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EFFECTS OF TEA CULTIVATION ON SOIL QUALITY IN THE LAM DONG, VIETNAM

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Abstract

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

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

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

Acknowledgement

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Chapter1: Introduction

Agriculture is one of the most important components of Vietnam. Soil is a critical part of successful agriculture and is the original source of the nutrients that we use to grow crops. The healthiest soils produce the healthiest and most abundant food supplies. Adding fertilizer is one important way to keep agricultural production systems sustainable. In nature, plants use soil nutrients, and then they die and are decomposed by microorganisms. This returns the nutrients to the soil. In an agricultural setting, the crops take up nutrients, but then are removed from the field so people and livestock can eat them and in turn get the nutrients. This removes nutrients from the field. In order to maintain nutrient levels in soil, it is important to apply fertilizer, whether from natural sources, such as manure, or human-made sources, such as ammonium

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

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

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

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

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 Lam Dong 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.

Chapter 2: Literature Review

2.1. Agricultural and Socio-Economic Conditions in Vietnam and Lam Dong province

2.1.1 Background

Over the past quarter century, Vietnam's agricultural sector has made enormous progress. Steady advances in smallholder rice productivity and intensification through the 1990s and beyond have played a central role in Vietnam's successes in poverty reduction, national food security, and social stability. Vietnam once experienced hunger yet its per capita food availability now ranks among the top tier of middle-income countries. Many countries are trying to learn from Vietnam's food security success. Vietnam's average rice yields now trail only those of China among Asia's emerging economies. The country has also achieved explosive growth in agricultural exports and now ranks among the top five global exporters in products as diverse as shrimp, coffee, cashews, rice, and pepper. Vietnam's performance in terms of agricultural yields, output, and exports, however, has been more impressive than its gains in efficiency, farmer welfare, and product quality. Vietnam lags behind regional peers in relation to agricultural land, labor, and water productivity and has seen its once robust growth in total factor productivity decline in recent years. A chasm is forming between farm and non-farm incomes, and income inequality is rising within rural areas. Most of Vietnam's agricultural trade is in the form of raw commodities, typically sold at prices lower than those of leading competitors due to quality or other differences. At home, there are growing concerns about food safety. More output has come from more and more inputs, at increasing environmental cost. A large proportion of Vietnam's agricultural growth has stemmed from expanded or more intensive use of land and other natural resources, and relatively heavy use of fertilizer and other agro-chemicals. As a result, aspects of Vietnam's agricultural success have come at the expense of the environment. Environmental consequences of Vietnam's agricultural success have ranged from deforestation and fishery resource depletion, to a growing incidence of land degradation and water pollution. Hence, Vietnam's agricultural growth has relied very heavily on human, natural, and chemical factors of production. Vietnamese agriculture now sits at a turning point. The agricultural sector now faces growing domestic competition—from cities, industry, and services—for labor, land and water. Rising labor costs are beginning to inhibit the sector's ability to compete globally as a low cost producer of bulk undifferentiated commodities. The consequences of over-intensive input- and natural resource-use—both for the environment and for farmer profitability—are increasingly coming into view. Some environmental problems are now adversely impacting both productivity and the international position of Vietnam's commodities. Vietnam faces bright opportunities in both domestic and international markets, yet effectively competing in these will depend upon the ability of farmers and firms to deliver (food and other) products with reliability, and with assurances relating to quality, safety, and sustainability. Going forward, Vietnam's agricultural sector needs to generate "more from less." That is, it must generate more economic value—and farmer and consumer welfare—using less natural and human capital and less harmful intermediate inputs. Future growth can rely primarily on increased efficiency, innovation, diversification, and valueaddition. There are currently many initiatives aiming in these directions. Yet achieving the shift these represent on a large, sector-wide scale, will require important changes in certain economy-wide and sector-specific policies and, over time, major changes and additions to the core institutions servicing agriculture. It calls for an ambitious and ongoing process of learning and experimentation, and several potential directions are offered below for consideration.

2.1.2 Agricultural and Socio-economic Conditions of Lam Dong, Vietnam

Agricultural environment of Lam Dong province, which is located in central highland area, is totally different from that of other lower areas in Vietnam. In Lam Dong province, abundant plant resources were naturally grown such as pine trees, taxus, and wild orchids, which can grow in high mountainous area. In Lam Dong, the field proportion of perennial crops was higher than that of annual crops. However, the field proportion and yields of vegetables were highest among the all cultivated crops, estimating 38% (36,552ha) and 72% (993,082MT), respectively. Especially in Da Lat, vegetables, flowers, orchids, and industrial crops were mainly produced because this area is geographically close to Ho Chi Minh city. And also in Da Lat, 64% (8,447ha) and 36% (4,777ha) of farm fields were used for producing annual and perennial crops, respectively, and the yields of fresh vegetables in this area was estimated to 213,478MT which was 21.5% of the whole yields in Lam Dong province. Thus Korea, Taiwan, Japan, France, and Holland have invested to agriculture in Da Lat for producing and exporting flowers, vegetables, and tea. In 2009, flower cultivation area of Da Lat was over 55% in Lam Dong province and average amount of values were 9,781 million USD, which was higher than that of al other crops. Thus following strategies could be suggested for the development of agriculture in Lam Dong province. The first, agricultural cooperation with Da Lat, Lam Dong, should be characterized to horticulture and floriculture, followed by supporting both appropriate RnD techniques and equipments. And then agricultural system should be made in relationship with the local companies. Finally, agricultural cooperation program should be conducted toward the direction for both donor and recipient countries.

2.2 .Tea Production

2.2.1 Introduction

All tea comes from the tropical plant known as Camellia sinensis. The tea plant grows best in a warm climate with long sunlit days, cool nights and an abundance of rainfall. Tea plants grow at altitudes ranging from sea level to 7,000 feet and on latitudes as far north as Turkey in the mid-east and as far south as Argentina in South America.

China, Tibet, and northern India are the origins of tea, though it is cultivated in many other countries across the globe, including Sri Lanka, Japan, Kenya, Turkey, Indonesia, Vietnam, Argentina, Tanzania, Taiwan, Malawi, and Zimbabwe. The most complex teas grow at higher altitudes and many bushes can be cultivated for over 100 years. Tea bushes cover about six million acres of the earth and are harvested every week during the almost year-long growing season.

After each winter season, the first small leaves and buds of the tea bush are hand-plucked and harvested. Once exposed to air, the leaf will begin to wither.

When the picked leaf becomes pliable, it can then be turned into different types of tea.

A common misperception is that the various styles of tea are grown from different types of plants. The fact is that all styles of tea come from the same Camellia sinensis tea plant; however, the method in which they are processed varies, yielding the main classifications and varieties of tea. White, Green and Yellow tea are produced by steaming the leaves after plucking, thus eliminating the oxidation process. Oolong tea is allowed to oxidize for a short period of time, and Black tea is allowed to react with the air and oxidize, turning the green leaves black. Pu-erh tea is a style of black tea that has been piled and allowed to ferment considerably.

Although tea has been enjoyed in Vietnam for thousands of years, it has only been produced within the country since the 1880s, when French colonists established the first Vietnamese tea plantations in the area around Pho Tho, northwest of Hanoi. Today Vietnam is the seventh largest global producer of tea, with much of the crop grown by independent smallholders who are contracted to sell a percentage of their tea leaves to state-owned farms or large processing plants. The rest they are free to process themselves as distinct artisanal varieties, or to sell on the open market.

The Vietnamese value tea for its simple purity and thus tend to prefer teas with light, delicate flavours. Small amounts of black, white and oolong tea are produced, but green tea is by far the most popular variety of tea in Vietnam and is usually enjoyed plain, without extra flavourings.Today, tea plants are widely grown in the world with a very long history, about more than 4,000 years. So far, tea is produced in 58 countries with different sizes, distributed across 5 continents. Asia occupies the leading position in terms of tea planting area and output, followed by Africa, at least Oceania. Asia has 17 countries and Africa has 15 growing countries tea.

Vietnam is one of the top 10 countries in the world in terms of tea area and output, and ranks 8th in terms of tea exports. Changes in tea area, output, and export turnover of our country in recent years are listed

However, fresh, flower-scented teas are also popular in many areas. For instance, one Vietnamese speciality is lotus tea, which is traditionally prepared by sealing high-quality green tea leaves within a lotus flower and leaving them to absorb the fragrance overnight. Jasmine tea, aglaia tea and chrysanthemum tea are among the other flower varieties that can be found in certain regions of Vietnam. Today Vietnam has five principal tea producing areas – the northern highlands, the northwest, the northern and central coastal areas, the midlands, and Viet Bac, the area to the north of Hanoi. The province of Lam Dong in the central highlands is the largest tea growing area in Vietnam, closely followed by Thai Nguyen in the northeast. Northern highland regions such as Yen Bai are also known for their ancient tea forests

According to the Sub-Department of Cultivation and Plant Protection of Lam Dong province, the province currently has about 11.2 thousand hectares of tea, of which the tea planting area for consuming in markets is 11.1 thousand hectares with an average yield of 14 tons/ha; output reaches 160 thousand tons. Tea production area of the province is mainly concentrated in Bao Lam district; Bao Loc city and some other districts and cities of the province.

Lam Dong's tea products are currently mainly consumed in the domestic market with a rate of about 74%, the rest are exported to markets such as Taiwan, Pakistan, Afghanistan, Russia, and the US, etc. In order to improve the quality and value of tea, over the past time, Lam Dong's agricultural sector has focused on changing varieties and encouraging the development of high-tech models. Accordingly, the area of old seed tea every year is planned by localities to change to a high-yield and high-quality tea associated with purchasing and processing enterprises such as TB14, O Long, Tu Quy, Kim Tuyen, Ngoc Thuy variaties. "The current proportion of local tea varieties is quite diverse. In which, high yield tea TB14, LD97 account for 34.85%; high quality tea Kim Tuyen, Tu Quy, O Long, Ngoc Thuy account for 44.05%; The rest is 21.10% of other tea variaries," said Ha Ngoc Chien.

According to the Sub-Department of Cultivation and Plant Protection of Lam Dong province, over the past time, tea production in the locality has been affected by the precarious and unstable consumption market. In addition, the marketing and development of Lam Dong tea brand has been implemented, but the competitiveness is still low. The competitiveness of enterprises in the province is still weak, especially domestic private enterprises with small scale and limited resources, making it difficult to invest in technology and expand export markets.

In order for the tea sector to develop, Lam Dong province is focusing on reviewing and re-planning the area and encouraging businesses to build their own raw material areas to improve productivity and quality. At the same time, Lam Dong is developing tea production areas applying hi-tech agriculture in Bao Loc city and Bao Lam district to improve the value and brand of products.

Lam Dong's agricultural sector also promotes activities to develop B'Lao Lam Dong tea brand and simultaneously maintain the traditional market along search for and expand the export markets.

In addition, in order to access the market, Lam Dong province has increased innovation in production lines and processing technology to ensure product quality suitably with the tastes and preferences of consumers to focus on producing adaptive products. The province also aims to organize the production of high-class teas with high competitiveness such as: Fruit flavored tea, canned tea drinks, medicinal teas, herbal teas, etc.

Lam Dong will put high-yielding, good-quality tea varieties suitable for local ecological conditions into mass production. At the same time, the province guide farmers to apply scientific and technical measures to production, especially in terms of new varieties, collection and preliminary processing, and then invest in production of certified and qualified products safety for domestic and export markets. Along with that, one important task is building and maintaining the development of linkages between processing enterprises and tea growers.

Lam Dong currently has 155 tea processing companies with a capacity of 29,000 tons/year and 90 tea processing establishments with a scale of 17.4 thousand tons/year. In which, there are 6 companies and tea processing facilities applying ISO management system and 1 establishment applying HACCP management system. With the current processing capacity, raw materials are not enough due to a sharp decrease in tea area and output.

Recently, due to a shortage of raw materials or after-processed products that could not be sold to the market due to price competition, many businesses and establishments stopped operating.

Table 2.1. Tea growing area in Bao Loc - Di Linh (period 2015 - 2021)

Unit: ha

	2015	2016	2018	2019	2020	2021
total	**25.535**	**26.553**	**24.083**	**23,900**	**23.557**	**23.529**
1. Bao Lam district	12,341	13.478	13,188	13.255	13,246	13,350
2. City. Bao Loc	9.661	9.544	8.713	8,475	8.208	8050
3. Di Linh District	2015	2015	1.019	983	886	886
Other districts	1.518	1.516	1.163	1.187	1.217	1.243

Source: Department of Agriculture and Rural Development of Lam Dong province

b. Converting tea varieties:

In recent years, the locality has actively changed tea varieties, many new varieties of tea with high yield and quality have been put into mass cultivation and have shown superior economic efficiency compared to the old tea varieties. Some quality tea varieties. High quality such as: Olong, Kim Tuyen, Thuy Ngoc, Tu Quy Spring ... are concentratedly planted. In traditional tea areas, cuttings are substituted for varieties sown by seeds. High yielding tea varieties such as TB14, LD97, LDP1, LDP2... to replace the old, low yielding tea gardens.

The percentage of branch tea in the study area accounted for 44%, 2 times higher than the general rate of Lam Dong province, of which high yield tea accounted for 26%, high quality tea accounted for 18%. The area of tea branches accounts for 68% of the total tea area available

2.2.1.2. Tea processing

Concentrated tea growing areas have applied sprinkler and drip irrigation technology, using chemicals and fertilizers that are not harmful to the environment. At the same time, tea growers also use appropriate intensive farming methods to ensure the planting area of new varieties with high yield and good quality of raw materials.

Fig 2.1: MAP DISTRIBUTION STATUS BAO LOC - DI LINH AREA, LAM DONG PROVINCE

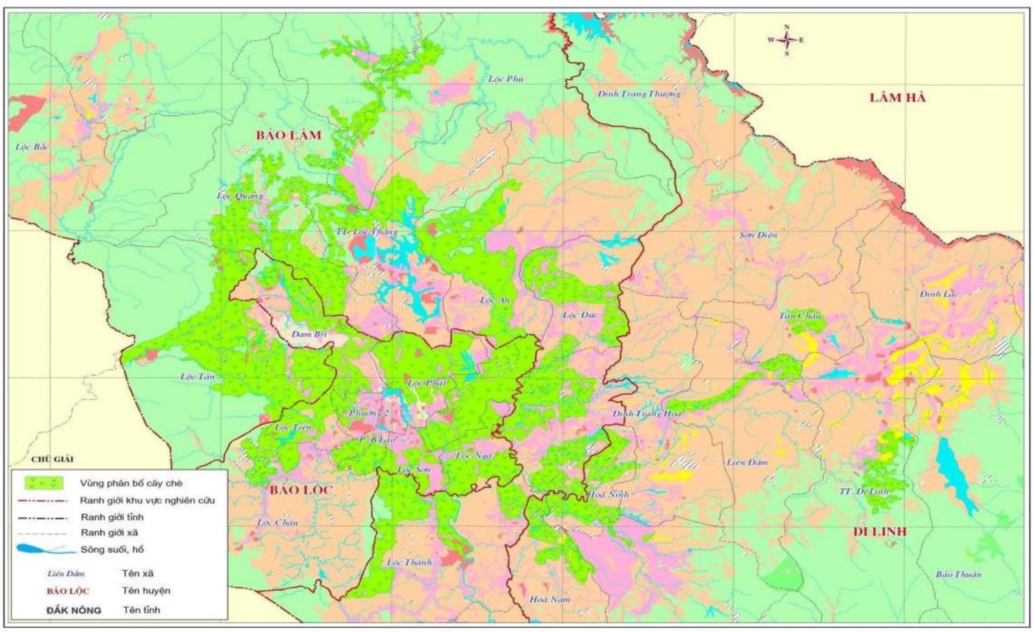

Table 2.2: Production of fresh bud tea in Bao Loc - Di Linh area in the period 2015-2021

Unit: tons

	2015	2016	2018	2019	2020	2021
total	**161.938**	**170.543**	**178,979**	**171.683**	**204.031**	**209.016**
1. Bao Lam district	80,735	80,500	92,340	97,340	117.761	123,657
2. City. Bao Loc	63,982	70.696	74.446	60,773	72.707	68,817
3. Di Linh District	10,350	11.480	6,499	6,615	5,640	7.656
Other districts	6871	7867	5694	6955	7923	8886

Source: Department of Agriculture and Rural Development of Lam Dong province

Tea processing has also seen significant improvements. The picture of tea production and processing has also changed positively. Households are playing an important role in local tea growing and processing. The number of households with large-scale land for perennial industrial crops such as tea and coffee is increasing, but the number of households producing tea on a small scale (under 5 hectares) is still very large.The development of the farm economy with this type of tea cultivation is limited because tea requires regular care and more complicated planting and processing techniques.

