, soil water content is assessed by feeling the soil. Plant growth and crop yield also were important criteria used by farmers to evaluate soil quality. Many farmers perceived that their soils were still fertile if crop yields were comparable to those achieved in previous years with the same management level.

Table 6.13. Diagnostics of soil quality indicators based on farmer experiences.

Indicators	Qualitative soil quality indicators used by farmers
Soil organic matter	Soil is dark-colored and feels 'good' to the touch
Soil chemical fertility	Based on yield response and observing plant growth
Soil acidity	Looking for the presence of selected weed species in the field
Soil compaction	Soil feels 'hard' when ploughing or hoeing
Soil moisture	Soil feels moist to the touch, observing the leaves at noon and evening.
Surface (A horizon) thickness	Observing the depth of dark colored soil when ploughing or hoeing.
Soil erosion	Observing the surface after rain; comparing year-to-year variations in topsoil depth when ploughing at upper and lower slope positions.
Soil structure	Observing soil when ploughing or hoeing.
Earthworm population	Observing earthworm casts at the surface in the morning or after rain.
Weed incidence	Observing evidence of weed species and communities in the field.

Whereas weed incidence was generally observed to decrease as the tea plants became more established (i.e., as the plantations aged; see Table 6.11), the occurrence of some wild plant species in the tea fields was a viewed as an indicator of some soil properties. For example, experienced farmers linked the presence of certain weed species (e.g., *Blatus cochinchinensis*, *Medimilla spirei*, and *Lophathe rumgracille*) in the tea fields to increased acidity. Likewise, species such as *Chrysopogon asculatus* were used as indicators of poor nutrient potential (soil fertility) and dryness of the soil, both of which are indicators of soil degradation.

Selection of soil conservation technologies by farmers. Various soil conservation methods and technologies have been introduced to farmers in the Northern Mountainous Zone by agronomists from the agricultural extension programs for tea cultivation. The number of farmers applying these technologies (Table 6.14) increased in the order: intercropping < mulching < balancing fertilizer applications < returning plant residues to the soil ≈ contour planting. In general, the number farmers adopting a soil conservation technology reflects the farmers' perceptions of the socio-economic benefits of the technology. Most farmers plant tea in rows running along the contour and return plant residues to the soil when pruning because these practices were strict requirements of the state run tea enterprises as they attempted to minimize soil erosion and improve soil organic matter. Experienced farmers cultivating upland soils readily accepted these methods when land ownership was shifted from the state enterprise to individual households.

Table 6.14. The most common soil conservation methods used by farmers.

Methods	Number of farmers	Percentage
Contour planting/ploughing	34	81
Returning plant residue to soil	33	79
Balancing fertilizer applications	26	62
Mulching	25	59
Intercropping with leguminous trees	7	17

Achieving a proper fertilizer balance (i.e., a proper N:P:K ratio) is important to maintaining soil fertility and, in turn, this was recognized by many farmers as being essential to maintaining soil quality and agricultural sustainability (see Table 6.12). The number of farmers applying fertilizers in the recommended amounts, however, was only 62% (Table 6.14). Farmers who did not apply enough fertilizer were generally under some degree of economic stress. Likewise, although mulching the soil is an effective way to prevent weed growth, reduce water erosion, and conserve soil moisture, only 59% of the farmers surveyed used mulching because materials were not readily available.

The intercropping of tea with leguminous trees (e.g., *Crotalaria sp.*, *Acacia sp.*) can improve both the quantity and quality of organic residues available for incorporation into the tea soils. However, because intercropping reduces the amount of arable land devoted to tea, only a few farmers (17% of those surveyed) practiced intercropping. In addition, because their land leases were relatively short (25 to 30 years), many farmers were wary of implementing soil conservation methods that require a long time to produce results. Because farmers are more likely to accept a technology if they are sure to derive a benefit from it, the government should consider allowing long-term leases to farmers as a means of promoting soil conservation technologies that require longer terms to produce the desired effect (i.e., enhanced soil quality).

6.3.3 Analysis of Factors Affecting Crop Productivity.

Crop yield, as an indicator of the sustainability of tea cultivation, was estimated based on the Cobb-Douglas production function (see Eqn. 4). Production elasticities for the estimated yield model were calculated using multiple regression analysis, and an estimated yield function was developed (Eqn. 5).

$$\begin{aligned}\ln Yield = {} & 4.498 + 0.37 \ln N + 0.190 \ln P + 0.201 \ln K - 0.060 \ln Ca + 0.020 \ln Lbr + \\ & 0.005 \ln Mnr + 0.010 \ln Pest - 0.009 \ln Slope - 0.027 \ln FrmS - \\ & 0.151 \ln Time + 0.095 Econ + 0.148 Tech + 0.042 Edu \qquad (5)\end{aligned}$$

where $R^2 = 0.655^{***}$. However, the regression analysis also revealed that only a small subset of the indicator variables were statistically significant (Table 6.15). Taking this into account, Eqn. 5 can be reduced to:

$$\ln Yield = 4.470 + 0.360 \ln N + 0.162 \ln P + 0.202 \ln K - 0.159 \ln Time + 0.091\, Econ + 0.174\, Tech \qquad (6)$$

where $R^2 = 0.627^{***}$.

Table 6.15. Regression coefficients used to develop the estimated yield function.

Variables	Coefficient	Significance level
Intercept	4.498***	0.000
ln *N*	0.370***	0.000
Ln *P*	0.190*	0.022
ln *K*	0.201**	0.010
ln *Ca*	-0.060	0.065
Ln *Lbr*	0.020	0.860
ln *Mnr*	0.005	0.273
ln *Pest*	0.010	0.790
ln *Slope*	-0.009	0.756
ln *FrmS*	-0.027	0.455
ln *Time*	-0.151***	0.000
Econ	0.095*	0.048
Tech	0.148**	0.003
Edu	0.042	0.523

*, **, *** Statistically significant at the ≤ 0.05, ≤ 0.01 and ≤ 0.001 levels of probability, respectively.