By 2020, the existing tea processing facilities have ensured to process all output of tea buds in the area. However, only a few processing establishments in the foreign-invested enterprise sector and a few state-owned enterprises have advanced processing technology that meets high-quality tea processing standards. The remaining establishments mainly process tea for domestic consumption. The current distribution of tea processing facilities is not really reasonable. Bao Lam district is a large tea area of Lam Dong province, but the number of tea processing establishments is not much. In the tea industry development strategy of Lam Dong province, post-harvest tea processing facilities in rural areas will soon be established to ensure the quality of raw materials for finished tea, and at the same time increase income for tea farmers. tea growers

2.2.2 Important Characteristics of Tea Soils

Three considerations in planning a tea estate are climate, soil acidity, and labour availability. A suitable climate has a minimum annual rainfall of 45 to 50 inches (1,140 to 1,270 mm), with proper distribution. If there is a cool season, with average temperatures 20 °F (11 °C) or more below those of the warm season, the growth rate will decrease and a dormant period will follow, even when the cool season is the wetter one.

Tea soils must be acid; tea cannot be grown in alkaline soils. A desirable pH value is 5.8 to 5.4 or less(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 $A1^{3}+$ (Jakia Sultana et al. 2014); thus, requiring an adequate supply of exchangeable Al and Fe indicated that a high pH and low content of exchangeable AI, Zn, and Fein soils caused high mortality and stunted the growth of the tea plant.

Tea tree is a leaf-harvest crop widely native to tropical and subtropical areas, especially in Asia, Africa, and Latin America. The optimal soil environment for tea growth is a pH of 4.0–5.5, well-drained, with more than 2% organic matter (OM) content, and suitable for sandy loam or sandy clay with rich humus in general (Willson, K.C.; Clifford, M.N , 2013) As for a high nitrogen (N) requirement crop, it has been reported that applying NH_4^+-containing fertilizer can improve growth performance and strongly increase yield as well as enhance the level of free amino acids and caffeine while increasing or decreasing the polyphenol level (Qiao, 2018). Fertilizing with N, potassium (K), and magnesium (Mg) have been demonstrated to promote the synthesis of glutamic– pyruvic transaminase (GTP), glutamate dehydrogenase (GLD), and amine oxidase to amino acids and thus decrease the PP/AA ratio (polyphenol/amino acid ratio), which used to be an index for qualifying tea quality (Ruan, J.Y.; Wu, X.; Hardter, , 2007) The results of earlier research have also highlighted that N and phosphorus (P) fertilizer could enhance the level of theanine, caffeine, and esterified catechins to improve the quality of tea infusion(Chen, P.A.; Lin 2015; Lin, Z.H, 2012) . Moreover, most micronutrients act as electron transports, activators of enzymes, or cofactors in the physiological function of tea plants, such as iron (Fe), which is involved in the synthesis of chlorophyll protein complexes; polyphenol oxidase (PPO) in tea leaves has also been noted to be made up of copper (Cu)(Steffens, J.C.; 1994) In addition, the characteristics of tea trees include aluminum (Al) and manganese (Mn) hyperaccumulation. It has been reported that Al may be the beneficial element for tea root growth and has a high tolerance under high Al availability conditions with low pH (Sun, L.; Zhang, 2020) Therefore, the antioxidant properties having a strong influence on polyphenolic levels were altered to be in defense against oxidative stress (Tolra, R.; Martos, 2020).

However, the availability of element nutrient mainly depends on pH. The nutrient uptake is affected by soil texture, cation exchange capacity, and any physical and chemical properties, elemental antagonism, or synergism effect (

Brady, N.C.; Weil, 2013) Therefore, soil conditions should be dominant in tea plantation management in this quality-driven agricultural industry. Although the studies in this decade that investigated single fertilizers applied to the soil for crop yield and tea quality were versatile, the integrative evaluation for soil management of the tea garden was few and far between

2.2.3 Effects of Management on Tea Soil

The conventional approach of tea cultivation based on agro-chemical is causing soil degradation . The development of land for tea cultivation in the area has resulted in significant soil degradation (Ahsan, 2011); decline in soil organic matter (OM), loss of N and P through erosion and leaching, fixation of P, reduction of soil microorganisms, and acidification associated with nitrogenous fertilizers. The productivity has declined and expansion of the industry has threatened by poor conventional management practices. The traditional cultivation practices, such as excessive cultivation, continue cropping, removal of crop residues and excessive use of chemicals are contributing in land and environmental degradation. The excessive and unbalanced use of agrochemicals has led to increase production costs but decline in farm productivity. Thus, there is growing emphasis in the region for ecological and/or sustainable (integrated natural resource based farming) approach in tea cultivation to replace the conventional (chemical fertilizer based farming) approach (BTB, 2009; RTRS, 2012). Moreover, tea growers are using chemical fertilizers for higher production of tea but this approach is harmful for the productivity of tea farm. Now sustainability of conventional tea farm production in the region is under threat. Farm yield has declined substantially due to indiscriminate use of agro- chemicals and conventional practices. Thus, sustainable and or ecologically suitable management is highly demanded to sustain tea plantation in the region. However, the key research question of this project is whether integrated natural resource management is a viable alternative for the conventional soil management of tea plantations? This case study will focus on soil management by integrated approach that will reduce the demand of external fertilizers, increase farm resource utilization and soil fertility restoration. Successful adoption of integrated approach through efficient resource management might have positive impacts on soil health, tea productivity and farm sustainability. Thus, farm economic viability and social impacts will sustain longer.

Sustainable production integrates the idea of natural resources utilization to generate increased output and income by less or no depletion of the natural resource base. In this context, INRM maintains soils as storehouses of plant nutrients that are essential for plant growth. INRM's goal is to integrate the use of all natural and man-made sources of plant nutrients so that plant productivity increases in an efficient and environmentally suitable manner. This will ensure soil productivity for future generations. Nutrient conservation and uptake of nutrients from the soil is another critical component of INRM. Addition of fertilizer from various organic sources is supposed to prevent the physical loss of soil and nutrients through leaching and erosion, and maintenance of natural soil fertility. Green manuring, mulch application, cover crops, intercropping and biological nitrogen fixation might help to improve soil health. Organic manures such as animal and green manures substantially aid in improving soil structure and replenishing secondary nutrients and micronutrients (Ch Srinivasarao, 2021).

Sufficient and balanced application of organic and inorganic fertilizers is a component of INRM.

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 a fertilizer application on the shoot extension rate and the rate of regeneration have a positive impact on tea yield (Mokaya, 2016). Under favorable temperature, rainfall, relative humidity, and evaporation conditions, tea yield is increased by nitrogen nutrition without having any adverse effects of large amounts of nitrogen supply (Hajiboland, 2017). Increased N supply of up to 600 kg/ha/year resulted in favorable yields ranging from 5800 to 6400 kg made tea/ha per year in high-yielding clones. The incredible response of the tea plants to nitrogen fertilizer applications is stimulated by frequent harvesting of the shoots (Cheruiyot et al., 2010). In tea cultivation, phosphorus is essential for the growth of new wood and roots of tea plants. After nitrogen, potassium is the most essential nutrient for tea (Hajiboland, 2017). Significant amounts of K are lost from the soil during harvesting, just as they are with N, and the tea plant has a moderate to high K requirement (J et al., 2014). Micronutrient availability is influenced by a variety of factors, including soil and rhizosphere PH . High soil P H results in the retention of micronutrients in the soil, thus limiting their uptake by tea plants (Rengel, 2015). Both organic and inorganic fertilizer applications are done like small and big in present time in most of the countries. More research studies have been conducted to find the effects of organic and inorganic fertilizer application in tea cultivation.

Cultivation of tea plants caused soil acidification and soil acidity increased with the increase of tea cultivation period. Soil pH of composite samples from cultivated layers decreased by 1.37, 1.62 and 1.85, respectively, after 13, 34 and 54 years of tea plantation, as compared to the surface soil obtained from the unused land. Soil acidification rates at early stages of tea cultivation were found to be higher than those at the later stages. The acidification rate for the period of 0–13 years was as high as 4.40 kmol H^+ ha^{-1} $year^{-1}$ for the cultivated layer samples. Soil acidification induced the decrease of soil exchangeable base cations and base cation saturation and thus increased the soil exchangeable acidity. Soil acidification also caused the decrease of soil cation exchange capacity, especially for the 54-year-old tea garden. Soil acidification induced by tea plantation also led to the increase of soil exchangeable Al and soluble Al, which as responsible for the Al toxicity to plants (Hui WANG, 2010).

Decreases in soil pH and increases in exchangeable Al and Fe have a significant influence on soil quality and productivity. One study on fonner tea lands of Sri Lanka indicated that Ae+ 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 aI., 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 detennine 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 At3+ concentration and percent Al saturation were high.

Soil forms from fresh parent material through various chemical and physical weathering processes and SOM is incorporated into soil through decomposition of plant residues and other biomass. Although these natural soil building processes regenerate the soil, the rate of soil formation is very slow. For this reason, soil should be considered a nonrenewable resource to be conserved with care for generations to come. The rate of soil formation is hard to determine and highly variable, based on the five factors of soil formation. Scientists have calculated that 0.025 to 0.125 mm of soil is produced each year from natural soil forming processes (Montgomery 2007, Wakatsuki & Rasyidin 1992). Because of the time required to generate new soil, it is imperative that agricultural practices utilize best management practices (BMPs) to prevent soil erosion. The soil which is first eroded is typically the organic and nutrient enriched surface layer which is highly beneficial for plant growth. Thus, the primary on-site outcome is reduced crop yield as only the less fertile subsurface layers remain. Soil erosion also pollutes adjacent streams and waterways with sediment, nutrients, and agrochemicals creating serious off-site impacts.

Historically, conventional agriculture has accelerated soil erosion to rates that exceed that of soil formation. Erosion is often accelerated by agricultural practices that leave the soil without adequate plant cover and therefore exposed to raindrop splash and surface runoff or wind (Singer & Munns 2006). Throughout human history, soil erosion has affected the ability of societies to produce an adequate food supply. Poignant examples of this can be seen in the eroded silt built up in the ancient riverbeds of Mesopotamia, making irrigation problematic (Hillel 1992), and the United States Dust Bowl of the 1930s where a devastating drought increased wind erosion, carrying fertile topsoil from the Midwest hundreds of kilometers to Washington, DC (Montgomery 2007). Figure 3 is a stunning photograph demonstrating the devastating effects of this severe wind erosion. The Dust Bowl made soil erosion a high priority in the American public consciousness of the 1930s, and it remains a top priority today.

The soil microbial biomass is involved in the decomposition of organic materials and thus, the cycling of nutrients in soils. Reductions in the size and activity of the microbial biomass are frequently used as an early indicator of changes in soil chemical and physical properties resulting from management and environmental stresses in agricultural ecosystems. In a laboratory-incubated soil, we found a strong relationship between microbial biomass C and microbial biomass N. Irrespective of the type of plant residues added, soil pH was significantly correlated with microbial biomass C and microbial biomass N. Different C/N ratio of the residues was the main characteristic that affected soil microbial biomass C, N and soil pH. Microbes played a main role in plant residues decomposition and indirectly influenced of soil pH (Yunfeng Wanga, 2010).

The effects of management on chemical and physical properties of tea soils. Soil texture classes varied from sandy loam to light clay, which was affected by different terrains along the transect lines as well as severe disturbance such as terracing and earth excavation. The levels of total C and total

N were correlated with increasing garden age, suggesting the replenishment of soil organic matter pool by the addition of plant residue and manure. Meanwhile, the soils showed strongly acidic nature with the average pH(H2O) of 3.7 at the surface and 3.9 at the subsurface. The effective cation exchange capacity (ECEC) was low at 4.7 and 4.9 cmolc kg−1, respectively, and dominated by exchangeable Al3+. Soil acidification was exacerbated with increasing garden age. However, a relatively large saturation of exchangeable calcium (Ca2+), potassium (K+), and magnesium (Mg2+) on the ECEC was found in the surface soils. The levels of available P were high, occasionally exceeding 1000 and 500 mg kg−1 at the surface and subsurface, respectively. In spite of strongly acidic condition, ammonium (NH4-N) applied as fertilizer was converted to nitrate (NO3-N) to move down to deeper layers. The levels of the bases, P, and mineral N seem to be principally determined by management practices. Significant portion of these nutrients was likely to exist in water soluble forms without adsorption onto soils.(Hoang Huu Chien, 2018)

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 aI., 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 AI, 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 AI 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 300/0, 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 is one of the three components of environmental quality, besides water and air quality (Andrews et al., 2002). Water and air quality are defined mainly by their degree of pollution that impacts directly on human and animal consumption and health, or on natural ecosystems (Carter et al., 1997, Davidson, 2000). In contrast, soil quality is not limited to the degree of soil pollution, but is commonly defined much more broadly as "the capacity of a soil to function within ecosystem and land-use boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health" (Doran and Parkin, 1994, Doran and Parkin, 1996). As Doran and Parkin (1994) state explicitly, animal health includes human health.

This definition reflects the complexity and site-specificity of the belowground part of terrestrial ecosystems as well as the many linkages between soil functions and soil-based ecosystem services. Indeed, soil quality is more complex than the quality of air and water, not only because soil constitutes solid, liquid and gaseous phases, but also because soils can be used for a larger variety of purposes (Nortcliff, 2002). This multi-functionality of soils is also addressed when soil quality is defined from an environmental perspective as "the capacity of the soil to promote the growth of plants, protect watersheds by regulating the infiltration and partitioning of precipitation, and prevent water and air pollution by buffering potential pollutants such as agricultural chemicals, organic wastes, and industrial chemicals" (National Research Council, 1993 as cited in Sims et al. (1997)). Soil quality can be assessed both for agro-ecosystems where the main, though not exclusive ecosystem service is productivity, and for natural ecosystems where major aims are maintenance of environmental quality and biodiversity conservation. Given the scope and readership of this journal, the "non-ecological functions" of soil *sensu* Blum (2005), such as the physical basis of human activities, source of raw materials, and geogenic and cultural heritage, are beyond the scope of this review.

Extrinsic factors such as parent material, climate, topography and hydrology may influence potential values of soil properties to such a degree that it is impossible to establish universal target values, at least not in absolute terms. Soil quality assessment thus needs to include baseline or reference values in order to enable identification of management effects. Soils often react slowly to changes in land use and management, and for that reason it can be more difficult to detect changes in soil quality before non-reversible damage has occurred than for the quality of water and air (Nortcliff, 2002). Therefore, an important component of soil quality assessment is the identification of a set of sensitive soil attributes that reflect the capacity of a soil to function and can be used as indicators of soil quality.

Because management usually has only limited short- term effects on inherent properties such as texture and mineralogy, other indicators, including biological ones, are needed. The distinction between inherent (static) and manageable (dynamic) attributes, however, is not absolute and also context-dependent (Schwilch et al., 2016). For example, stoniness as an inherent property is nevertheless manageable, e.g. by removal of stones from an area to facilitate tillage and to build separating walls between fields, or by addition of gravel and stones to improve friability, to accelerate soil warming in spring or decrease evaporation. Soil management by humans has even given rise to separate classes in the soil taxonomic system, such as Plaggic anthrosols, the plaggen soils of northwestern Europe (e.g., Blume and Leinweber (2004)), and Terric anthrosols, the Amazonian Dark Earths, also known as Terra Preta de Índio (Glaser and Birk, 2012).

The history of the concept of soil quality shows that it is rooted in two different approaches that either put more emphasis on the inherent soil properties or on the effects of human management. The oldest mention in the scientific literature is by Mausel (1971) who defined soil quality as "the ability of soils to yield corn, soybeans and wheat under conditions of high-level management. The choice of these crops to reflect soil quality in Illinois is due to their overwhelming agricultural economic dominance." This definition emphasises agricultural production and is linked to land evaluation (see below). A similar description was provided by SSSA (1987; cited in Doran and Parkin, 1994) as the "inherent attributes of soils that are inferred from soil characteristics or indirect observations". This definition is comparable to the more recent term soil capability, defined as the intrinsic capacity of a soil to contribute to ecosystem services, including biomass production (Bouma et al., 2017). The emphasis on inherent, more static soil properties was closely connected to soil taxonomy. It also took management for granted ("under conditions of high-level management"), without specifying those conditions. Larson and Pierce (1991) expressed uneasiness with the focus on agricultural productivity and proposed to disconnect soil quality from productivity. Doran and Parkin (1994) observed that definitions of soil quality included the capacity of soils to function sustainably, but likewise considered the focus on production to be too restrictive. They wanted a definition of soil quality to stress the main issues of concern regarding soil use. Besides productivity, they therefore included the ability of soils to contribute to environmental quality and to promote plant, animal and human health in their definition as cited above.

The concept of soil quality by Doran and Parkin (1994) was heavily criticized in a series of papers (Letey et al., 2003, Sojka and Upchurch, 1999, Sojka et al., 2003). That criticism contained various elements. First, these authors claimed that the concept of soil quality could transform soil science from a value-neutral science into a value system and even referred to soil quality as promoting ideas of a politically correct soil. Second, they expressed discontent with the idea of a universal soil quality index, to which they referred as institutionalizing soil quality. Third, they criticized the concept because of its bias towards certain soil types as a consequence of the focus on intrinsic properties. And finally, they criticized the definition because in its original form it puts too much emphasis and value on a limited number of annual crops that provide cheap food and that are heavily subsidized. Their proposal to replace the term soil quality management by the term quality soil management did not find support, but their criticisms did influence the further development of an operational concept of soil quality, in which management has become the central issue: agricultural productivity does not hold a privileged position any longer, trade-offs are explicitly recognized at the expense of a universally applicable index, and the role of soil scientists in relation to societal stakeholders who manage soils (farmers, owners of land for nature conservation, policy makers, etc.) has changed. A particular recommendation of Sojka and co-authors was to speak of soil use rather than soil functions, so that the responsibility to maintain the quality of the soil can be clearly assigned to the user of the soil. Soil quality assessment then provides the scientific tools for evaluation of the management of soil resources, considering also the societal demands of the various benefits that soils, if managed well, can provide to humankind. The valuation of soil quality hence becomes connected to the valuation of the ecosystem services provided by soils. A further benefit of such a soil quality concept is that it raises awareness and enhances communication between stakeholders regarding the importance of soil resources (Karlen et al., 2001). Recently, there has been renewed interest in this educational aspect, either by focusing more on visual soil assessment (Ball et al., 2013) or by proposing interactive soil quality assessment tools, such as LandPKS (https://www.landpotential.org/) and the app currently being developed in the EU Horizon-2020 project 'Interactive Soil Quality Assessment in Europe and China for Agricultural Productivity and Environmental Resilience (iSQAPER - http://www.isqaper-project.eu/).

2.4. Soil fertility, land quality, soil capability, soil quality and soil health

Various forms of soil assessment are encapsulated in different concepts. Apart from mining minerals, the main interest in soil has traditionally been in its potential for agricultural production. Assessments of the suitability of soil for crop growth may have been made even before the evidence of written records. Documentation can be found in ancient Chinese books such as "Yugong" and "Zhouli", written during the Xia (2070–1600 BCE) and Zhou (1048–256 BCE) dynasty, respectively (Harrison et al., 2010), and in the work of Roman authors such as Columella (Warkentin, 1995). Ethnopedology also provides several examples of indigenous soil classifications that focus on indicators that allow judgement of the suitability of particular soils for various crops (e.g., Barrera- Bassols and Zinck, 2003). The suitability of soil for agricultural production is captured in the concept of *soil fertility*, originating from the German literature on "Bodenfruchtbarkeit" that is predominantly aligned to crop yields (Patzel et al., 2000). Accordingly, the FAO describes soil fertility as "the ability of the soil to supply essential plant nutrients and soil water in adequate amounts and proportions for plant growth and reproduction in the absence of toxic substances which may inhibit plant growth" (www.fao.org). Mäder et al. (2002) extend that scope in proposing that a fertile soil "provides essential nutrients for crop plant growth, supports a diverse and active biotic community, exhibits a typical soil structure and allows for an undisturbed decomposition". Nevertheless, the concept of soil fertility is generally operationalized chemically and partly physically in terms of the provision to crops of nutrients and water only.

To address physical and/or biological characteristics of soil, other concepts are more commonly used. One of the earliest is *land quality*, which integrates characteristics of soil, water, climate, topography and vegetation (Carter et al., 1997, Dumanski and Pieri, 2000) in the context of land evaluation, which aims to assess the use potential of land, based on its attributes (Rossiter, 1996). An early comprehensive elaboration of the concept is the FAO Framework for Land Evaluation (FAO, 1976). Soil survey is part of land quality assessment for land evaluation. It is done once or only repeated over large time intervals, relying heavily on field observations, supplemented with very few measured parameters (Huber et al., 2001). Land evaluation anticipates decisions on the optimal allocation of land for various uses and is, hence, the first step to sustainable land management. In countries with low population densities, the main purpose of land evaluation in the past was to identify fertile land for agricultural production, whereas in more densely populated regions such as Europe it was more targeted at identifying deficient factors in agriculture that could be remedied, in particular by manuring (van Diepen et al., 1991). However, land evaluation has also been used as part of a strategy to assess broader land use options (van Latesteijn, 1995). Similarly, *soil capability*, i.e. the intrinsic capacity of a soil to contribute to ecosystem services (Bouma et al., 2017), provides a neutral assessment of what soils can do and how their potential can be reached.

Since Mausel (1971) introduced the term *soil quality*, it has sometimes been used in the context of land quality and land evaluation (e.g. Eswaran et al., 1997). Whereas land quality and land evaluation primarily address the inherent soil properties that do not change easily and are often assessed for the entire profile, soil quality is more focused on the dynamic soil properties that can be strongly influenced by management and are mainly monitored in the surface horizon (0–25 cm) of the soil (Karlen et al., 2003). However, when studying direct impacts of soil quality on water quality it is imperative that inherent soil properties in deeper parts of the soil profile are included in the assessment.

Typically, the concept of soil quality is considered to transcend the productivity of soils (Larson and Pierce, 1991, Parr et al., 1992) to explicitly include the interactions between humans and soil, and to encompass ecosystem sustainability as the basis for the benefits that humans derive from soils as well as the intrinsic values of soil as being irreplaceable and unique (Carter et al., 1997). The term soil quality in this broader sense was already used by Warkentin and Fletcher (1977). Recently, soil quality assessment is increasingly incorporated in land evaluation, as land evaluation procedures are now used in many different ways and for a range of purposes, including sustainable land management (Hurni et al., 2015), environmental risk assessments, monitoring of environmental change (Sonneveld et al., 2010) and land restoration (Schwilch et al., 2012). In the land-potential knowledge system LandPKS, general management options are based on long-term land potential (depending on climate, topography and inherent soil properties) and can be modified according to weather conditions and dynamic soil properties (Herrick et al., 2016). The integration of soil quality and land evaluation goes as far as developing soil natural capital accounting systems, stressing the importance of soils for human wellbeing (Robinson et al., 2017).

In a program to assess and monitor soil quality in Canada (Acton and Gregorich, 1995), the term soil quality was used interchangeably with *soil health* and, in spite of the wider context in which it was presented, defined primarily from an agricultural perspective as "the soil's fitness to support crop growth without becoming degraded or otherwise harming the environment". The term soil health originates from the observation that soil quality influences the health of animals and humans via the quality of crops (e.g. Warkentin, 1995). Indeed, linkages to plant health are common, as in the case of disease- suppressive soils (Almario et al., 2014). Soil health has also been illustrated via the analogy to the health of an organism or a community (Doran and Parkin, 1994, Larson and Pierce, 1991).

The debate about soil quality vs. soil health arose quickly after the concept of soil quality was criticized in the 1990s. In contrast to soil quality, soil health would "capture the ecological attributes of the soil which have implications beyond its quality or capacity to produce a particular crop. These attributes are chiefly those associated with the soil biota; its biodiversity, its food web structure, its activity and the range of functions it performs" (Pankhurst et al., 1997). These authors further consider "that the term soil health encompasses the living and dynamic nature of soil, and that this differentiates it from soil quality". They therefore "adopt the view that although the concepts of soil quality and soil health overlap to a major degree and that in many instances the two terms are used synonymously (….), soil quality focuses more on the soil's capacity to meet defined human needs such as the growth of a particular crop, whilst soil health focuses more on the soil's continued capacity to sustain plant growth and maintain its functions". Meanwhile, the debate subsided and partly changed focus. For example, Moebius-Clune et al. (2016) consider that soil quality includes both inherent and dynamic soil properties, and that soil health is equivalent to dynamic soil quality. The differential usage may also link to the observation of Romig et al. (1996), that, whereas soil quality is the preferred term of researchers, soil health is often preferred by farmers.

The differences between land quality and soil quality observed by Karlen et al. (2003) and between soil quality and soil health observed by Pankhurst et al. (1997) and Moebius-Clune et al. (2016) can be summarized in a transition in focus from land quality to soil quality and soil health going from inherent to dynamic soil properties. states that "soil health, also referred to as soil quality, is defined as the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans". We conclude that the distinction between soil quality and soil health developed from a matter of principle to a matter of preference and we therefore consider the terms equivalent.

Like in land quality assessment and land evaluation, approaches to soil quality and soil health go beyond the reductionist approach of measuring (indicators of) soil properties and processes. Although such measurements remain important from a practical perspective (Kibblewhite et al., 2008a), the concepts of soil quality and soil health also include the capacity for emergent system properties such as the self-organization of soils, e.g. feedbacks between soil organisms and soil structure (Lavelle et al., 2006), and the adaptability to changing conditions.

2.5. Linking soil quality to soil functions and ecosystem services

Ecosystem services are defined as "the benefits which humans derive from ecosystems" (Costanza et al., 1997). With the early concept developed by Doran and Safley (1997), soil quality was addressing not only one ecosystem service such as provision of food, but also trying to represent and balance the multi-functionality of soil. This has recently been further embedded in the development of "functional land management", which assesses both the benefits and trade-offs of a multifunctional system for managing soil-based ecosystem services in agriculture (Schulte et al., 2014) and a wider range of land uses (Coyle et al., 2016).

Among scientists, the concept of ecosystem services is often used in connection with the concept of soil functions. 'Function' is, however, variably used as a synonym for 1) process, 2) function*ing*, 3) role and 4) service (Baveye et al., 2016, Glenk et al., 2012). Therefore, Schwilch et al. (2016) advise against using the term, but Baveye et al. (2016) note that function "in a narrow and well- defined context (…) has been used in connection with soils for over 50 years, and has served as a conceptual foundation for an appreciable body of research and significant policy making, at least in Europe" (e.g., the Soil Thematic Strategy of the European Commission, 2006). Therefore, we concur with Baveye et al. (2016) that "it makes sense to try to retain both "function" and "service" terminologies, as long as they can be articulated (…) with respect to soil properties and processes". In their seminal paper reconstructing how the notion that nature meets, or gets in the way, of the needs of people has pervaded concepts and theory in ecology vs. soil science argue that mainstream ecology, by its emphasis on organisms, tended to neglect the soil, in particular the non- living soil, whereas mainstream soil science tended to avoid the term ecosystem, emphasizing the importance of soil properties and processes in landscape terms. In accordance with Glenk et al. (2012), we define soil functions as (bundles of) soil processes that underpin the delivery of ecosystem services. This definition will suffice for all practical purposes related to manageable soil functions, which can be used to address the gap between "what is" and "what can be", based on soil capability, i.e. "what soils can do" (Bouma et al., 2017), which is, in the context of this review, what living soils can do. Complementary to this bottom- up approach, soil functions can be used in a top-down approach when identifying the gap between what is currently measured in soil assessment schemes and what should be measured in view of assessing the soil functions that are impacted by, or to be managed in view of current and upcoming policies (van Leeuwen et al., 2017), possibly through the use of environmental accounting systems increasingly adopted by policymakers, such as the soil natural capital accounting system proposed by Robinson et al. (2017).

Just as ecosystem services are influenced by (bundles of) soil processes, the latter are in turn affected by soil threats. The EU Soil Thematic Strategy identified the main threats to soil quality in Europe as soil erosion, organic matter decline, contamination, sealing, compaction, soil biodiversity loss, salinization, floodingand landslides (EuropeanCommission 2002, Montanarella, 2002). Soil threats have been emphasized in order to inform risk assessment exercises indicating (geographical) areas where soil functioning is potentially hampered (van Beek et al., 2010). Different schemes linking soil-based ecosystem services and soil functions have been developed (Haygarth and Ritz, 2009, Kibblewhite et al., 2008a, Tóth et al., 2013), but none of them includes soil threats. The scheme presented by Kibblewhite et al. (2008a) and modified by Brussaard (2012) was developed as a conceptual basis for the iSQAPER project, including soil threats as affecting the various soil functions and associated ecosystem services (Fig. 2). The soil functions in Fig. 2 equate almost entirely to the "intermediate services" defined by Bennett et al. (2010), which are similar to the soil processes presented by Schwilch et al. (2016). It has been argued that soil quality can indeed only be assessed in relation to one or several soil functions, ecosystem services or soil threats (e.g. Baveye et al., 2016, Bouma, 2014, Sojka and Upchurch, 1999, Volchko et al., 2013). Therefore, clear definitions of these terms as well as firmly established associations with soil quality indicators are the basis of any functional soil quality concept.

As soil quality plays a role in decision-making in the face of soil threats, the DPSIR (driver–pressure–state–impact–response) framework (EuropeanEnvironmentAgency, 1998) has frequently been adopted for use in EU policy to support decision-making and as a means to bridge the science-policy gap (Tscherning et al., 2012). Applying the DPSIR framework to soil (Fig. 3), "drivers" are pedoclimatic conditions and land use policies, while "pressures" are land use and management and the associated soil threats. Pressures and drivers and their variabilities and interactions determine the "state" of the soil, with subsequent "impact" on soil and ecosystem functioning, and the "response" in terms of the delivery of ecosystem goods and services. Subsequent adaptive management may be re-active to observed deterioration of soil functioning or pro-active to reach transitions to newly desired soil functioning. To assess any changes in the status of soil quality, assessment tools are needed.

2.6. Approaches to soil quality assessment

A plethora of soil quality assessment and monitoring tools have become available since the 1990s. Here, we give an overview of the main developments in different countries, before addressing aspects of soil quality indicators in more depth in section 4.

2.6.1. Analytical approaches to soil quality

National assessments of soil quality are often based primarily on analytical approaches (Table 1). One of the earliest national programs to assess and monitor soil quality was started in Canada in 1988 (Acton and Gregorich, 1995), using benchmark sites to assess changes in soil quality over time, especially in relation to the soil threats erosion, compaction, organic matter loss, acidification and salinization (Wang et al., 1997). While the Canadian soil quality monitoring program as such was not consistently continued, the data are still partly used in the assessment of agri-environmental indicators that cover soil, water and air quality (Clearwater et al., 2016). At a coarser scale, a GIS- based approach to characterize primarily inherent soil quality was presented by Macdonald et al. (1998).

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. Every farm needs fertile soil to produce healthy crops. Soil quality and health is an essential factor in growing vegetables, plants, flowers and much more. Industrial and small farms survive off of quality earth, though each sector cultivates it through different methods. Commercial agriculture often consists of farming techniques that deplete the land, which can lead to failed crops. However, small farmers aren't without their troubles — degraded soil affects them, too.A better foundation equals increased plant growth. The solution to poor crops often lies with the simplest factor — dirt. Agriculture can improve by leaps and bounds by employing better ideas for soil management.(Jane Marsh , 2005)

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 aI. (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 aI., 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 aI., 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 aI., 1995). Therefore, land quality is a broader concept than soil quality (Carter et aI., 1997). Land quality refers to the conditions or health of a parcel of land and its capacity for sustainable use and management (Pieri et aI., 1995).

2.7. Soil Quality Indicators

Soil indicators sensitive to variations in management are needed to compare the effects of a management practice on soil through time. If the indicators are insensitive to changes in management, they are of little use in monitoring soil quality change (Doran and Parkin, 1994). Soil texture and depth are soil properties that would change little over a period of time for a given soil, and so they would not be very useful for assessing management effects. Soil bulk density varies among soils of different textures, structures, and organic matter content, but within a given soil type, it can be used to monitor degree of soil compaction and puddling. Changes in soil bulk density affect a host of other properties and processes that influence water and oxygen supply. Measurement of soil strength using a cone penetrometer may be the best way to index the influence of soil density on root proliferation and growth (Powers et al., 1998).