Soil variables making a significant contribution to the yield function (i.e., which explained a significant proportion of the yield differences) were the application of N, P, and K fertilizers, which increased crop yields significantly. Indeed, the model estimates that every 1% increase in applied N, P, or K fertilizer resulted in a 0.36%, 0.16%, or 0.20% increase in yield function, respectively. It is likely that under long-term tea cultivation crop yields are dependent largely on the type and amount of fertilizer applied. This was consistent with the results obtained from the 'soil test' approach taken to assess the effects of fertilizer application on productivity (see Chapter 5). Clearly, fertilization is an important factor in maintaining crop yields and soil fertility under long-term tea cultivation.

Age of the tea plantations had a significant negative effect on crop yield, which presumably reflects the effect of diminished soil quality caused by long-term tea cultivation. The farmers also considered time to be an important factor influencing yield (see Appendix 7).

Soil variables that had a negligible impact on the yield function included lime (*Ca*), manures (*Mnr*), and pesticide (*Pest*) applications. The fact that Ca applications (applied as lime or superphosphate fertilizer) had no effect presumably reflects the fact that tea plants tend to grow better in slightly acidic soils (Liang et al., 1995). The low impact of organic fertilizers (manures) on the yield function may reflect the fact these nutrient sources decompose only slowly and, hence, release nutrients for plant uptake gradually. Thus it may require more than a single year's data to adequately assess the effect of organic fertilizers on crop yield. Pesticides were thought to have little effect on crop yield because they are usually applied at higher than recommended rates, which may negate any actual effect of the pesticides on the predicted yield function. In addition, there was no significant effect of landscape position (i.e., slope) on crop productivity.

The economic variable (*Econ*) exerted a strong influence on the estimated yield function (Table 6.15), demonstrating the importance of the state of the household economy. Higher yields were generally associated with more affluent farmers, probably because higher fertilizer inputs were being applied. Similarly, the implementation of soil conservation technologies (*Tech*) exerted a positive influence on the yield function, indicating a yield response to improved soil quality. As with fertilizer inputs, the more affluent farmers, the more likely they were to adopt new soil conservation technologies.

Labour was not a critical factor for tea production. That is, the high population density, relatively small farm size, and shortage of land in the region, all contributed to a surplus of labour. The education variable (*Edu*) also was not significant. This is most likely a reflection of the fact that most farmers had at least a secondary education (Table 6.4) and that most were experienced farmers (Nguyen et al., 1999).

6.4 Summary and Discussion

The socio-economic conditions affecting farmers in the study area were evaluated with attention to local, or micro-level, factors. The size of an average farm household was only three to four people. The heads of households were generally experienced tea farmers who were responsible for their own decisions regarding farming practice and, ultimately, for the economic well-being of their families. The labor force (primarily 18 to 60 year-old men and women) accounted for approximately 70% of the total population. Both females and males old enough to work the fields have equal standing in work and society. The education level of farmers in the labour force was relatively high, with as many as 93% having some type of formal education. All heads of households had at least a primary education and many had completed high school. The economic situation of the households was more diverse, with 36% of households living below the economic standard usually considered sufficient.

Tea farms were relatively small (0.5 to 2 ha) with fragmented and scattered holdings. The small farm size reflects both high population pressure and a lack of agricultural land in the region. These factors pose a significant threat to the future economic development of farm families in the region (Nguyen and Thai, 1999). However, these factors also contribute to the surplus of available farm labour, which helps keep labour costs down.

Farmers were quite interested in the causes of low crop yields because they are directly related to the declining profitability of long-term tea production. Most farmers reported that tea yields decreased with increasing age of the plantations, with a rapid decline in productivity after 25 years of continuous cultivation. As indicated in the production function analysis (as well as in soil quality analysis, see Chapters 4 and 5), maintaining a balance of fertilizers is an important approach to maintaining crop yields. However, many farmers indicated that the type and amount of fertilizer applied to the tea fields were chosen based on economic considerations (i.e., household income), rather than those needed to compensate for nutrient losses from soils due to cropping. Tea cultivation without proper fertilization probably is not sustainable in the long term.

Critical socio-economic indicators of the sustainability of tea cultivation include economic factors and the acceptability of farming practices. The economic status of farmers was dependent on the level of farm outputs (crop yield), which in turn was dependent on the amount of inputs applied to the crop. Farmer interviews indicated that the more affluent farmers invested higher inputs and implemented more soil conservation technologies for tea cultivation than farmers with fewer economic resources.

Crop productivity and the overall sustainability of tea cultivation were limited by traditional farming practices (e.g., the crop productivity relied mainly on the inherent properties of a soil rather than the use of external inputs). Clearly, one way to enhance productivity, and ultimately improve farm household income, is to introduce new soil conservation technologies. It is equally evident, however, that this must be carried out in a manner that is acceptable to the farmers. That is, the soil conservation technologies must have clearly defined goals that are easily understood by the farmers (e.g., planting tea in rows along contour lines to prevent erosion and maintain fertility). New technologies also must fit the socio-economic conditions under which the farmers operate (Smyth and Dumanski, 1995). For example, new technologies will be adopted only if their cost does not exceed the short-term benefits derived by the farmer (Camboni and Napier, 1994). Only the more affluent farmers are likely to look at the long-term benefits offered by adopting a new soil conservation technology. Even in the short-term, however, new technologies must be affordable. Indeed, many farmers who understand the benefits of soil conservation are unwilling (or unable) to implement these practices because of the economic difficulties faced by their households. Therefore, farmers should have access agronomic and economic information about technologies and receive extension assistance in their adaptation to local climate, soil and social conditions (Heffernan and Green, 1986).

Lockeretz (1990) reported that land ownership is often linked to resource utilization and protection. Moreover, he reported a strong connection between resource degradation and lack of land ownership. Thus, government land policies (which determine land ownership) also have an important role in sustainable tea production. Indeed, the shift in land ownership from state-run farms to individual farm families had a significant impact on the attitudes of farmers as they relate to maintaining the productive potential of the land (i.e., protecting the soil quality). As a result, farmers are now more likely to increase their inputs and adopt more soil conservation technologies in an effort to enhance productivity, and hence their own economic status, as well as protect the land.

Market access also affects tea production. Although an open-market economy has existed in Vietnam since 1986, there is still little competition in the market for tea. When a market is not perfectly comparative, the equilibrium quantity produced and consumed is not socially optimal (Townley, 1998). Limited access to the tea market influences not only the economic return to farmer, but also the long-term sustainability of tea production. Farmers who do not receive adequate compensation for their product are unlikely to reinvest in their farm, resulting in a downward spiral in both economic and productive sustainability. Artificially depressed tea prices, resulting from limited market access, also hinder any future expansion of the tea enterprise. That is, expansion of the tea plantations will continue only as long as the market price for tea exceeds the minimum input cost needed to produce an additional unit of output (Townley, 1998).

Farm families generally work and live on their land for generations, resulting in an accumulated knowledge of how the land has changed since it has been in crop production. Consequently, any effort to implement new soil conservation programs requires a good understanding of the indigenous knowledge of the farmer (Douglas, 1990; McCallister and Norwark, 1999). In the present study, farmers identified organic matter, inherent fertility, and compaction as the most important soil quality indicators. Consequently, soil conservation programs targeted at tea growers should be developed to address these factors. This farmer-based, observational (or qualitative) approach to identifying soil quality indicators can, and should, be linked with soil testing (quantitative approach) to provide more effective diagnostic tools for evaluating soil quality, crop productivity, and long-term sustainability.

7. General Synthesis, Discussion, and Conclusion

7.1 General Synthesis and Discussion

The overall objective of the research was to assess changes in soil quality under tea cultivation following forest clearance and relate these changes to productivity. The hypothesis was that long-term tea cultivation degrades soil quality, which in turn decreases crop productivity. The research consisted of two separate but inter-related components, quantitative evaluation of soil quality under long-term tea cultivation and a study of socio-economic conditions and farmer attitudes towards sustainable tea cultivation. The study area was located in the Song Cau tea enterprise of Thai Nguyen Province, the largest tea production area in the Northern Mountainous Zone. Tea is the main cash crop in the region, farms are small and the tea plantations vary in terms of age, topography and management.

7.1.1 Important Inherent Characteristics of the Study Soils

Intrinsic soil properties including soil color, clay mineralogy, particle size distribution, and Fe- and Al-oxide contents and forms were measured, and comparisons made between the native, forest soils and soils under tea cultivation for 10, 25 and 40 years. Clay content of the soils ranged from 42 to 46% in the surface horizons, increasing with depth to a maximum at 40- to 60-cm depth, where dense clay layers limit root growth. The clay fraction is dominated by kaolinite with some mica and vermiculite.

The typical reddish yellow color is an indication that oxidizing conditions predominate, with Fe- and Al-oxides being the most abundant elements. These soil minerals play an important role in nutrient dynamics in the soil environment, particularly P adsorption (Huang and Wand, 1997), and also influence soil physical properties, such as the stabilization of soil aggregates (Huang, 1988; Hillel, 1999).

A kandic horizon (similar to an argillic horizon) was present in all soils at the 40- to 80-cm depth, with clay contents up to 60% and dominated by low activity clays. Based on clay mineralogy, soil texture and soil morphology, as well as on moisture and temperature characteristics, the soils were classified as Kanhaplustult Ultisols (Soil Taxonomy, 1998).

Knowledge of the basic inherent properties of soils is necessary to identify soil quality indicators and assess the natural variability of these indicators. The variability in inherent soil properties (expressed in terms of the CV) was low to moderate and, at a given depth interval, was similar for all soils, indicating that the soils have undergone similar development. The general uniformity of soils in the native forest and the tea plantations also indicates that measured differences in the more dynamic soil properties can be attributed mainly to the effects of cultivation, as opposed to sample variability.

7.1.2 Dynamic Soil Properties as Indicators of Quality under Tea Cultivation

The identification of important soil quality indicators was based mainly on the sensitivity level of soil properties in relation to tea cultivation. They included chemical properties such as organic C, nutrient supplying power (N, P, K and S) and pH; and physical properties such as mechanical resistance, bulk density, total porosity, PAWC and MWD of aggregates; and earthworm population as a bio-indicator. In general, changes in most soil quality indicators occurred at a faster rate during the initial period of cultivation, with the greatest amount of change occurring during the first 10 years and then progressively leveling off. Changes in soil quality due to cultivation were most pronounced for the upper soil horizons (0- to 40-cm depth), suggesting that this is the depth increment that should be considered in any future work.

With long-term tea cultivation, organic C and soil nutrients such as N, S and K decreased; total P levels, on the other hand, increased. The increase in total P was attributed to additions of P fertilizer to soils that are naturally quite deficient in P and have a strong P fixation potential. Despite this increase in total P, the plant available P fraction decreased with time–again reflecting the high P fixation potential of the soils. Cropped soils were more acidic than those under forest. Long-term tea cultivation resulted in decreased concentrations of the basic cations (particularly K^+, Mg^{2+} and Na^+) but with little change in exchangeable Al^{3+}. Increased bulk density, mechanical resistance and PAWC were consistently observed in the older tea plantations. In contrast, total porosity, the MWD of aggregates, and earthworm populations were much lower in the cultivated soils than in the forest soils.

Soil organic C is a key indicator of soil quality because of its influence on other soil properties (Reeves, et al., 1997). The decrease in organic C due to cultivation is related to depletion of nitrogen, increases in bulk density, deterioration of soil structure and decease in water retention capacity. Likewise, the soil nutrient indicators such as N, P, K and S were most important in determining nutrients available for plant growth. The depletion of soil nutrients (particularly total N and K, and available P and K) in the older tea soils indicated declining soil fertility with cultivation. A low pH associated with high Al saturation in the soils may affect the bioavailability of soil nutrients, and lead to a further increase in P fixation.