Indicators of water infiltration, retention, availability, drainage, and water/air balance are universally important for monitoring all soil functions. Available water holding capacity and saturated hydraulic conductivity are the two most frequently found in mini-mum data sets of soil quality indicators. Available water holding capacity measures the relative capacity of a soil to supply water, and saturated hydraulic conductivity is an indicator of the rate of soil drainage that can be used to judge water/air balance in soils. Soil structure is the arrangement of soil particles into definite pattern. Soil quality indicators may be simple state variables as just described, or they can be more complex constructs of several soil variables such as `soil tilth index', which includes measures of bulk density, strength, aggregate uniformity, soil organic matter, and plasticity index (Singh et al., 1990). Furthermore, they may include a time or rate dimension which makes them dynamic, these indicators are termed pedo-transfer functions (Bouma, 1989) and are generally used to describe functions in which routinely-measured properties are used to predict other properties that are not measured (Kay and Grant, 1996). Many researchers have proposed a minimum data set, which is smallest set of soil properties or indicators needed to measure or characterize soil quality Some of the important soil health indicators include aggregation, water holding capacity, pH, EC, NPK reserves, organic carbon, microbial biomass and community composition (Rajendra Prasad et al. 2009).

2.7.1 Soil Chemical Indicators

Many chemical processes occur in soil due to metabolic activities of organisms living in the soil, water saturation, and interactions with the atmosphere and groundwater. Essential nutrients such as nitrogen and phosphorus are stored in the soil and are available for plants and microorganisms. Chemicals used by people, such as those found in fertilizers, are also absorbed into the soil. Analyzing soil chemistry can determine if nutrients are available at levels that can support ecosystem functions or at higher, toxic levels. It can also reveal if the soil is contaminated with a toxic chemical or heavy metal. 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 aI., 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). Researchers at Teagasc Johnstown Castle (Karen Daly and Giulia Bondi) describe soil chemical indicators that influence nutrient supply and storage as part of the SQUARE project. Nutrients such as nitrogen (N) and phosphorus (P) are essential for crop growth and animal health and these nutrients can be stored in soil and made available when crops need them. A healthy soil will have the ability to immobilise (store) and mineralise (supply) nutrients and this function relies on a number of soil properties to be in good working order. Soil organic matter is often called the engine room inside the soil matrix, and this is where many of the soil chemical and biological reactions occur. A healthy amount of soil organic matter is essential for many of the processes that control nutrient supply and storage in soils. If soil organic matter is depleted or reduced, this inhibits the soils ability to provide soluble forms of nutrients, and more importantly our ability to store and sequester carbon. As we move towards low emission agriculture, our soil carbon stocks will be hugely important to protect and enhance. Also, for nutrient supply to function at full capacity other soil chemical conditions must be met, for example, soil pH provides the right environment for nutrients to become soluble and for reactions on clay surfaces to happen. The moisture content of soil is also important when it comes to providing nutrients in the soil solution for diffusion into plant roots, and this links back to soil structure, where soil drainage class plays an important role, and the amount and type of clays and organic matter provide surfaces for nutrient reactions to happen.(Karen Daly and Giulia Bondi, 2021)

2.7.2 Soil Physical Indicators

Crop production and ecosystem health are strongly affected by soil physical quality (Topp et aI., 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 aI., 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).

2.7.3 Soil Biota

There is growing evidence that soil microbial attributes are potential early indicators of changes in soil quality because they are more sensitive than a soil's chemical and physical properties (Miller and Dick, 1995; Bandick and Dick, 1999; Kandeler et al., 1999; Bending et al., 2004; Geisseler and Horwath, 2009; Peixoto et al., 2010). One of the major challenges in soil quality assessments using microbial indicators, however, is the diffi culty in interpreting their individual values (Dick, 1992; Trasar-Cepeda et al., 1997; Gil-Sotres et al., 2005). Unlike the chemical indicators of soil fertility, for which the reference levels (low, medium, adequate, and high) are relatively well defi ned for each element and soil type (usually taking characteristics such as texture, organic matter content, and the management system into account), it is diffi cult to simply measure and interpret a series of microbial indicators independent of a comparative control or treatment (Dick, 1992). The use of reference criteria (comparative assessments) has been suggested because the ideal values for the bioindicators can vary with climate, soil type, mineralogy, management, and land use. Two diff erent approaches to establishing reference criteria for soil quality assessments have been proposed: (i) the use of native, undisturbed soils under climax vegetation and with minimal anthropogenic impacts; and (ii) the use of reference soils capable of maintaining a high level of productivity and environmental performance (Doran and Parkin, 1994; Gil-Sotres et al., 2005). Another alternative is to use temporal variation (dynamic assessment) to monitor soil quality bioindicators. In this case, the values determined for the bioindicators can be monitored to assess trends with time (Kandeler et al., 1999). In fact, the comparative and dynamic assessments are complementary, allow diff erent rating scales, and each one has advantages and disadvantages (Gil-Sotres et al., 2005).

Earthworms are often observed in agricultural soils and provide a useful indication of soil quality (Linden et aI., 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 aI., 1987; Turco et aI., 1994). Scientists and farmers consider earthworms an important indicator of soil fertility or soilhealth. 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 aI., 1994).

2.7.4 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 aI., 1997). Any change of soil properties generally leads to a change in yield. Maddonni et ai. (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 aI., 1997; Maddonni et aI., 1999).

2.7. Critical Levels of Soil Quality

2.7.1. 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 aI., 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 aI., 1993; Eswaran and Venugopal, 1993; Kawamura, 1995; Neave et aI., 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).

2.7.2 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 fanning 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 fann 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) detennined 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 fann 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 detennination of sustainability or un-sustainability can be made when the trend of a system, observed over time, is above or below the critical value.

2.8 Soil Quality and Long-term Cropping

The importance of healthy soils for sustainable development has gained increasing attention during the last decade (Safeguarding our soils, 2017). Soils provide essential services that include food production, nutrient cycling, water filtration and carbon (C) storage (Batjes, 1996). While undisturbed soils can maintain their characteristics over time, cultivation alters this ability, challenging the long-term provision of services that support human needs. In addition, soil cultivation practices that induce the release of stored soil C have played an important role in anthropogenic greenhouse gas emissions in the last century (Amundson et al., 2015). Therefore, it is crucial to identify and implement management strategies to restore and safeguard soil health. In this study, we focus on how sustainable agricultural production can affect soil functions. Amongst others, soil functions are related to several physical properties, such as bulk density, wet stability of aggregates and porosity. Wet stability of aggregates reflects the ability of soil to resist disintegration induced by external stresses, such as soil cultivation, water or wind. A low wet stability of aggregates may thus impair the potential for crop establishment and early growth by increasing the risk of soil cementing and hard and non-friable aggregates (Schjønning et al., 2012), soil erosion (Le Bissonnais, 2016) as well as the risk of transport of fine particles carrying pollutants to the water environment (Nørgaard et al., 2013). Pulido Moncada et al. (2015) indicated that if the percentage of water stable aggregates (WSA, 1–2 mm air-dry aggregates) was above 70 then soil is very stable, across different soil types. The pore-size distribution of a given soil is crucial for water and nutrient availability, microbial activity, percolation and hence soil organic matter turnover and availability of water and nutrients essential for plant growth (Kravchenko and Guber, 2017; Rabot et al., 2018). Total soil porosity can be divided in > 30 µm and < 30 µm pore size classes, which mainly is defined by soil structure and soil texture, respectively (Dexter et al., 2008a). A low volume of > 30 µm pores may reduce soil gas exchange and affect root growth negatively, while a low volume of < 30 µm pores relates to a decrease in the capacity to store plant-available water. Lipiec and Hatano (2003) identified an air-filled porosity of 0.10 m3 m− 3 as a critical limit for soil aeration. In addition to the pore-size distribution, the degree of pore continuity or pore organization is an important parameter for soil aeration as well as infiltration of water and thus crop growth (Schjønning et al., 2007). Several soil physical and biological properties, e.g., bulk density, aggregate stability and soil microbial biomass are related to the content and turnover of soil organic matter (SOM). Organic matter and clay are intimately linked by a range of physical, chemical and biological processes, playing a crucial role in the formation of soil aggregates, affecting stability at different scales (Totsche et al., 2018). Thus, it is vital to include both clay and organic matter when identifying critical thresholds for soil functioning. In particular, the content of soil organic C (SOC) interacting with clay is of critical importance in determining soil physical behavior. Dexter et al. (2008b) identified a critical threshold in soils, where clay/SOC ratio values below 10 had higher soil structural stability and were less impacted by management practices (Jensen et al., 2017; Jensen et al., 2019).

Among soil biological properties, earthworm abundance can be used as an indicator of soil quality; earthworms play an important role in the transformation of litter and in the formation of soil aggregates, and respond to several agricultural practices (Pulleman et al., 2012). In cultivated systems, factors such as crop rotation, cover crops, fertilizer applications and tillage events have been found to influence soil functions by affecting both physical and biological properties (Riley et al., 2008; Munkholm et al., 2013). Riley et al. (2008) found adding leys into the crop rotation improved soil structure, increased aggregate stability and reduced bulk density. In addition, the inclusion of at least one year of ley provides favorable conditions for proliferation of earthworms, especially when ley cuts are mulched, resulting in greater cast production that contributes to formation of SOM and availability of nitrogen (N) (Froseth et al., 2014). In a similar way, the inclusion of legume-based cover crops was shown to have a positive effect on soil structure (Munkholm et al., 2013), to increase SOC concentration, soil microbial biomass and mycorrhiza colonization and to reduce bulk density (Daryanto et al., 2018). The formation of SOM is largely dependent on the quality and amount of organic material inputs. Thus, adequate fertilization is crucial to promote plant production and the resulting return of C (and N) in residues to the soil, as well as the stabilization of C in soils by increasing the availability of nutrients for microbial processes (Kirkby et al., 2014). Since fertilization with animal manure adds organic matter to the soil, it generally leads to greater SOC as well as lower soil bulk density and greater content of soil microbial biomass C compared to mineral fertilizers (Edmeades, 2003; Schjønning et al., 2007). Changes in SOC as a consequence of different management practices require time, thus long-term crop rotation experiments are valuable tools to assess effects that would not be detectable in the short term (Autret et al., 2016). In a previous study, based on the long-term crop rotation experiment in Foulum, the temporal variation in SOC was investigated (Hu et al., 2018).

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 aI. 1982; Pennock et aI., 1994; Acton and Gregorich, 1995b; Gregorich et aI., 1995; Li et aI., 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 a!., 1994; Gregorich et a!., 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 a!., 1997).

Tiessen et aI. (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 aI., 1982) and the reduction in P fertility was closely tied to soil organic matter losses (Tiessen et aI., 1983; Nziguheba et aI., 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 aI., 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 aI., 1994; Selles et aI., 1995). According to Selles et aI. (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 fanning 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 com-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 tum, affects susceptibility to soil erosion and long-term crop production potential (Larson et aI., 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 aI., 2000).

The cultivation of crops without application of manures or fertilizers caused a drastic exhaustion of the native pool of nutrients from the soil under the present agro - climatic condition (dry land Vertisol). The combined application of organic source such as FYM (50 per cent of the requirement) with nitrogenous fertilizers N i.e., urea (50 per cent of the requirement) + sustained the higher availability of N, P and K (Suresh Lal, Mathur BS, 1988).

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 aI., 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).

2.9.2 Socio-Economic Evaluation of Sustainable Agriculture

The Market Economy, Institutions and Sustainable Agriculture The idea of sustainable agriculture is an alternative to intensive agriculture, still subsidized by the EU according to the rules of production efficiency. However, such intensive agricultural production leads to a deterioration of natural resources and at the same time to production of food containing significant levels of technical contaminants hazardous to human health. Approximately 1/3 of our planet's surface is degraded due to man's activities, agricultural activities being responsible for half of the damage. Instead, the technologies of sustainable agriculture activate the natural mechanisms of agricultural production through using natural means of production, ensure permanent ferti8 lity of soil and the security of plants and animals. Sustainable agriculture, therefore, strives for the integrated use of a wide range of pest, nutrient, soil, and water management technologies. It aims at an increased diversity of enterprises within farms related by increased linkages and flows among them. By-products or wastes from one component o~ enterprise become inputs to another. As natural processes increasingly replace external inputs, so the impact on the environment is reduced. So, ecological agriculture is an important factor contributing to the protection of rural landscape, natural resources (both renewable and exhaustible), protection of the natural environment in the countryside and preservation of rural cultural heritage. Sustainable agriculture integrates three main goals: environmental stewardship, farm profitability, and prosperous farming communities. These goals have been defined by a variety of philosophies, policies and practices, from the vision of farmers and consumers. Tradition can be a strong point in introducing a more sustainable agriculture by way of a more ecological agriculture. It is making use of the way in which farmers are used to produce the so-called "backwardness", together with the introduction of quality control. Maybe the most important is the creation of local markets because of the low development of logistic solutions. An interesting idea in this respect is the creation of "ecological sites" (Platje and Veislsand, 2003). Besides a change in the way of farming, there are also opportunities to change packaging, storage and patterns of agricultural products. With the introduction of logistic systems, which vary from very simple solutions like farmers organizing common storage and transport, up to highly sophisticated solutions for more specialized producers, this idea may lead to ad-31 vantages in the field of packaging (e.g., less material used, less use of plastic), storage, transport costs (and the connected externalities), etc. As mentioned by J. Platje (2003), the transformation of the agricultural sector and challenges of the development towards sustainable agriculture can result from studies within an institutional framework too. Also, the institution factor is very important, because, as stressed by J. B. Tschirley (1997), "human and institutional capacity to manage the development process through participatory and transparent approaches is fundamental to sustainable agriculture". D. C. North (1990, 3) defines institutions as the rules of the game in the society. According to him, the most important role of institutions is to reduce uncertainty byestablishing a stable (not necessarily efficient) structure for human interaction. A stable legal framework that protects property and enhances contract enforcement is likely to stimulate entrepreneurship and economic activity. Although New Institutional Economics has been mainly applied to the transformation of the economic system from plan to market and the economic consequences of privatization, some attempts have been made to apply it on processes of achieving sustainable agriculture (e.g., Gatzweiler et aI., 2002). An especially important tool in analyzing challenges for sustainable agriculture is property rights economics. But, as mentioned by J. Platje (2003), in East European countries can arise one big problem for the effectiveness of "institutional governance": it is the low level of trust. This may cause problems in developing sustainable agriculture, as the introduction and enforcement of new institutions needed for sustainable agriculture become more difficult. On the other side, institutional change in agriculture is accompanied by uncertainty. As mentioned by J. Platje (2003), when institutions like laws and regulations (e.g., the system of subsidizing) change very often, this increases uncertainty in the economy and makes it almost impossible to keep up with all the changes. As a consequence, economic subjects have less reliable information, which in turn negatively influences economic activity. This may be a threat in the process of adapting the agricultural systems of the Central and Eastern European countries to EU requirements. It must be taken into account, too, that when Central and Eastern countries would follow the "industrial" agricultural model, this should lead to a more capital-intensive agriculture and lower demand for labour. Thus, agricultural policy should go together with infrastructure policy, which should stimulate multifunctional rural development where jobs are created for people who leave agriculture. According to property rights economics, markets, freedom of contract and private property provide stronger incentives for economic efficiency and lead to lower transaction costs compared to the other co-ordination mechanisms. When markets function properly, they lead to an increase in social welfare. However, it is mainly the profit motive that provides incentives for economic activity. A proper institutional framework is indispensable for stimulating sustainable activities. The costs of activities where the environment is involved should be included in market prices (internalised). But a problem is that the market rather focuses on short-term profits. Without a proper institutional framework, the profit motive may lead to unsustainable cost savings, soil degradation, landscape change, reduction ofbiodiversity (where once were natural habitats, now lie huge areas of man's monocultures) and depopulation of the countryside. 9 This puts sustainable agriculture within the concept of rural development. Infrastructure is needed in order to prevent depopulation of the countryside by way of stimulating agriculturally related as well as non- agricultural economic activity that helps to increase farmer's income, so that unsustainable intensification or extension of scale is not necessary. We must take into account that although the market may be one of the best (or least worst) allocation systems, in agriculture it leads to many difficulties. As mentioned by J. Platje (2003), an agricultural market based on family farming may lead to stronger incentives and lower transaction costs compared to other systems.

However, markets create price and income instability for farmers, and do not take inter-generational aspects into consideration. Furthermore, the market tends to lead to enlargement of scale, leading to landscape change and depopulation of the countryside. Thus, the question is whether a market can stimulate the development of sustainable agriculture. A condition is that institutions should be developed, and the mechanisms exist that stimulate the internalisation of externalities and the inclusion of long-term and inter-generational costs and benefits into the decisionmaking process. In order to achieve sustain ability, co- operation between different stakeholders and the introduction of logistic solutions are needed. However, it is very unlikely that agriculture will become sustainable without the aid and regulation from governments, as governments may be able to use a longer time-horizon in policy and decision-making (Platje, 2003). It is possible to say that a change towards a more sustainable agriculture is in fact a process of institutional change, creation of the rules of the game, hardware and enforcement mechanisms that stimulate sustainable agricul10 ture activities, and a step-by-step evolution of institutions (endogenous change) may be most sustainable. However, in some cases a revolutionary institutional change may be preferred. This requires "institutional engineerint' (exogenous change). An advantage of evolutionary institutional change is that formal rules often are supported by informal rules. With "institutional engineering" there is a greater danger of institutional disequilibrium, which may increase control costs. An implication of the factors hampering the introduction of efficient institutions is that transformation towards sustainable agriculture is cumbersome, while there are many threats of entering a wrong path towards maybe even more inefficient institutions.