Physical properties such as bulk density and mechanical resistance are useful indicators of soil compactness, which affects the translocation of water, aeration and root growth (Chen, 1999). An increase in bulk density reflects the related increase in compaction, and reduced transmission of air through micropores. The decrease in PAWC is an indication of soil degradation due to cultivation. The smaller MWD of the aggregates in the cropped than in the forest soils indicates a breakdown of soil structure due to cultivation. The decline in soil structure may well be related to the observed reductions in earthworm populations in the cropped soils, in that their burrowing action and worm casts favour more aggregated soils (Lodsdon and Linden, 1992).

7.1.3 Soil Properties of Limited Value as Soil Quality Indicators

Soil color, clay mineralogy, texture, Al- and Fe-oxides, Cd concentration and ECEC changed little with cultivation. Soil color, clay mineralogy, texture and Al- and Fe-oxides are inherent properties and can be expected to be virtually static (Carter et al., 1997). Changes in inherent properties are part of soil formation, requiring a long period for significant change (Huang, 1998).

The reasonably uniform Cd content in the soils was surprising because Cd is a common impurity in the P fertilizers that were continuously being applied to the tea soils. The fact that Cd content did not increase with P fertilization is a positive result, indicating that the well-fertilized systems are sustainable, at least in terms of soil quality and its relation to quality of tea products (Williams and David, 1976). The changes of ECEC due to cultivation were negligible. This is probably because exchangeable Al that accounted for a large proportion of ECEC was relatively constant.

7.1.4 The Effects of Farming Practice and Management on Soil Quality

Limiting soil erosion on sloping topography. Water erosion accentuates the differences between soils in the lower and upper slope positions (Dau et al., 1998). The soils in this study exhibited no significant differences in soil properties between the upper and the lower slope positions, even after 40 years of cropping. This result was attributed to the adoption of soil conservation practices in which the farmers' plant their tea in rows along the contour and at a high plant density; thereby, minimizing soil erosion by water and its associated degradation of soil quality.

Effects of crop management (fertilization) on soil quality. In most tea fields, fertilizer applications did not balance the nutrient losses from the soil, which include nutrient removed in the harvested tea and stored in the above ground plant biomass. Consequently, continuous cropping resulted in an ever increasing deficit of these elements in the soil nutrient budget. Adequate fertilizer applications, therefore, represent an important management practice needed to maintain soil fertility–particularly in an intensive crop production system like tea. Adequate fertilization is also necessary to maintain crop productivity in older tea plantations. Indeed, the 40-yr-old tea stands still maintained good productivity when provided with adequate fertilizers.

7.1.5 Critical Levels of Soil Quality Indicators for Economically Sustainable Tea Cultivation

The sustainability of the tea production system is discussed in terms maintaining both production (yield) and economic viability. Maintenance of crop production requires the maintenance of soil quality. The 40-yr-old tea plantations still have a good harvest potential when provided adequate nutrients, suggesting that tea yields in the older tea plantations are limited primarily by declining soil fertility. Organic C, total K, available P and PAWC made significant contributions to the yield functions, and are considered to be important soil quality indicators for economically sustainable tea production.

Economic analyses suggest that under current management, the benefit:cost ratio calculated for the 40-yr-old tea plantations was only marginally above the "break even" point, so that any further decline in soil quality would be expected reduce yields to the point where the system would no longer be economically viable. Measured values of the soil quality indicators, particularly organic C, total K, available P and PAWC, in the 40-yr-old tea soils were considered to be estimates of limiting level for sustainable tea cultivation in the Mountainous Zone.

7.1.6 Socio-Economic Indicators and Farmers' Perspectives on Soil Quality

The maintenance of soil quality in agroecosystem depends upon the ability of farmers to manage the soils and the social institutions controlling access and use (Lynam and Herdt, 1992; Warkentin, 1995). The ability of this study's farmers to maintain soil quality depended largely on their economic status. Thus, the economic status of farmers is an important socio-economic indicator of sustainability in tea cultivation. In general, farmers whose income is at a subsistence level generally applied smaller amounts of fertilizers. Tea yields from these farms were generally low, and together with the small size of the farms, resulted in low incomes. The cycle was then repeated, resulting in a downward spiral of soil quality, crop productivity and farm income.

The education of farmers, particularly that of the heads-of-household, is an important socio-economic indicator for many sustainable agricultural systems (Nguyen et al., 1999; Gana, 2000). In this study, however, the impact of education on the crop production was not clear. Only a few farmers (10%) had low education levels (primary school level), but they were also quite experienced in tea cultivation. Likewise, the availability of a labor force was not a critical factor–reflecting the small farm size and high population density in this area, all of which contributed to a surplus of labour.

Farming practices reflect the acceptance of soil conservation technologies by farmers. Traditional farming practices with monoculture tea and imbalanced fertilizer applications are still common in this region. In these farming practices, crop productivity relies primarily on the intrinsic fertility of the soil rather than the use of external inputs to supplement this fertility and enhance crop growth. Traditional farming practice, therefore, is a limiting factor for sustainable tea cultivation and needs to be replaced by new soil conservation technologies.

Land tenure and market access are other appropriate socio-economic indicators of the sustainability of an agricultural system. The change in land ownership from government to individual households motivated farmers to improve yields and soil quality by increasing fertilizer inputs and labour for tea cultivation. Along with the change in land policy, improved market access for tea also motivated farmers towards more sustainable tea cultivation systems. That is, by adopting methods to maintain/enhance soil quality and crop productivity, increased returns from tea production can be expected.

Farmers have intuitive knowledge derived from their long experience, thus their perceptions are useful for planning soil conservation programs. Farmers recognized many important soil indicators affecting tea yields, for example, depletion of organic C, losses in soil fertility, and soil compactness. These perceptions closely link with results of scientific research. In addition, farmers are able to identify appropriate soil conservation technologies. Technologies that have been accepted by most farmers should be considered within the cultural and socio-economic conditions of farmers, and the long-term and short-tem beneficiary of technology.

7.2 Recommendations for the Future of Soil Conservation

Sustainable tea cultivation is an important goal for the economic development of the Northern Mountainous Zone, because tea is the main crop providing a livelihood to farmers in the region. Declining soil quality resulting from cultivation leads to low crop productivity which, in turn, adversely affects the total income of farmers. Maintenance of soil quality, therefore, is necessary to sustainable tea cultivation, requiring a combination of technologies, incentive policies from the government, and farmer activities.

Soil organic C is related to the nutrient supplying power of the soil, as well as other chemical and physical processes, and as such was identified as a key indicator of changes in soil quality. The maintenance of soil organic C, therefore, should be of prime concern. Balanced fertilizer application (i.e., N, K and available-P) and increased nutrient recycling by returning prunings to the soil are thought to be good approaches to maintaining organic C and other nutrients. Other soil chemical and physical indicators appear to be less important for sustainable tea production due to their limited effect on the soil environment and crop growth. Crop yield is a sensitive indicator of soil quality status and the sustainability of tea production, but does not identify the causes of declining yield.

Maintaining soil quality depends largely on the economic capacity of farmers, and their ability to supply inputs to replace those removed in the crop (Douglas, 1990). About one-third of the farmers in the Northern Mountainous region are poor, lacking the capacity to provide adequate fertilizers. Under these conditions, continuously cropped and unfertilized soils will degrade rapidly. To offset this, government policies must be established to help poor farmers improve their production potential and protect the long term sustainability of the tea production system. Economic viability must be of prime concern, along with procedures of improved land management for tea cultivation.

Complex topography, increased population pressures, small farm size and the fragmentation of holdings are important characteristics of tea farming in the Northern Mountainous Zone. To meet the basic needs of the people, intensive farming for high yields is necessary, but maintaining soil quality for the long-term must also be considered (i.e., maintaining organic C and other soil environmental conditions). Sustainable agricultural management, therefore, must have clearly defined goals and be considered to be long-term.

Soil conservation technologies must be appropriate for the physical and socio-economical conditions that prevail in the Northern Mountainous Zone. More importantly, to be readily accepted by the majority of farmers, new technologies must consider both the long-term sustainability and short-term economic benefit to the farmers. For new tea plantations, practices such as planting tea in rows along the contour line is necessary to control erosion. Recycling of organic biomass and supplying adequate fertilizers should be of prime concern for the sustainability of older tea plantations.

Changes in land tenure from the government to individual households appear to have made tea cultivation more sustainable, both economically and environmentally. Farmers have changed their attitudes regarding increased use of fertilizer, labor and appropriate technology to make tea production more profitable. The lack of long-term leasing arrangements is an impediment to the adoption of substantive land improvement technologies. Thus it is recommended that leases be extended for longer periods so that farmers will feel more confident when applying soil conservation technologies aimed at long-term sustainability. Likewise, market access for tea production must be completely open and allow free competition. The government should encourage more private sector participation in the export market so that maximizing profit in tea production is a result. Highly competitive markets are important to farmers, not only for seeking a good price, but also in providing opportunity for farmers who have access to credit to take advantage of technologies to increase production or decrease costs, as an efficient production decision (Boehm and Burton, 1997).

The indigenous knowledge possessed farmers should be considered when planning soil conservation programs. Farmers must have access to agronomic and economic information as well as receive extension assistance to exploit results from scientific research. Indigenous knowledge (the farmer-based approach) and modern scientific technologies are complementary to each other, and when combined can achieve results that neither could accomplish on their own (Chambers, 1983). Importantly, by combining the qualitative approach of soil quality evaluation with scientific study the costs of research and soil conservation programs can be reduced.

This study recommends a series of soil quality and socio-economic indicators that could be useful in evaluating the sustainability of tea cultivation in the Northern Mountainous Zone (Table 7.1).

Table 7.1. Summary indicators for evaluation of sustainable tea cultivation.

Evaluation factors	Indicators	Diagnostic criteria
Soil quality	- Organic C, soil fertility (N, P, K and S), pH, Bulk density, porosity, PAWC, resistance, MWD, earthworms	- Sensitivity change and level of effects on crop productivity
Crop production	- Yield	- Change in yields
Socio-economics	- Operating cost - Household economics - Acceptance of farming practice	- Profit and benefit - Sufficient - Social and economic perceptions of technologies
Government policies	- Type of land ownership - Market access	- Change in farmers' attitude towards soil management