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

The weight of evidence suggests that on average, the application of elements of conservation Agriculture (CA) compared to conventional practices has positive economic impacts. Panell et al. (2014) provide a wide ranging review of the farm level economics of conservation agriculture with a focus on smallholder systems. The main thrust of Panell et al. (2014) review is that the volume of literature in the economics of CA in smallholder systems is still small. Moreover, few of the extant studies report the economics of the full package CA. From extant literature, one of the main advantages of CA is that reduced tillage lowers the costs involved in land preparation (Fowler and Rockstrom, 2001), such as reduced tractor and fuel costs as has been observed in places such as the indo- gangetic wheat and rice systems. In non-mechanized smallholder settings, these labor savings are not inevitable especially if herbicides are not available to manage increased weed pressure (Rockstrom et al., 2009; Erenstein et al., 2012). For example, Nyamangara et al. (2014) report on the reduced tillage practice in Zimbabwe involving planting basins dug out by hand hoes. They found that labor demand on this reduced tillage system was more than twice that of conventional systems involving oxen ploughing. This was due to increases in weed populations and now the fields required more frequent hand weeding.

The evidence is mixed on the yield increases due to reduced or minimum tillage and yields could even decline in initial years. It is possible that yields under minimum tillage could exceed those of conventional practices but only after several years of consistent implementation (Giller et al. 2009 cited in Panell et al., 2014). Erenstein (2010), estimated that some 620,000 farmers in India had adopted zero-tillage wheat cultivation practices in some form across approximately 1.8 million hectares, earning annual benefits on the order of US$180–340 per household from both reductions in production costs and gains in yield. Having considered various sources of recent evidence on the performance of minimum tillage as a critical part of CA, Panell et al. (2014) conclude that minimum tillage is likely to succeed among farmers with [low discount rates], those who have little uncertainties about the costbenefit calculus of adopting this practice and among farmers who have larger farms with concomitantly more resource endowments. The evidence on mulching is also mixed, being complicated by the critical tradeoffs between mulch, feed and other uses (Jaleta , 2015). Using data from a study conducted in Morocco, Magnan, Larson and Taylor (2012) calculated the opportunity costs of crop residue in zerotillage systems and found that the shadow value (its value in livestock feeding as opposed to soil mulch) was 25 percent of the total value of the crop produced during normal rainfall and 75 percent during drought (when crop residues become most valuable as animal feed). Their findings suggest that the value of crop residues in alternative uses are very significant in this context, and should be considered carefully when promoting CA among smallholders because it can be a deterrent to use of crop residues for mulch. Similarly, Valbuena et al. (2012) compare CA practices in South Asia and Africa south of the Sahara to demonstrate how the opportunity 7 costs of residues are a key determinant in CA profitability and adoption. Their study gives evidence to show that crop residue use in zero-tillage cultivation is most feasible in what they describe as “high- potential areas” where, despite high population and livestock densities, biomass production levels are sufficient to meet the demands of both livestock and mulching. Low- and medium-potential areas, biomass production levels are lower and the pressure for residue use in feeding livestock is higher, making mulching for zero-tillage systems much more difficult. In high rainfall areas, mulching can lead to yield reductions (Rusinamhodzi et al. (2011). A review of the economics of crop associations (especially rotations or intercrops using legumes) in the context of CA was done by Panell et al. (2014) whose broad conclusion is that the profitability of legumes crop associations (compared to mono-cropping) though generally positive is context dependent3 . The application of the full suite of CA technologies is a rare phenomenon among smallholder farmers (Giller et al. 2009, Kaumbutho and Kienzle, 2007). When the full suite is combined, FAO (2001) and Knowler and Bradshaw (2007) showed that the majority of studies report that CA practices have better financial returns than conventional practices. The crux of the matter then is how to get farmers to eventually the complete set of CA components for maximum benefit.

Chapter 3: MATERIAL AND METHOD

3.1. Physicall Conditions of the Study Sites

3.1.1 Site Selection

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

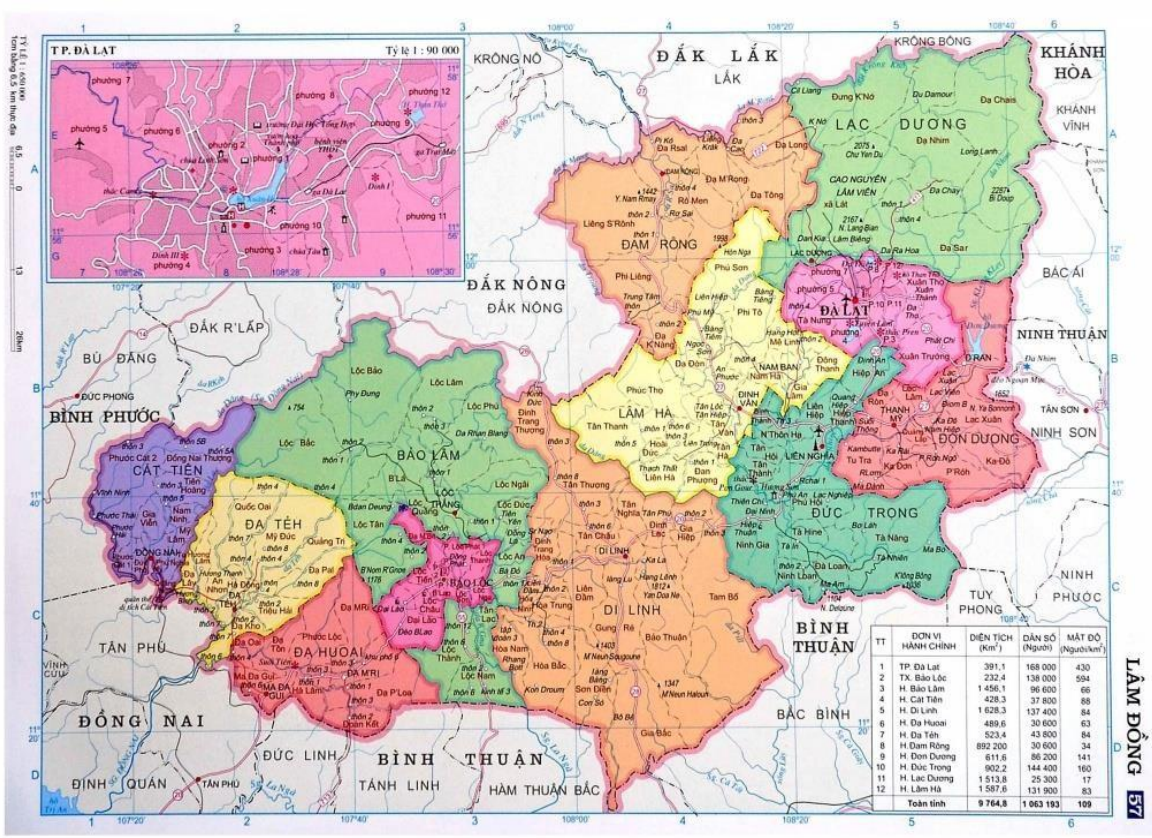

Figure 3.1:

3.1.2. Topography

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

Based on the height, it can be divided into four types of topographies:

Mountainous terrain:

Mountainous terrain distributes in the east - northeast and extends in band-shaped to the south, up about 60% of the province. The elevation of this terrain is above 1000 meters. Peaks and rivers is narrow, mountain slopes above 30 degrees.

The valley is in V-shaped with the average cleaved depth of 200 - 300m. Rivers, streams, develop mainly in the form of tree with the density from 2.5 to 4 km/km2. Plant is mainly timber.

Highland terrain

Highland terrain distributes in each arch almost in series and create a band near centre to the northeast - southwest, about 20% of the province. This type of terrain was created by the denudation surface of basaltic lava creates basins, arches relatively flat, curved and sub-staged marking the eruption phase. Level 800 – 900m is composed of basalt and lake sediment as Bao Loc arch. Level 900 - 1,000 m is also composed of basalt, but was cleaved by stream level 1 and 2 have fire-beam form (typically as the communes in the north and south of Di Linh).

The cleavage of this terrain is average from 0.8 to 1.5km/km2 depending on different levels. Plant here is mainly long-term industrial trees.

The two large highlands are Lang Bian Di Linh - Bao Loc highland.

Lang Bian highland is an ancient valley, from 1,600m - height to 1,400 down to the south, there are high peaks over 2,000m. Its limits in the west, north and east are the arch-shaped mountains with the height nearly 2,000m. Leveled surface is made of shale, sand, powder, clay, ... Eruption sediment was strongly cleaved and created long hills with fairly sloping sides.

There is an ancient east to west valley in Di Linh - Bao Loc highland, the height from 1,000 m to 800m, is covered with mountains with the height from 1.100m to 1.200m.

Bao Loc region, in the height of about 800m with quite large valleys, convex valley sides and slope angle, base and peak are wide and flat.

Adjacent to Di Linh - Bao Loc highland in the south and west is Song Be – Dong Nai peneplains with the height 200 - 300 m and its fields and some mountain with above 300 m height

3.1.3. Soil classification system of the study area

According to classification according to soil phylogenetics, the soil classification system in Bao Loc - Di Linh area includes 10 soil units, belonging to 5 soil groups. The spatial distribution of land units is shown on the land map of Bao Loc - Di Linh area at scale 1: 50,000 (table 3.1).

In the area of Bao Loc - Di Linh commune, the red and yellow soil group dominates with 92.77% of the natural area with 305,468.06 ha. The group of red-yellow humus in the mountains has the smallest area of 1,132.25 (0.42% of the natural area). In 10 soil units, red yellow soil on acid igneous rock (Fa) has the largest area of 108,762.00 ha, equivalent to 32.85% of natural area, the smallest is red yellow humus on acidic igneous rocks (Ha). .

Table 3.1: Soil classification system in Bao Loc - Di Linh area, scale 1: 50,000

TT	SYMBOL	NAME BY FAO-UNESCO	AREA (ha)	RATIO (%)
I	**P**	**Fluvisols**	7.629,24	2,30
1	Py	Dystric Fluvisols	4.741,17	1,43
2	Pg	Gleyic Fluvisols	2.888,08	0,87
II	**R**	**Luvisols**	2.893,42	0,87
3	Ru	Humic Luvisols	2.893,42	0,87
III	**Fđ**	**Ferralsols/ Acrisols**	305.468,06	92,27
4	Fk	Humic Ferralsols	35.864,35	10,83
5	Fu	Xanthic Ferralsol	82.970,53	25,06
6	Fd	Rhodi- Skeletic Acrisols	14.371,05	4,34
7	Fs	Ferralic Acrisols	63.500,13	19,18
8	Fa	Ferralic Acrisols	108.762,00	32,85
IV	**H**	**Alisols**	1.132,25	0,34
9	Ha	Humic Alisols	1.132,25	0,34
V		**Gleysols**	7.100,03	2,14
10	D	Dystric Gleysols	7.100,03	2,14

3.1.4.Climate

According to climate classification, Lam Dong province’s climate belongs to the area No 4 of Central Highlands with monsoon tropical climate. On the whole territory, due to complex terrain, it has differences of height and cover rate of vegetation. However, Lam Dong has temperate climate, it is warm around year and rarely change yearly.

Air temperature

Results of monitoring of temperature varies of Lam Dong (Table 1) recorded by the meteorological station (Doi Cu Station periods 1977-1991, Bao Loc station period 1981-1990, Lien Khuong stations in 1995) tell us that Lam Dong temperature changes significantly across the regions, more higher area more temperature decreases (Table 2). Average of yearly temperature changes from 16o to 23oC. The average temperature difference between months of the year in each area is not much, although day/night temperature amplitude is high, especially in high areas such as Da Lat

Table 3.2: Air Temperature In Lam Dong

Month	Medium			Extremely high medium			Extremely low medium		
	A	B	C	A	B	C	A	B	C
1	15,8	20,0	19,8	22,5	30,3	27,3	11,4	11,6	15,0
2	16,6	21,0	19,3	24,1	31,7	27,9	11,5	11,4	14,7
3	17,9	22,2	21,1	25,4	32,2	29,0	12,6	14,0	17,5
4	19,0	23,1	23,0	25,4	32,2	30,6	14,5	16,1	17,7
5	19,4	23,3	22,7	24,6	34,5	28,9	16,0	17,8	18,5
6	19,0	22,6	22,3	23,2	31,0	28,9	16,3	18,8	18,9
7	18,7	22,3	21,9	23,0	29,4	27,7	16,0	18,1	18,6
8	18,6	22,1	21,9	22,5	28,8	27,7	16,3	18,5	18,7
9	18,4	22,0	21,6	22,8	29,9	26,6	15,8	17,5	19,0
10	18,0	22,0	21,3	22,5	30,0	27,0	15,1	17,2	17,7
11	17,2	21,3	20,6	21,8	30,7	26,0	14,3	14,4	16,6

12	15,9	20,0	19,9	21,5	29,6	25,9	12,4	11,9	15,6

Source A: Doi Cu meteorological station (1977-1991)

B: Bao Loc station (1981-1990)

C: Lien Khuong station (1995)

Table 3.3: Characteristic Of Teperature Distribution As Per Altitude

CHARACTERISTIC	Elevation (m)			
	< 500	500-1.000	1.000-1.500	> 1.500
Annual average temperature(0C)	>22	20-22	18-20	<18
Monthly average temperature (0C)	>20	18-20	16-18	<16

Compared to other deltas with the same latitude, Lam Dong temperature is lower but the yearly temperature variation is very similar

Humidity

Hhumidity is one of the micro-climate factors affecting to social life as well as to the adaptation and development of the ecosystem, including animals and plants.

Due to the geography and topography, the humidity in the area of Lam Dong province is also different (Table 3)

Table 3.4: Humidity of Lam Dong

Month	Humidity (%)		
	Da Lat (1977-1991)	Bao Loc (1981-1990)	Lien Khuong (1995)
1	80	79	73
2	77	77	69
3	78	79	70
4	84	83	73
5	87	87	80
6	90	90	85
7	90	91	87

8	91	92	88
9	91	91	90
10	89	90	89
11	85	87	86
12	82	83	78

Relative humidity in the months of rainy season is quite high (84-91%). There have the have the largest relative humidity (90%) in June, July, August and September. The dry months: 69-83% in Da Lat, in Lien Khuong 73-80%, 83- 92% in Bao Loc

Rainfall regime

Lam Dong terrain is separated complexly and sloped from northwest to southeast, from average altitude above 1,500 meters in Da Lat down to 300 meters in Da Huoai. So that, the rain regime of Lam Dong has the characteristics depending on terrain separation and altitude (Table 4).

Rainfall

Annual rainfall is distributed irregularly on space and time, ranging from 1600 - 2.700mm. The rib extracting southwest wind (Bao Loc) has a large annual rainfall up to 3.771mm

Maximum total of annual rainfall, season rainfall, monthly rainfall change according to richness or absence the southwest wind.

Da Huoai and Bao Loc is situated on the southwest wind side, so the maximum rainfall month is August, while Lien Khuong and Don Duong are absent from win so maximum rainfall month is September. To the east, northeast, rainfall is decreased , only 1.756mm. Especially, in the valleys among high mountains, rainfall is less than 1.400mm. During dry season (from November to March), due to the influence of North-East monsoon, Lam Dong rainfall is very little, it is only 10-15% of rainfall of all year. Some year, There are 2-3 months without rain or negligible rain

The rainy season coincides with the southwest monsoon. Rainfall during this season accounts for 85-90% of annual rainfall; Some years, heavy rain, continuous rain has caused flood in some areas along Da Nhim river and 3 southern districts: Da

Rainfall day and Intensity

Average number of rainfall days are 162 - 195 days. In the dry season, there have only 15-20 rainfall days in areas of low rainfall and 40 rainfal days in which much rainfall.

Daily rrainfall intensity is distributed as following

Daily rainfall from 0,1 to 15mm is accounted the frequent rate of 65-80%.

Daily rainfall from 15,1 to 50mm usually occurs during the rainy season with a of 20-30%

Heavy rainfall with the intensity of over 100mm/day is rarely happened.