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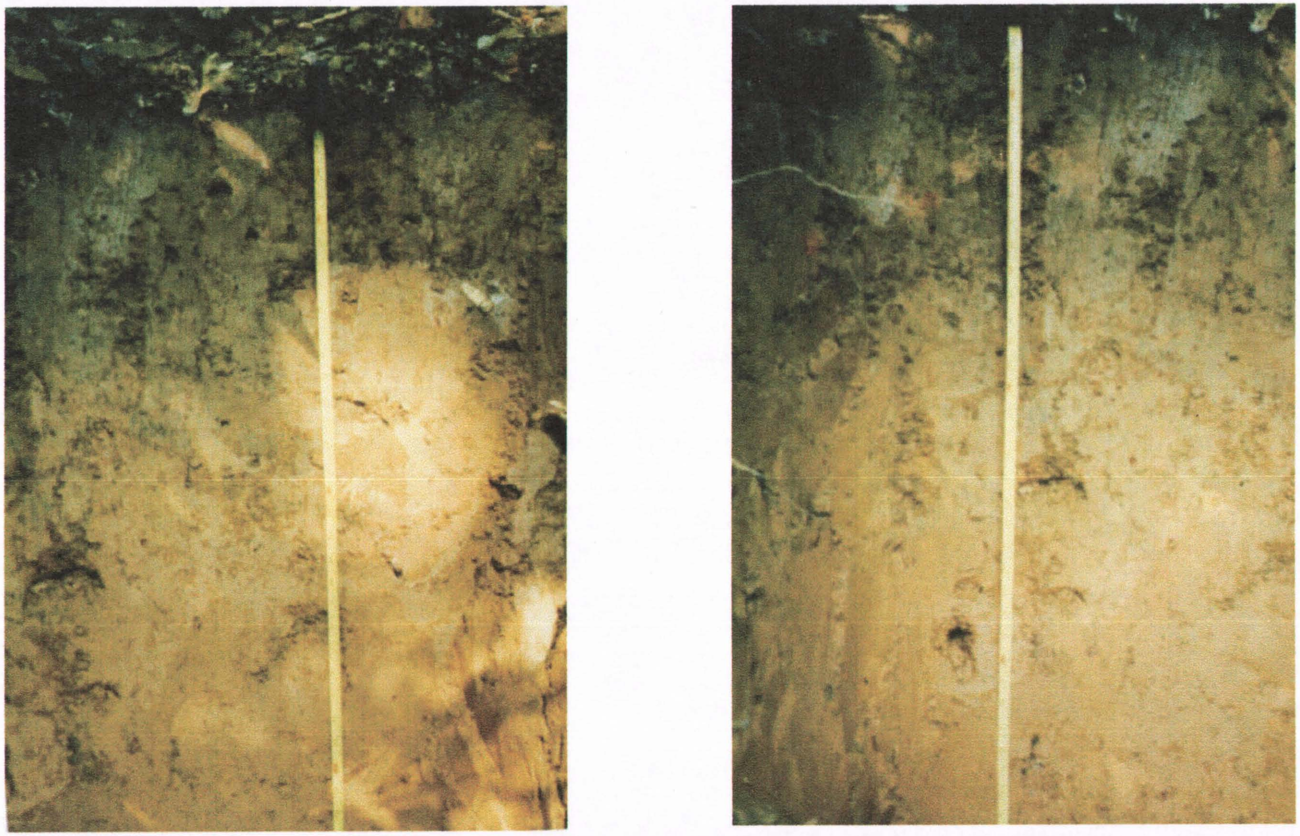
9. Appendices

Appendix 1. Representative Soil Profiles



Forest soil profiles

30 yr-old tea soil profile

40 yr-old tea soil profile

Appendix 2. Questionnaires for Socio-economic Survey

Part 1. Demographic and background information

1. Name household head:............................Sex..................
2. Village.........................Commune..
3. Ethnic group...
4. Age
5. Household composition
    a) Total people live in household:...
    b) Of them: Number of children under 15 year old.....,
       Male between 15-60yrs:........., Female between 15-60 yr.:..........,
    Males and females over 60 years............
6. Education

6.1 Education of household head (tick one)
  a) No formal education.......
  b) Primary school.........
  c) Secondary school.......
  d) High school........
  e) Agricultural training.........
  f) Other
     (specify)...

6.2 Education of family member
  a) How many family member between 15-60 year old are able to write and read:
  b) How many family member between 15-60 year old are not able to write and read:

7. Livelihood
  a) What is main income source of your family (tick one)
  - Agriculture:.......
  - Other
(specify):..
  b) If agriculture, which one is your main livelihood (tick one)
  - Tea cultivation..........
  - Crop (or agricultural activity) other than tea production
(specify).......................
  c) Do you have any off-farm employment? Yes-   No-

8. Livestock production. How much animal heads are in your household in this year
  - Water buffalo
  - Cow
  - Pig
  - Goat
  - Poultry

Part 2. Economics

1. Is your food production and other income from agriculture enough for (tick one)
  - Living (sufficient to feed your family throughout the year)

- Living and refund for input of production
- Saving
- Non of above

2. If not enough, which months of food shortage do you have in within last 5 years

3. What are the main reasons for your food shortage

....

....

4. How do you find money to buy food during food shortage months

....

....

5. How does your economic status affect tea production

....

Part 3. Land use pattern

1. Total land area and land use rights

Specific land use pattern	Area (m^2)	Land properties		
		Own long-term properties	Red book certificate[1]	Lease from stage enterprise/ co-operative[2]
Forest				
Lowland rice				
Upland crop other than tea				
Tea crop				
Aquaculture				
Home garden				
Other				

[1] certificate for long-term use; [2] Lease for certain time use.

2. Comments for land use rights

....

....

Part 4. Tea production information

1. Background information of your tea fields

Field #	Area (m^2)	Tea age	Crop/forest before tea	Land properties	Estimate slope		Soil type (sand/ loamy/ clay)
					Steepness (%)	Slope length (m)	
1 2 3 4 ...							

2. Input

2.1 Fertilizers used for tea crop in this year

N-fertilizer:

- List kind and amount of N-fertilizer that you have applied in this year

....

....

- Compare to last few years: No change......, increase......, decrease.........,
- Method used: broadcast......, band........., other.......;

P-fertilizer:

- List kind and amount of P-fertilizer that you have applied in this year:

....

....

- Compare to last few years: No change......, increases......, decrease.........,
- Method used: broadcast......, band........., other.......;

K-fertilizer:

- List kind and amount of fertilizers applied in this year: ....

....

....

- Compare to last few years: No change......, increases......, decrease.........,
- Method used: broadcast......, band........., other................;

Lime:

Within last 5 years do you apply lime for your tea crop:...........,

- If yes, how much:
- Method used: broadcast......, band........., other................;

Manure:

- Within last 5 years do you apply manure for your tea crop:..............,
- If yes, how much:

2.2 Pesticides

- List kind and amount of pesticides that you have used in this year (convert to a.i.g/1000m^2 if possible):

....

....

- Compare to last few years:

....

....

2.3 Is any difference of amount and kind of fertilizer applied to

- The difference of tea age group: Yes-----/ No-----------
- The difference of land type/slope position: : Yes-----/ No-----------

If yes, please specify how and why

....

....

....

2.4 In your opinion, what kind of fertilizer you want to invest more

....

....

3. Labor

3.1 Estimate how much labor days have been used for your tea crop/month
- Fertilizing:.............;
- Weeding:..............;
- Harvesting:............;
- Processing:.............;
- Other:..................;

3.2 Have you hired labor in these years: Yes...... No.....
If yes, please specify (for what activities and how much and what month)..
....

4. Harvest

4.1 Harvest in this year

Plot #	Total harvest (fresh yield by kg)	Compare to last few Year (incr./decr.)	What are reasons that cause the change of yield
1 2 3 4 ...			

4.2 Have you noticed any change in your tea yield after
- 5 yr: no change..... , increase........., decrease............,
- 10 yr.: no change..... , increase........., decrease............,
- 15 yr.: no change..... , increase........., decrease............,
- 20 yr.: no change..... , increase........., decrease............,
- 30 yr.: no change..... , increase........., decrease............,
- 40 yr.: no change..... , increase........., decrease............,

5. Knowledge on soil quality and soil conservation technologies

5.1 How long do you have experience on tea cultivation:...
- Do you think your soil is good for tea crop:........, please explain:

....

5.2 In these years have you noticed any change in the condition of your tea soil
- Compaction (tick one): no change......., increase.........., decrease..............,
- Soil color: no change ...., increase.........., decrease..............,
- Soil OM: no change..........., increase.........., decrease..............,
- Soil moisture (in dry season): no change..........., increase.........., decrease..............,
- Earthworm: no change..........., increase.........., decrease..............,
- Soil texture: no change..........., increase.........., decrease..............,
- Thickness of soil surface: no change..........., increase.........., decrease........,
- Soil conditions at the upper and lower slope position: no difference...., little difference......, much difference..........;
- Occurrence of weed: no change..........., increase.........., decrease..............,
- Soil acidity: no change..........., increase.........., decrease..............,
- Declining soil fertility: yes/no.........

- Other (specify)...

....

5.3 Please rank soil properties listed above (question #3) from 1 (most important) to 12 (least important)

....

....

5.4 How do you know the changes in your soils

....

....

6. If your tea crop become worse after long-term cultivation, what do you intent to do
   - Re-planting with a new tea crop;
   - Re-placing with another crop;
   - Keeping tea crop with special cares;

7. In your opinion, how old of your tea crop should be replanted:......................

8. Comparison between tea soil and other upland cultivation soils in your region, which one is better after long-term cultivation
   - Tea soil vs. annual food crop soil
   - Tea soil vs. fruit tree soil
   - Tea soil vs. forest soil

9. List major problems related to maintaining your land productivity

....

....

10. What practices have you applied to improve your crop productivity and soil fertility

- Mulching:.......... - Intercropping with tree /or legume crop.............
- Increasing fertilizer:........... – Manure amendment:................................
- Watering in dry season......... - Return plant residue to soil when annual pruning...
- Hedgerowing..................
- Other.......................

11. How do you know these techniques

....

12. Do you want to increase area of tea cultivation within next few years

13. Your comments to sustaining yield in the older tea plantation......................

Part 5. Market access and government policy affect tea production

1. How and where do you find market for your products

....

2. Price of tea product in this year compared to last 5 years
   not much change........, significant increase........., significant decrease...........,

3. Price of fertilizer in this year compared to last 5 years
   not much change........, significant increase........., significant decrease...........,

4. The change of Tea price is fair enough to the change of fertilizers' price

....

5. Do you have any subsidies from government when market price of tea going down

……………………………………………………………………………………

6. With shifting land from tea enterprise/cooperative to farmers

- How long have you leased these lands
- Have you noticed any change in your soils since you have leased these lands better………, worse……., no change……….. .

Please explain

……………………………………………………………………………………………

……………………………………………………………………………………………

……………………………………………………………………………………………

- Inputs that you have invested for tea crop increased or decreased if compared with the time when lands were directly managed by enterprise :………
- Crop yields increase or decrease if compared with before :……..

7. Other comments for improve your soil and tea production

……………………………………………………………………………………………

……………………………………………………………………………………………

……………………………………………………………………………………………

……………………………………………………………………………………………

……………………………………………………………………………………………//

Appendix 3. Correlation Analysis Among Dynamic Soil Properties

Table A3.1. Pearson correlation coefficient among chemical soil properties (0-40 cm depth).

Indicator	Org.C	Total N	Total S	Total P	Total K	Avail. K	Avail.P	pH
Total N	0.876**							
Total S	0.255**	0.383**						
Total P	0.454**	0.492**	0.272*					
Total K	0.104	0.126	-0.137	-0.163				
Avail.K	0.412*	0.444**	0.285*	0.310	0.083			
Avail.P	0.211**	0.275**	0.132	0.421*	-0.158	0.284*		
pH	0.107	-0.025	-0.151	-0.276**	0.065	-0.265*	0.172	
ECEC[1]	0.186*	0.209	0.780	0.230**	0.215*	0.167	0.159	-0.289**

*,** Correlation is significant at the 0.05 and 0.01 level, respectively;

[1] ECEC- effective cation axchange capacity.

Table A3.2. Pearson correlation coefficient of organic-C and physical indicators (0-20 cm depth).

Indicator	Soil C	Bulk density	MWD[1]	PAWC[2]
Bulk density	-0.767**			
Aggregate	0.406*	-0.148		
PAWC	0.622**	-0.736**	0.143	
Soil resistance	-0.225	0.337*	-0.095	-0.443**

*,** Correlation is significant at the 0.05 and 0.01 level, respectively;

[1] MWD-mean weight diameter of aggregates; [2] PAWC-plant available water capacity.

Appendix 4. Effects of Slope and Fertilization on Soil Quality

Table A4.1. The t-test for difference of means of soil properties between upper and lower back slope positions (0- to 10-cm depth).