According to measurements, Bao Loc has the largest amount of rainfall reached to 455mm, while the others have not exceeded 150mm/day

Rainfall periods

The starting and ending time of rainy season

Rainy season of most areas in province begins in the mid-April, particularly for the eastern, north-east, it just begin in early May. Rainy season usually ends in late October and early November. Da Huoai Area, Bao Loc is situated in the southwest monsoon side so rainy season lengthen and lately end (mid November).

In fact, in April, May, the southwest monsoon just starts, it is almost showers and thunderstorms in the afternoon. When the southwest monsoon season is stable, the rainy season of Lam Dong is also table.

3.2. 'Pedological Characteristics' and 'Inherent Properties' of Tea Soilsin the Lam Dong,Vietnam

3.2.1 Material and Methods

Soil Sampling.

The soils for this study were chosen from the native forest, and from 5- ,10 -, and 20 -Yf-old tea plantations in Lâm Dong of Vietnam. Each age class was replicated three to six times. Field sampling was carried out during the winter growing season in 2020 and 2021 (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 (lO-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-Yf-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 Hel to remove carbonates was not necessary.

Bulk soil was sieved to obtain the :::; 2 mm fraction and a 109 sub-sample transferred a 500 mL flask. Organic matter was removed by treating with H202 (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 Jl1TI) 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 20-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 20mL of O.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 Fein 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. Dynamic Soil Properties Under Long-term Tea Cultivation Systems in Lam Dong of Vietnam

3.3.1. Materials and Methods

3.3.1.1. Research Design and Soil Sampling

A series of tea plantations ranging from 1- to 20 -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.

3.3.1.2 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 2021. 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 ton 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.

3.3.2. Laboratory Methods

3.3.2. 1. 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 Nand 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 H2S04 and H202 (Thomas et aI., 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 HN03, HCI04 and HF (Sheldrick, 1984).

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

Phosphate fractions were extracted using a fractionation scheme adapted from Hedley et ai. (1982) and Tiessen and Moir (1993) (FigA.l). The NaHC03- extractable P fraction was not determined based on knowledge that resin P in tropical soils includes most of the available P (Maroko et aI., 1999).

Soil (0.5g)

Shake 16 h in 30 mL deionized water with
two small strips (1cm x 5 cm) of anion ---i.~ Available P
exchange membrane
Residue
Shake 16 h in 30 mL 0.1 M NaOH. Hydroxide
extractable
Centrifuge, and analyze for Pi and Po. ---i.~ Pjand Po
1 Residue
Shake 16 h in 30 mL 1.0 M HCI.
Centrifuge, and analyze for Pi. ---i.~ Ca-associated Pi
Residue
Heat with 10 mL conc. HCI at 82°C for 10 min
Centrifuge, and analyze Po and Pi. ---i.~ Hot HCI Pi and Po
Residue
H2S04 and H_20_2 digestion to analyze for total P ---i.~ Residual P
1 Pi - inorganic P, and Po - organic P

Exchangeable cations were extracted using 0.1 M BaCh (Hendershot and Duquette, 1983; Hendershort et aI., 1993). Soil samples (3 g) were shaken on an end-over-end shaker for 2 h with 30 mL of 0.1 M BaCh, followed by centrifugation (700 x g) for 15 minutes. Cations in the supernatant were measured using AAS, except for N a 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).

3.3.2.2. 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 (PAWe) 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 diame1ter of each size fraction and the proportion of the total sample weight occurring in the cOITesponding size fraction, which can be expressed as:

$$M\backslash VD = \sum_{i=1}^{n} X_i W_i$$

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 tnm. 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 aI., 1967). Phosphate in the digestion solution was measured by a Technicon autoanalyser. The total K in the solution was detennined using AES. Total Ca, Mg, Fe and Al were measured by AAS.

3.3.2.3. 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.

3.4. Identification of important soil quality Indicators and Their Critical Levels for Sustainable Tea Cultivation

3.4. 1. Materials and Methods

3.4. 1.1. Soil Sampling

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

3.4. 1.2. Crop Yield and Farm Input

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

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

3.4. 2. Laboratory Methods

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

Soil physical properties also were determined using standard procedures (Black et aI., 1965). Bulk density was estimated using the core method described by Kalra and Maynard (1991). Plant available water-holding capacity (PAWC) was calculated as the difference between field capacity (FC) and the permanent wilting point (PWP) and was determined using a pressure chamber apparatus (0.033 MPa for FC and 1.5 MPa for the PWP) (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).

3.4. 3. 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> O.

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

3.5.1. Methodology

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

3.5.2.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.

3.5.3. Farmer Interviews

The survey was conducted in the Lam Dong tea enterprise. 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.

3.5.4. 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:

(1where: Y is the output and $Xl, X2,$ 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 aI., 1995) and, hence, is a common approach. The Cobb-Douglas production function can be presented as:

$$Y = X;ai \times Xjd^{j} \cdot x \,..\, Xn^{an} \tag{2}$$

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

$$\text{InY} = ajlnXj + a)nAj \ldots + anlnXn \tag{3}$$

where: Y is the output; ai, aj and an are 'production elasticity' coefficients calculated using regression analysis; and Xi, Xj 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:

$$\text{InY} = 1 + \text{allnN} + \text{a21nP} + \text{a31nK} + <l41nCa + aslnLbr + 061n\,Mnr + a71nPest$$

$$+ aglnSlope + \sim\text{lnFrmS} + alOlnAge + \sim\text{IEcon} + \sim 2\text{Tech} + \sim 3\text{Edu} \tag{4}$$

where the dependent (output) variable, Y, is the tea yield (Mg ha- ^{l}) estimated by the farmer; I is the intercept of the regression equation; aI, $a2$, ..., alO are regression coefficients for the 'nonnal' variables; and PI, PI, and P3 are regression coefficients for the 'dummy' variables. The independent (input) variables are defined in Table. 6.1

Table 3.5:. Input variables used to defme the Cobb-Douglas production (yield) function[l] . Description

N Nitrogen fertilizer applied (kg ha- l); *P*

Phosphate fertilizer applied (kg ha-l);

K Potassium fertilizer applied (kg ha- l);

Ca Lime applied (kg ha- l);

Lbr Labour (man day-I);

Mnr Manure application (Kg ha- l);

Pest Pesticide application (grams active gradient ha-l);

Slope Slope of tea field (degree);

FrmS Fann size (m^2);

Age Age of the tea plantation;

Econ Dummy economic variable: *Econ* =1 if the fanner'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 fanner, otherwise (e.g., use oftraditional 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* = O.

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 infonnation with regard to soil conservation technologies, and had equal treatment in tenns of government policies and society (Nguyen et aI., 1999); and all benefits derived by the farmers were based on tea production as the output variable.

Chapter 4: Results and Discussion

4.1. 'Pedological Characteristics' and 'Inherent Properties' of Tea Soils in the Lam Dong,Vietnam

4.1.1 . Profile Description

Soils developed on weathering products of basalt (referred to as basalt soil) are considered to be the most advantageous soils of the Central Highlands. These soils have thick effective soil layer, porous structure, good permeability and water holding capacity, higher nutrient content than many other soils. However, most of the basalt soils in the Central Highlands are now exploiting and planting long-term industrial crops, through long-term monoculture cycles, soil properties have been changed, some soil properties have been degraded to different degrees. The area of basalt soils in the Central Highlands is over 1,549,292 ha; accounting for about 25% of the natural area of the whole region and over 50% of the total basalt land area of the country; distribution runs from Kon Tum, Gia Lai, Dak Lak, Dak Nong provinces to Lam Dong. Lam Dong province alone has 229,216 ha of basalt land (accounting for 23.5% of the province'snatural area); in which, the area of Bao Lam, Di Linh and City districts. Bao Loc (referred to as Di Linh - Bao Loc area) is located on the central basalt block of Lam Dong province with 134,008 hectares of land.

According to the Soil Phylogenetic Classification System, the Di Linh - Bao Loc area has 4 groups of basalt soils (group of red and yellow soil, black soil, valley soil due to sloping products and erodible soil), with 5 units. soil, in which the red and yellow soil group occupies the largest area (about 90.0% of the area's basaltic soil area), this is also an area specialized in long-term industrial crops (tea, coffee, mulberry). ,...) is the largest in Lam Dong province. However, the tropical highland climate conditions with heavy and concentrated seasonal rainfall, high temperature combined with steep and fragmented terrain have contributed to promoting a number of soil processes in unfavorable directions such as: Erosion, leaching and mineralization of organic compounds, reducing the amount of nutrients in the soil. many cycles of shifting At the same time, undergo cultivation settlement, andshiftingslashcultivation-and-burn cultivation and monoculture of long-term industrial crops with a high degree of intensification, the nutrient source in the soil has been exhausted, the natural fertility and health The production of basalt soil in this area declined seriously. In many places, the basalt soil formed under the highland humid tropical forest has become a barren grassy land.

Anatomy: LD 01

Location: Dai Lao Commune, Bao Loc City, Lam Dong Province

Coordinates: Latitude: 11° 28' 54.9” B Longitude: 107° 44' 37.7” RED

Altitude: Relative: 822 m

Slope : 8° - 15°

Current status of vegetation: Tea intercropped with jackfruit

Cultivation mode: Industrial crops

Sample material: Basalt

Soil name: Reddish brown soil on basalt - Humic Ferralsols

4.1.2. Current soil degradation

* Chemical degradation signs:

There have been a number of pedicures and soil improvement houses to look for signs of soil degradation in terms of physical chemistry and nutrition. Up to now, some limits on humus, nitrogen, phosphorus and acidity have been preliminarily confirmed experimentally. Due to the wide range of chemical and nutritional elements and their varied seasonal activity, it is difficult to give a specific limit of each chemical and nutrient element to confirm soil degradation. The process of soil degradation is generally the reduction of nutrients to the poverty line. For example, when the humus in the soil is less than 2%, the total P_2O_5 is less than 0.01%, the total K_2O is less than 0.1%... The chemical composition of the soil is closely related to the parent rock that forms them. Elements and factors that have a lot to do with plant nutrition need attention.

Soil degradation is the occurrence of factors limiting biogeochemical for the crop group per unit of soil structure such as acidity, acidity of the soil, etc. Among dozens of possible chemical factors manifest in one or more degenerative factors. Along with the degradation of the vegetative cover is the manifestation of signs of chemical degradation of the soil. Soil degradation also manifests itself in the law of differentiation of criteria in the soil profile. In terms of surface layer, most soils show a very acidic reaction, ranging from 3.66 to 4.49. Most soils have moderate to high humus content, but there is considerable variation among soil types possibly due to land use type. Total nitrogen is quite good (0.115 - 1.035%), total phosphorus is mainly poor to good (0.049 - 0.170%).

Meanwhile, total potassium is poor in soil Fa and Fk, the rest are quite rich and the content of Ca^{2+} and Mg^{2+} cations are very low

The current land degradation map reflects land degradation at the time of the study. The basis for the current degradation map is to pay attention to the chemical and nutritional degradation properties; Physically, vegetation morphology represents land use types. Thus, the process of building the current land degradation map requires the alignment of the soil fertility map, the current land use map, and the vegetation map. Within the limitations of the collected data, the land degradation assessment criteria mentioned here are mainly vegetation morphology and land use types in the study area in 2020.

* *Signs of vegetation morphology shown on land use types*

Natural broadleaf, coniferous, and mixed broadleaf forests: Under the forest canopy, the soil has good structure and high nutrient content due to the large vegetation cover that protects the soil from erosion and leaching. . Thus, the land is almost not degraded or slightly degraded. Deciduous forests (drip forests) are secondary forest types that develop after the primary forest vegetation has been destroyed. There are only deciduous forests with typical species of the Diuaceae and Bang family such as tea ben oil, copper oil, etc. low density, simple stratigraphic structure can be developed on laterite ferralite soil near the surface. unfavorable physical properties, poor in nutrients, very short of water in the dry season, sometimes flooded in the rainy season, the underlying soil layer is seriously degraded. Thus, on the basis of determining the distribution of this type of forest on the map, the current strong land degradation areas are identified.

4.1.2. Physical degeneration

The characteristics of Bao Loc - Di Linh tea are sloping tea hills, tea is grown in rows with canopy diameter of 1-1.5 m, rows 0.5 - 1.0 m apart. This distance ensures enough space for tea rows to grow buds, and is also a way to fertilize tea roots and collect tea buds when it is time to harvest. However, the process of trampling by humans to care for and harvest tea for a long time makes the soil surface hard, callous, and has poor water permeability. Table 2.21 shows that the average percentage of clay in the topsoil of tea samples in the study area is 26.3 - 39.20% and the common mechanical composition is medium silt, clay content is increasing gradually. according to sectional depth...

Thus, the analysis data on the current status of tea land in the study area has shown that the process of exploiting tea cultivation land for many years has facilitated the process of washing away clay particles in the soil layer. face decreased sharply. The manifestations of deterioration in mechanical composition, soil structure in the profile form are clear manifestations of physical signs of soil degradation.

Table 4.1: Structure of tea soil samples in Bao Loc - Di Linh

Type of farming	Dept (cm)	Percentage of grain grades (%)		
		0.2 - 0.02 mm	0.02 - 0.002 mm	< 0.002 mm
BL 828 Perennial tea	0 - 20	39.16	21.64	39.20
	20 - 42	30.16	20.64	49.20
BL 248 Specialty tea	0 - 22	54.76	9.62	35.62
	22 - 54	52.10	7.52	40.38
BL 259 Specialty tea	0 - 25	49.56	24.14	26.30
	25 - 50	40.09	13.50	46.41
T1 Specialty tea	0 - 30	50.23	12.23	37.54
	31 - 60	52.87	9.15	37.98
T2 Specialty tea	0 - 30	53.19	12.48	33.61
	31 - 60	55.39	11.00	33.61
LD 01 Tea interspersed with jackfruit	0 - 15	29.67	37.18	33.15
	15 - 35	32.29	34.74	32.97
LD 03 Intensive tea	0 - 10	51.53	10.67	37.80
	40 - 50	49.19	9.21	41.60

Source: Synthesized from the results of physical and chemical analysis of tea soil samples

4.1.3. Chemical degradation

Tea require high amounts of nitrogen, moderate amounts of phosphorus and potassium. In long-term tea cultivation, attention should be paid to balanced fertilizer application to compensate for the nutrients lost due to absorption, leaching and erosion (mainly N and K). However, the overuse of fertilizers and the incorrect dosage means that the degradation level of the soil is enhanced instead of improved soil for sustainable use, which is reflected in the acidic reaction of the soil, affecting the properties of the soil. soil physicochemical properties.

The results of analysis of some representative tea soil samples in Bao Loc, Bao Lam, Di Linh show that the soil reacts from acidic to very acidic, the pH ranges from 3.72 to 5.1, although the characteristics of the tea plant is acidic, but with a low pH as above, it also shows a degree of soil degradation. The humus content of the topsoil is quite good due to regular fertilization but decreases sharply in the lower layers, the content of nitrogen, phosphorus, and potassium in the total topsoil is quite to rich, availble potassium is very poor to poor.

Table 4.2: Chemical composition of tea soil samples in Bao Loc - Di Linh

Type of farming	dept (cm)	pH KCl	OM (%)	Total (%)			Availble (mg/100g soil)		Cation exchange (ldl/100g soil)	
				N	P_2O_5	K_2O	P_2O_5	K_2O	Ca^{2+}	Mg^{2+}
VN38 Tea interspersed with coffee	0-20	4.00	5.15	0.170	0.190	2,320	5.09	3.35	-	-
	20-65	4.43	3.51	0.090	0.130	2.010	3.47	4.12	-	-
BL 828 Perennial tea	0-20	4.40	3.56	0.224	0.049	0.062	2.55	3.58	1.47	0.89
	20-42	4.70	2.38	0.124	0.039	0.050	2.79	1.97	1.05	0.62
BL 248 Specialty tea	0-22	3.72	3.42	0.172	0.122	0.190	6.70	4.00	0.94	0.18
	22-54	3.87	2.15	0.128	0.050	0.190	5.00	4.80	1.00	0.18
BL 259 Specialty tea	0-25	4.03	1.76	0.134	0.171	0.140	9.60	5.60	1.78	0.32
	25-50	3.91	1.66	0.106	0.172	0.150	4.80	7.20	1.16	0.32
T1 Specialty tea	0-30	5.20	4.41	0.070	0.220	2,620	50.99	3.65	-	-
	31-60	-	2.92	0.570	0.120	2.020	38.79	4.60	-	-
T2 Specialty tea	0-30	5.10	2.92	0.560	0.270	3,570	157.78	2.50	-	-
	31-60	4.90	2.63	0.510	0.280	3.60	117.39	2.35	-	-
LD 01 Tea interspersed with jackfruit	0-15	3.93	4.31	0.280	0.073	0.050	0.61	3.25	0.40	2.65
	15-35	3.97	4.11	0.190	0.088	0.940	-	2.31	0.15	0.20
LD 03 Intensive tea	0-10	3.84	4.37	0.172	0.132	0.186	5.53	4.11	1.37	0.27
	40-50	4.10	3.04	0.123	0.051	0.159	3.79	4.82	1.09	0.13

Source: Synthesized from the results of physical and chemical analysis of tea soil samples

4.1.4. Soil Texture

Clay content of the soils ranged from 31 % to 39 % at depths from 0- to 40-cm, 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-em 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 20 years.

Table 4.3. Sand, silt and clay content (%) of representative soils from all sites.

Particle size	Forest	5-yr	10-yr	20-yr	P>F[1]
		0- to 10-em depth			
Sand	21	30	30	26	0.28
Silt	43	28	27	31	0.08
Clay	36	32	33	33	0.72
Textural class	clay	clay	clay	clay	
		10- to 20-cm depth			
Sand	20	28	27	24	0.36
Silt	43	35	34	40	0.06
Clay	37	37	39	36	0.90
Textural class	clay	clay	clay	clay	
		20- to 40-cm depth			
Sand	20	28	27	24	0.27
Silt	43	35	34	40	0.29
Clay	37	37	39	36	0.51
Textural class	clay	clay	clay	clay	

Note: 1 P>F values show statistically significant differences of means among the forest, 5-, 10- and 20-yr-old soils.

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

4.1.5 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 aI., 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 aI., 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 aI., 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 160/0 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 4.4) 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 4.4: Coefficients of variation (O~) of the textural components of soils.

Particle size	Forest	5-yr	10-yr	20-yr
		0- to1O-cm dept--		
Sand	42	40	24	45
Silt	15	30	18	22
Clay	17	14	12	23
		10- to 20-cm depth-		
Sand	34	41	26	52
Silt	13	38	40	20
Clay	15	14	26	20
		20- to 40-cm depth-		
Sand	37	43	27	53
Silt	15	36	20	21
Clay	17	11	16	19

Coefficients of variation for the Al and Fe oxides were between 13 and 40% (Table 4.5), 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 10- and 20 -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 4.5. Coefficients of variation (ʘ~) of free aluminium and iron content of soils.

Depth (cm)	Forest	5-yr	10-yr	20 -yr
	Al extracted by DCB--			
0-10---------------------	14	16	21	39
10-20	16	14	20	31
20-40	14	15	20	38
-----------------------	Al extracted by oxalate acid ----			
0-10	23	15	14	25
10-20	19	25	14	20
20-40	22	14	18	22
	Fe extracted by DCB ---			
------..................-.......-	----------------			
0-10	18	17	32	41
10-20	16	19	25	24
20-40	16	19	29	34
-------------------------	Fe extracted by oxalate acid -----			
0-10	26	33	24	29
10-20	32	23	26	30
20-40	19	22	22	31

4.1.6 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 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 aI., 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 ernol kg-^{l} (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).

4.1.7. 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 playa 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 aI., 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.

4.2 Dynamic Soil Properties Under Long-term Tea Cultivation Systems in the Lam Dong,Vietnam

4.2.1.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 4.5). 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 aI., 1998). This suggests that changes in soil properties, in response to long-tenn tea cultivation, are mostly due to management factors, rather than the effects of landscape position.

Table 4.6. 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-l)	0.77	0.03	0.52
Total N (mg g-l)	0.32	0.05	0.69
Total P (J..lg g-l)	0.29	0.01	0.83
Total K (mg g-l)	0.45	0.03	0.96
Total S (mg g-l)	0.42	0.08	0.09
Total Cd (J..lg g-l)	0.56	0.16	0.70
Available P (J..lg gl)	0.34	0.02	0.92
Available K (J..lg gl) pH	0.56	0.00	0.32
Bulk density (Mg m-3)	[illegible]	0.00	0.72
Porosity (%)	0.69	0.00	0.96
PAWC I (% Vol.)	0.69	0.00	0.96
MWD 1 (mm)	0.41	0.00	0.53
Mechanical resistance (MPa)	0.73	0.02	0.44

4.2.2 .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* ~ 0.05) decrease during the first ten years of cultivation. 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 aI., 1994; Acton and Gregorich, 1995b).

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 nativeforest, the soil OC content of the 10- to 20-cm sample exhibited a significant *(P* ::; 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 . In the subsurface soils, however, changes in soil OC with 20 years of cultivation (~OC40) were generally much smaller than those in the surface soils and were not significant *(P::;* 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 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 ($P \sim 0.05$) 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-em, and 20- to 40-cm depths) was greatest during the first 5 years of cultivation, reaching a steady state after 5- to 10-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 20 years of cultivation and tea production.

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 (l-yr) cultivation than long-term cultivation. Whereas this is primarily a reflection of the greater soil OC content of the l-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- to 1O-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. 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 4.7. Effect of long-term cultivati n and tea production on C:N ratios.

Depth (cm)	Forest	l-yr	5-yr	10-yr	20-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	NAt	NA	11.52	12.86
60-80	10.70	NA	NA	10.57	11.53

1 NA: not available.

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. 4.7).Moreover, there was a significant (*P* ::; 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 5 and 10 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 20-yr-old tea soils received fewer fertilizer inputs, again resulting in a decrease in both the total and available soil K.

Total phosphorus. With the exception of the surface (0- to lO-cm) soil, total P concentrations in the forest soil were generally the same as those in the cultivated soils (Fig. 4.1). 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 lO- to 40-yr was significantly (*P* ::; 0.05) greater than that in the forest soils. This reflects the fact that the soils of the Lam Dong,Vietnam have a high potential to fix added P. Thus, P being the most limiting plant nutrient, large amounts of Padded as fertilizer were 'fixed' by the soil, resulting in the observed increase in 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 ($P \sim 0.05$) 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 aI., 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 $P0_4$-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 . 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 aI., 1986). The dilute HCI extractable Pi represents the P in close association with Ca (Tiessen and Moir, 1993). Increased Ca-Pi in the cropped soils was attributed, in part, to the use of superphosphate fertilizers (Wagar et aI., 1986). However, as with most tropical soils, the tea soils of the Lam Dong,Vietnam are acidic and, hence, are frequently limed for tea production. In tum, chemical reactions between the lime and superphosphate fertilizers would lead to the formation of Ca phosphates.

Table 4.8 Phosphate fractionation of forest and soils under long-term tea cultivation.

Depth (cm)	0 (Forest)	l-yr	5-yr	10-yr	20-yr
		J\"aila1>le J> (~~ ~-l) ----------------------			
0-10	7.97a[2]	8.61 a	31.521>	20.26c	9.38a

10-20	2.93a	4.45a	9.381>	3.70a	2.66a
20-40	1.93a	1.75a	2.70a	1.35a	1. lOa
		Hydroxide-J>i (~~~			
0-10	33.39a	NJ\3	94.731>	93.291>	105.37c
10-20	22.89a	NJ\	33.51a	28.16a	38.64a
20-40	20.03a	NJ\	26.32a	19.61a	24.47a
		~a-J> (~~ ~-l)			
0-10	1.46a	NJ\	14.061>	22.87b	13.231>
10-20	1.42a	NJ\	5.86a	2.38a	2.l6a
20-40	1.41a	NJ\	2.99a	1.67a	1.21a
		1rotal J>o (~~ ~-l)			
0-10	79.35a	NJ\	79.09a	89.40a	88.89a
10-20	57.97a	NJ\	50.58a	57.52a	66.66a
20-40	50.86a	NJ\	48.89a	38.38a	49.31a
		Ftesistault J> (~~ ~-l)			
0-10	114.60a	NJ\	129.29a	128.12a	140.93a
10-20	102.80a	NJ\	111.89a	93.15a	117.62a
20-40	112.l2a	NJ\	108.71a	101.63a	115.04a
		~/J>o			
0-10	331a	NJ\	260a	236a	268a
10-20	279a	NJ\	257a1>	239bc	198c
20-40	234a	NJ\	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 orgaulic J> (J>o) contents were greatest in the surface horizon, accountin~ for 32% of the total J> in the forest soil auld 23% to 250/0 of the total J> in the cropped soils, thou~ there were no significault differences amon~ the tea soil a~e classes (1ra1>le 4.3). O"er the lon~-tenn, the dynamics of J>o in soils is closely linked to that of the soil O~ (Stewart auld 1riessen, 1987) auld 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 (l-yr-old) soils to about 4.0 in the cropped soils. The lower pHs in the cropped soils (*P* ~ 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 aI., 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 At3+. 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 aI., 1995; Johannes et aI., 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* :::; 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 4.9. Weighted mean (0- to 40-cm) of pH and exchangeable cations of forest and soils under long-term tea cultivation.

Property	Forest	l-yr	5-yr	10-yr	20-yr
	I				
pH	4.20a	4.40b	3.90c	3.94c	4.05d
K (Cmol kg-I)	O.IOa	0.09a	0.I5b	0.I4b	0.08a
Na (Cmol kg-I)	0.06a	O.l2b	0.04c	0.05c	0.04c
Mg (Cmol kg-I)	O.la	O.l5b	0.08a	0.05c	0.05c
Ca (Cmol kg-I)	0.23a	0.24a	0.24a	0.26a	0.27a
Al (Cmol kg-I)	4.53a	4.51a	4.73a	5.l6a	4.76a
ECEC (Cmol kg-I)	5.02a	5.l3a	5.26a	5.67a	5.11a
Base saturation (%)	lOa	12a	11a	9a	9a
Al saturation(%)	90a	88a	89a	91 a	91 a

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 (l-Yr-old) soils (Table 4.8). Cultivation-induced increases in bulk density (*P*

~ 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 ~ 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 aI., 1997).

Table 4.10. Bulk density and total porosity of the forest and cultivated soils.

Depth (cm)	Forest	l-yr	5-yr	10-yr	20-yr
------------------------		Bulk density (Mg m -3)		-------	
0-10	1.02a[1]	0.97a	1.15b	1.21c	1.22c
10-20	l.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 acone penetrometer, is considered to be a good measure ofsoil's strength (Hillel, 1998). In general, mechanical resistance increased with depth, reflecting the increased clay content and bulk density of the subsurface soils (Table 4.11). In addition, mechanical resistance values were significantly (P S; 0.05) greater in soils cropped for 1- or 20 yr than in the forest or 5 -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 4.11. Soil resistance (MPa) of forest and soils under long-term tea cultivation.

Depth (cm)	Forest	5-yr	10-yr	20-yr
3	0.30a[l]	0.39ab	0.63bc	0.66c
5	0.81 a	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	4.81 a	4.95a	4.99a

l 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 10- and 20-yr-old tea soils, at both the 0- to 10- and 10- to 20-cm depths, was significantly *(P* s; 0.05) lower than that of the forest, 1- and 5-yr-old soils (Table 4.11). Whereas cultivation had no significant effect on the PWP of the soils, long-term cultivation resulted in significant *(P* s; 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 aI., 1997).

Table 4.12. Plant available water capacity (volumetric 0/0) of forest and soils under long-term tea cultivation.

Parameter	Forest	l-yr	5-yr	10-yr	20-yr
		0- to1O-em depth			
FC [1]	40.03a[2]	41.26a	39.42a	37.53b	38.45b
PWP	26.85a	28.39a	27.l9a	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).

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

Reduced earthwonn 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 earthwonn populations. In tum, cultivation-induced decreases in earthwonn population and activity could significantly impact the fertility status of the tea soils (Lodsdon and Linden, 1992). A reduction in the number of earthwonns 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.

4.2.3. Management Factors Affecting the Change in Soil Properties

Plant biomass. Whereas continuous cropping had no significant effect on tea yields during the first 10 -yr of cultivation, yields were decreased significantly *(P:::;* 0.05) in the 20 -yr-old tea plantations (Table 4.8). Likewise, the total amount of plant material (leaves and branches) added to the soil in the fonn of prunings was the same in the 5-and 10 -yr-old tea plantations, but was reduced significantly *(P* :::; 0.05) in the 20-yr-old tea plantations. Conversely, the above-ground biomass remaining after pruning increased in the order: 5 -yr-old tea plants < 10-yr-old tea plants < 20-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 4.13. Dry plant biomass and productiVity of tea plantations.

Tea age	Tea yield (Mg ha-ˡ yr	Plant prunings (Mg ha-[1] yr-[1])		Standing state[1] (Mg ha-ˡ)	
		Leaves	Branches	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

ı 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 tum, 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 aI., 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 4.12). That is, age of the tea plantations had no significant effect on tissue concentrations of N, Ca, or Mg. There were, however, significant *(P::;* 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 todevelop 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 20years.

Table 4.14. Concentration (0A») of the major nutrient elements in plant tissues.

Tea age	N	P	K	S	Ca	Mg
-----------------------	Young leaves and buds from harvesting -----------------------					
5-yr	6.02a [1]	OAla	2.36a	0.38a	0.45a	0.23a
10-yr	5.75a	0.37a	2.25a	0.33a	O.44a	0.20a
20-yr	5.70a	0.36a	2.09b	0.35a	OA7a	0.23a
---------------------	Mature leaves from pruning and standing crop --------------------					
5-yr	3.96a	0.20a	1.61a	0.32a	0.81a	0.18a
10-yr	4.06a	O.l9ab	1.56b	0.29b	0.69a	0.15a
20-yr	3.90a	O.l7b	1.52b	0.29b	O.70a	O.l5a
	IJranches from pruning ------...............................					
5-yr	1.02a	0.06a	0.59a	O.l2a	0.30a	0.05a
10-yr	0.90a	0.05a	0.62a	O.l3a	0.30a	0.04a
20-yr	0.99a	0.05a	0.55a	O.lOa	O.3la	0.05a
	Stems from standing crop ------------------------------					

5-yr	0.90a	0.05a	0.35a	O.lla	O.3la	0.03a
10-yr	0.91a	0.04a	OAOa	0.12a	0.39a	0.04a
20-yr	0.80a	0.04a	0.32a	0.12a	OAOa	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 IO-yr-old tea plantations, intermediate in the 10 -yr-old plantations, and least in the 20-yr-old plantations (Table 4.14). 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 4.15).

Table 4.15. Nutrient budget of plant removals, recycling, storage and additions.

Tea age	N	P	K	S	Ca	Mg
---- ----- Removed through harvest (kg ha-l yr-l) ------------------------						
5-yr	184	13	69	12	14	7
10-yr	174	11	66	10	13	6
20-yr	131	9	49	8	11	5
----------------- Recycled through pruning (kg ha-l yr-l) -------						
5-yr	119	6	54	11	27	6
10-yr	112	5	51	10	24	5
20-yr	89	4	37	7	19	4
------------- Total accumulation in the standing plants (kg ha-l) I --------- -----						
5-yr	284	14	102	29	81	10
10-yr	325	16	140	39	120	15
20-yr	340	16	146	48	153	22
-------- Added as fertilizer (kg ha-l yr-l) -------------------						
5-yr	205	88	81	NA[2]	168	NA
10-yr	194	90	83	NA	175	NA
20-yr	163	64	65	NA	204	NA
---- Balance between added as fertilizer and removed through harvest (kg ha-l yr-l)-						
5-yr	21	75	12	NA	154	NA
10-yr	20	79	17	NA	162	NA
20-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-tenn (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 4.15). 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 4.15), though such a scenario may be economically unsustainable.

4.2.4 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 (l-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, Sand 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 Pi (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 20-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 aI., 1995; and Johannes et aI., 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 aI., 1983; Topp et aI., 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.

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

4.4.1 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 4.16. Significant differences between means were identified using the F-test. For our purposes, a given soil property was considered to be a sensitive indicator of soil quality if the probability of a greater F-value (P>F) was ~ 0.05. Moreover, the smaller the probability value, the greater the sensitivity of the indicator variable. Conversely, a given soil property was considered to be a poor indicator of soil quality if the probability of a greater F-value was >0.05.

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

Table 4.16. Significance level of soil chemical, physical and biological indicators for difference of depth-weighted means among the forested, 5-,10- and 20-yr-old tea plantations.

Soil property)	Depth (cm)2	Forest (n=4)	5-yr (n=3)	10-yr (n=4)	20-yr (n=6)	Statistical significance[3]
			Soil chemical indicators			
Total C (mg g-l)	0-40	16.29	13.12	13.00	12.09	***
Total N (mg g-l)	0-40	1.41	1.12	1.03	1.03	**
Total P (*Jlg* g-l)	0-10	244.7	343.2	353.5	356.5	**
Total K (mg g-l)	0-40	15.07	12.21	13.20	10.25	**
Total S (mg g-l)	0-40	0.39	0.75	0.63	0.43	*
Avail. P (*Jlg* g-l)	0-20	5.45	20.44	11.97	6.02	**
Avail. K (*Jlg* g-l)	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 (*Jlg* g-l)	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

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 4.17.