Slope position	Forest	1-yr	10-yr	25-yr	40-yr
Total C (mg g^{-1})					
Upper	24.88a[1]	24.22a	18.07a	20.30a	18.27a
Lower	27.88a	25.32a	21.10a	21.18a	19.22a
Total N (mg g^{-1})					
Upper	1.91a	1.90a	1.53a	1.63a	1.76a
Lower	2.12a	1.97a	2.08b	1.74a	1.55a
Total P ($\mu\text{g g}^{-1}$)					
Upper	224.67a	237.21a	312.38a	348.65a	320.12a
Lower	224.90a	247.80a	374.00a	358.35a	392.94a
Available P ($\mu\text{g g}^{-1}$)					
Upper	6.29a	8.15a	31.48a	18.17a	8.66a
Lower	9.47a	9.06a	31.57a	22.34a	9.28a
Total K (mg g^{-1})					
Upper	14.84a	13.59a	11.47a	11.07a	10.13a
Lower	14.07a	14.55a	12.35a	12.06a	10.57a
Available K ($\mu\text{g g}^{-1}$)					
Upper	47.30a	69.81a	67.70a	63.66a	34.49a
Lower	56.90a	73.25b	90.10b	74.40a	35.28a
pH					
Upper	4.07a	4.39a	3.77a	3.91a	4.06a
Lower	4.09a	4.28a	3.84a	3.99a	4.09a
Bulk density (Mg m^{-3})					
Upper	1.05a	0.96a	1.20a	1.23a	1.28a
Lower	1.06a	1.04a	1.12a	1.20a	1.27a
MWD (mm)					
Upper	4.29a	NA[2]	3.03a	3.53a	3.64a
Lower	4.76a	NA	2.75a	3.23a	3.71a
PAWC (% Vol.)[3]					
Upper	13.40a	NA	12.98a	12.26a	8.98a
Lower	13.38a	NA	12.76a	12.21a	9.61a

[1] Means in the same column followed by the same script do not differ significantly at 5% level of probability (using t-test);

[2] NA- not available.

[3] PAWC-plant available water capacity, MWD-mean weight diameter of agreegates.

Table A4.2. Comparison of soil properties in 40 yr-old tea plantations with different fertilizer inputs.

Soil properties	Depth (cm)	High fertilizer inputs	Low fertilizer inputs	Significance level[1]
Total C (mg g^{-1})	0-10	20.85	16.63	0.09
	10-20	13.06	9.81	0.05
	20-40	11.68	7.44	0.02
Total N (mg g^{-1})	0-10	1.95	1.35	0.03
	10-20	1.02	0.82	0.14
	20-40	0.85	0.68	0.01
Total P (μg g^{-1})	0-10	482.38	228.61	0.05
	10-20	282.08	184.12	0.01
	20-40	207.05	148.74	0.00
Total K (mg g^{-1})	0-10	10.99	8.53	0.45
	10-20	11.26	9.87	0.56
	20-40	11.59	11.32	0.61
Avail.P (μg g^{-1})	0-10	11.09	8.10	0.62
	10-20	3.03	2.41	0.63
	20-40	1.18	0.54	0.23
Avail.K (μg g^{-1})	0-10	41.54	28.42	0.08
	10-20	32.13	18.10	0.06
	20-40	22.34	15.93	0.10
Total S (mg g^{-1})	0-10	0.76	0.34	0.00
	10-20	0.59	0.29	0.01
	20-40	0.56	0.28	0.03
Bulk density (g cm^{-3})	0-10	1.24	1.22	0.48
	10-20	1.30	1.36	0.06
PAWC (%)[2]	0-10	9.90	9.28	0.17
	10-20	11.97	11.73	0.13
MWD (mm)[2]	0-20	3.62	3.29	0.07
Resistance (Mpa)	10	2.04	2.15	0.07
	30	4.58	4.50	0.79

[1] Significance levels of t-test for difference of means of soil properties.

[2] PAWC-plant available water capacity, MWD-mean weight diameter of agreegates.

Appendix 5. Economic Analysis for 40-yr-old Tea Plantations with Different Fertilizer Application (by VND)[1].

Indicator	Low fertilizer inputs	High fertilizer inputs
Yield (Mg ha^{-1})	1.78	2.83
Total benefit (cost per ha, 1000 VND)	17800	28300
Total inputs (cost per ha, 1000 VND)	20556	22925
Benefit:cost ratio	0.85	1.19

---

[1] Tea plantations receiving high fertilizer inputs were defined as those receiving at least 150, 80 and 80 kg ha^{-1} yr^{-1} of N, P and K fertilizers, respectively (note: these are the minimum fertilizer inputs recommended by local agronomists for 40-yr-old tea fields); fields receiving fewer fertilizer inputs were classified as "low fertilizer".

Appendix 6. Sources of Living and Literacy Rate of farmers

Table A6.1. Sources of living of surveyed farmers.

Source	Number of households	Percentage
Mainly agriculture	38	90
Off-farm and agriculture	4	10
Total	*42*	*100*

Table A6.2. Literacy rate of people at the labour age (18-60 years old).

Status	Number of people	Percentage
Formal education[1]	117	93
No formal education	9	7
Total	*126*	*100*

Note: [1] Formal education accounted for those who have attended in at least primary school.

Appendix 7. Farmers' Perception about Changes in Crop Yields

Table A7.1. Recognition by farmers about the change in yield with length of continuous cropping.

Year after cultivation	Percentage of farmers (n=42)		
	Yield no change	Yield increase	Yield decrease
10	5	95	0
15	31	69	0
20	21	43	36
30	16	0	84
40	6	0	94

Table A7.2. Farmers' opinion about the reasons for reduction in crop yields.

Reason causing changes in crop yield	Percentage of farmers (n=42)
Aging of plants	52
Degradation of soil fertility	82
Lack of inputs (e.g. fertilizers)	55
Pests	31
Others (e.g. weather)	5