Results of the contrast analysis, including the direction of change, also were expressed in qualitative terms; i.e., i = significant (*P* ~ 0.05) increase in population mean, t = significant (*P* ~ 0.05) decrease in population mean, and H = no significant change (*P* > 0.05) in population mean (Table 4.17).

Table 4.17. Qualitative changes in soil quality indicators in response to tea cultivation[1]•

Properties	Effective depth (cm)	Forest vs. 5-yr	5-yr vs. 10-yr	10-yr vs. 20-yr
Chemical indicators				
Total C (mg g-I)	0-40	J,	H	J,
Total N (mg g-I)	0-40	J,	H	H
Total P (Jlg g-I)	0-10	i	i	H
Total K (mg g-l)	0-40	J,	H	J,
Total S (mg g-l)	0-40	i	H	J,
Avail. P (Jlg g-l)	0-20	i	J,	J,
Avail. K (Jlg g-l)	0-40	i	H	J,
Soil pH	0-40	J,	H	i
Physical indicators				
Resistance (MPa)	0-30	H	i	H

Bulk density(Mg m-3)	0-20	i	i	H
Porosity (%)	0-20	J,	J,	H
PAWC (% Vol.)2	0-20	J,	J,	J,
MWD *(mmi*	0-20	J,	H	H
	Bio-indicators			
Earthworms m-3	0-20 H	J,	J,	

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

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

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

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

4.4.2 Crop Yield as an Indicator of Soil Quality

During the 2022 season, crop yields from the 5- and 10 -yr-old tea plantations (5.06 and 5.02 ton/ha/, respectively) were significantly greater than those from the 20-yr-old plantations (3.30 ton ha^{-1}). Unlike annual crops, in which decreased yields following long-term cultivation are mainly due to a loss of soil quality (fertility), decreased yields of perennial crops (such as tea) following long-term cultivation can be attributed to the natural aging of the plants (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 4.18).

Table 4.18. Comparison of tea yields and total plant biomass in 20 -yr-old fields receiving high fertilizer inputs with those receiving low fertilizer inputs·

Biomass component	High fertilizer inputs (n=3)	Low fertilizer inputs (n=3)	Significance level [2]
Yield (ton ha^{-1})	3.3	1.78	0.01

. Standing crop (ton ha-[1])	38.54	34.83	0.00
Pruning (ton ha-[1])	5.09	3.19	0.00

Tea plantations receiving high fertilizer inputs were defined as those receiving at least 150, 80 and 80 kg ha $^{-1}$ yr $^{-1}$ ofN, 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 oft-test for difference in means.

Both total biomass production and crop yield were significantly *(P* ~ 0.05) plantations receiving low rates of fertilizer. Moreover, the 20-yr-old tea plantations receiving high rates of fertilizer produced tea total biomass and yields that were nearly equal to those of the 10-yr-old tea plantations (i.e., total yield and pruning biomass, representative for annual plant biomass, of the 20-yr-old

tea plantations was 7.92 tondecline in soil quality resulting from long-term tea cultivation can, to a considerable degree, be compensated for by fertilizer additions. In addition, it is apparent that the yield potential of the tea plants remains good even after 20 years of cultivation, provided an adequate supply of plant available nutrients is maintained through fertilization. This also suggests that tea yields in older plantations are limited primarily by declining soil quality rather than a decrease in the inherent yield potential of the tea plants themselves

4.4.3 Crop Yield Versus Change in Soil Quality

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

Plots of crop yield as a function of the individual soil properties are presented in Fig. 4.1 for the soil quality indicators that were most sensitive to change *(P* ~ 0.05) in response to cultivation.Regression analysis of the yield versus soil property data revealed that yield was positively correlated *(P* ~ 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* ~ 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 4.17 & 4.18), these results indicate that the observed decrease in long-term tea yields is a response to declining soil quality. Soil properties such as total P, pH, MWD of aggregates and earthworm populations were not significantly correlated with yield (data not shown), although they were found to be sensitive indicators of soil quality.

Soil properties that were identified as being sensitive indicators of cultivation-induced changes in soil quality (Table 4.19), 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 4.19.

Table 4.19. Regression coefficients for soil parameters in a multiple linear regression model with yield as dependent variable[1].

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

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

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

Results of multiple regression analysis (Table 4.19) indicated that total organic C and available P were the most highly significant variables (P ~ 0.05) in the predicted yield model; total K and PAWC were moderately significant variables (P ~ 0.1). Clearly, total organic C, available P, total K and PWAC can be considered the most important soil quality indicators for tea cultivation and, hence, the most important predictors of long-term tea productivity and sustainability. The relationship between yield and the soil chemical and physical propertie assessed using multiple regression analysis is presented in the following equation:

*y= O.1410C** + O.018Available-P** + O.054Total-K* + O.099PAWC**

R^2 *= 0.764****

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

4.4.4 "Critical Levels" of Soil Quality Indicators for Sustainable Tea Cultivation

Cost-benefit analysis. Cost-benefit analysis indicates that there is a significant difference in the total output among tea age-classes, with the highest output associated with the 10-yr-old tea plantations and the lowest output associated with the 20-yr-old plantations (Table 4.19). This result is a reflection of the decline in harvest associated with the oldest plantations. Conversely, total inputs remained unchanged or changed only a little among the 5-, 10- and 20-yr-old tea plantations (Table 4.18). As a result, the calculated total profit and benefitcost ratio (BCR) for the 20-yr-old tea plantations were significantly lower than those for the 5- and 10-yr-old plantations. Indeed, whereas tea yields from the 20-yr-old plantations were only about 26% lower than those from the 5 -yr-old plantations, there was a decrease of about 93% in the total net benefit associated with the 20-yr-old plantations (Table 4.20)

Table 4.20. Cost-benefit analysis of tea cultivation by age of plantations (in 2022).

Indicator	5-yr (n=3)	10-yr (n=4)	20-yr (n=6)
Yield (ton ha^{-1})	5.06	4.72	3.30
Total benefit (cost per ha, 1000 VND)	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 4.21) and relative net benefit (7%; see Table 4.22) 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 aI., 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 (Le., the farmer would lose money).

Table 4.21. Relative yield and net-benefit associated with long-term tea cultivation (determined relative to the yield and net benefit associated with the 5-yr-old tea plantations).

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

Given that changes in crop yield during long-term cultivation occur in parallel to changes in soil quality, critical levels for the appropriate set of soil quality indicators can be defined as the mean values measured for production systems operating at a profit of zero (i.e., at the threshold of economic sustainability). In this study, this threshold was reached after 40 years of continuous tea cultivation.Thus, measured values of the soil quality indicators from the 20-yr-old tea soils (Table 4.21) were considered to be estimates of the critical (limiting) levels below which productivity was no longer economically sustainable.

Table 4.22. "Critical levels" of the key soil quality indicators at the threshold of economic sustainability for tea cultivation.

Soil properties[1]	**Depth (cm)**	Critical level
Total organic C (mg g-I)	0-40	12.09
Available P (flf g-I)	0-20	6.02
Total K (mg g-)	0-40	10.25
PAWC (% Vol.)	0-20	9.43

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

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

4.4.4 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 aI., 1997) as well as crop yields. For example, a decrease in the soil organic C content of a given soil is related to (i) decreased nutrient supplying power, (ii) an increase in bulk density, (iii) deterioration of the soil structure, and (iv) decreased water holding capacity, all of which can adversely affected crop growth and yield. Likewise, crop yield can be severely affected by a decrease in the available nutrient pool. Economic considerations place fertilizers beyond the reach of many small farmers. Thus, there is a gradual degradation of the inherent soil fertility as the "nutrient surplus" (i.e., the supply of readily available nutrients present when soil was first broken and cropped) (van Kooten, 1993) is depleted. Depletion of the soil nutrients, particularly available P and K, due to continued cultivation with imbalanced fertilization, caused a degradation of soil quality.

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

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

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

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

4.5.1. 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 4.23).

Table 4.23. Number of people per household.

Number of people	Number of households	Percentage
2	4	8,7
3	6	13,04
4	24	52,17
5-8	12	26,09
Total	46	*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 4.24). 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 4.24. Distribution of people by age and sex.

Age	Sex	Number of people	Percentage
< 18	Male + female	52	27,37
18-60	Male	68	35,79
18-60	Female	62	32,64
>60	Male + female	8	4,2
Total		190	*100*

Education. The literacy rate for working age people in the Lam Dong tea enterprise was as high as 95% (see Appendix 6).. In particular, all heads of household had some type of formal education, with approximately 40 % having completed a high school level education, 51,12 % at a secondary school level, and 10% at a primary school level (Table 4.25). In addition, the level of education varied with the age of farmer, with younger farmers having received more formal education.

Table 4.25 Formal educational status of the heads of household (n=45).

Education level[l]	Age (years)	Number of people	Percentage
Primary school	53-60	4	8,89
Secondary school	30-55	23	51,12
High school	30-49	18	40

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 4.26). 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 4.26. Economic status of households in terms of tea farming producing an adequate income.

Economic status	Number of surveyed households	Percentage
Insufficient[1]	15	36
~ffici~	27	64,28

ı Insufficient fanners are those whose income were less than 6,000,000 VND per capita.

Farm characteristics. Individual farms in the Lam Dong tea enterprise are relatively small, with most farmers having less than 1 ha of cultivated land (Table 4.27). Indeed, only 26,78% of farmers had more than 1 ha of cultivated land and only 17,86% 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 4.27 Distribution of the tea households by farm size.

Farm size (ha)l	Number of households	Percentage
<0.5	17	30,36
0.5-1.0	14	25
1.0-2.0	15	26,78
>2	10	17,86

ı 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 (250 to 300 kg N ha^{-1} yr-l) was the predominant fertilizer element added to tea soils in the Lam Dong region. This was reflected in the fertilizer trends reported for the past five years (Table 4.28). During this period, P-fertilizer inputs have generally remained the same or decreased (85-100 kg P ha^{-1} yr-l). Potassium fertilizer usage also has been increasing, though not at the rate observed for N-fertilizer (80-100 Kg K ha^{-1} yr-l).

The technique of fertilizer application is not guaranteed, spreading on the ground is the main thing, so the efficiency of fertilizer use is low, and fertilizer is wasted. Most farmers in the tea growing areas of Bao Loc, Bao Lam apply organic fertilizers as well as use inorganic fertilizers to choose when it rains to spread manure and sprinkle it on the ground on both sides of the tea row. It is hoped that the fertilizer will be dissolved by rainwater and seep into the soil to provide plants for use. In fact , this method of fertilizing has caused waste of fertilizers, especially volatile fertilizers, which are easily washed away and at the same time increase the risk of degradation due to chemical fertilizers of tea growing soil.

Table 4.28. The situation of fertilizer use for tea land in Lam Dong

Yield	Organi c	Inorganic fertilizers

te Local	tons/ha	fertilizer kg/ha	(kg/ha)					
			Urea	Lan	K	N	P	K

			super								
Bao Loc	8.113	4,778	1.069	991	304	60.6	19.5	22.4	4.4	1.2	1.5
Bao	6.145	1.093	780	899	163	58.5	23.4	15.9	3.8	1.4	1.1
Lam	9.601	1,726	1,067	708	200	51.2	11.8	12.5	5.3	1.2	1.3
Di Linh	**7,790**	**1,937**	**943**	**798**	**216**	**56.1**	**16.9**	**16.7**	**5.0**	**1.3**	**1.3**

The unbalanced use of fertilizers not only adversely affects the soil, but also directly affects the quality of tea buds, high NO3 content in finished tea, less delicious tea, affecting the health of consumers. The tea garden is not fertilized with organic fertilizers, the pH decreases, the soil becomes increasingly poor in nutrients, the soil microorganisms reduce the efficiency of using low inorganic fertilizers. At the same time, it will cause the soil structure to be broken, reduce the ability to hold water, hold manure, increase disease. Improper fertilizing, poor soil organic matter often causes soil structure to degrade, soil density increases, and porosity decreases, making the soil tight, making it difficult for roots to develop. Degraded soil reduces moisture capacity, reduces effective water, plants easily wilt and increases the ability to leach nutrients in the surface layer. Reduces the number of soil microorganisms, adversely affecting the quality of tea.

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 4.29). 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 onlyrarely. In addition, labour inputs increased markedly with the fanners (now the landowners) spending more time working the fields and employing more soil conservation technologies.

Table 4.29. Farmers' perception of how the cost of fertilizer and price of tea affected tea production during the last five years (n = 45).

Parameter	Number of respondents	Percentage
Increase in the cost of fertilizer	30	66,67
Fluctuation of the price of tea	45	100

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,

Table 4.30. 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 4.31. Importance of the soil quality indicators based upon the farmers' perceptions.

Indicators	Total soil quality points}	Overall Rank
Soil organic matter	95	1
Soil fertility	112	2
Soil compaction	145	3
Soil structure	181	4
Moisture in dry season	187	5
Earthworm numbers	254	6
Soil erosion	288	7
Soil acidity	291	8
Topsoil thickness	298	9
Weed incidence	324	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 4.32. 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 4.32. 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 4.32), the occurrence of some wild plant species in the tea fields was a viewed as an indicator of some soil properties. For example, experienced fanners 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 fanners in the Lam Dong province by agronomists from the agricultural extension programs for tea cultivation. The number of fanners 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 fanners' perceptions of the socio-economic benefits of the technology. Most fanners 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 fanners cultivating upland soils readily accepted these methods when land ownership was shifted from the state enterprise to individual households.

Table 4.33. 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 tum, this was recognized by many fanners as being essential to maintaining soil quality and agricultural sustainability (see Table 6.12). The number of fanners 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 fanners 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 fanners were wary of implementing soil conservation methods that require a long time to produce results. Because fanners are more likely to accept a technology if they are sure to derive a benefit from it, the government should consider allowing long-tenn leases to fanners as a means of promoting soil conservation technologies that require longer tenns to produce the desired effect (i.e., enhanced soil quality).

5.3.3 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).

$$InYield = 4.498 + 0.37\ InN + 0.190\ InP + 0.201\ InK - 0.060\ InCa + 0.020\ InLbr +$$

$$0.005\ InMnr + 0.010\ InPest - 0.0091nSlope - 0.027\ InFrmS -$$

$$0.1511nTime + 0.095Econ + 0.148Tech + 0.042Edu \qquad (5)$$

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:

$$InYield = 4.470 + 0.360\ \text{InN} + 0.1621\text{nP} + 0.202\ \text{InK} - 0.1591nTime + 0.091\ Econ + 0.174\ Tech \quad (6)$$

where R^2 = 0.627***.

Table 4.34. Regression coefficients used to develop the estimated yield function.

Variables	Coefficient	Significance level
Intercept	4.498***	0.000
InN	0.370***	0.000
LnP	0.190*	0.022
InK	0.201 **	0.010
InCa	-0.060	0.065
LnLbr	0.020	0.860
InMnr	0.005	0.273
In *Pest*	0.010	0.790
In *Slope*	-0.009	0.756
In *FrmS*	-0.027	0.455
In *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 aI., 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 4.35), 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 4.36) and that most were experienced farmers (Nguyen et aI., 1999).

Chapter 5:
General Synthesis, Discussion, and Conclusion

5.1 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-tenn tea cultivation degrades soil quality, which in tum decreases crop productivity. The research consisted of two separate but inter-related components, quantitative evaluation of soil quality under long-tenn tea cultivation and a study of socio-economic conditions and fanner attitudes towards sustainable tea cultivation.. Tea is the main cash crop in the region, fanns are small and the tea plantations vary in tenns of age, topography and management.

5.1.1 Important Inherent Characteristics of the Study Soils

Intrinsic soil properties including soil color, clay mineralogy, particle size distribution, and Fe- and AI-oxide contents and fonns 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 460/0 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 venniculite.

The typical reddish yellow color is an indication that oxidizing conditions predominate, with Fe- and AI-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-em 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.

5.1.2 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 *Ae+.* 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 aI., 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).

5.1.3 Soil Properties of Limited Value as Soil Quality Indicators

Soil color, clay mineralogy, texture, AI- 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 aI.,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.

5.1.4 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 aI., 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.

5.1.5 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 benefitcost 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.

5.1.6 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, andtogether 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 aI., 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, fanners are able to identify appropriate soil conservation technologies. Technologies that have been accepted by most fanners should be considered within the cultural and socio-economic conditions of farmers, and the long-term and short-tern beneficiary of technology.

5.2 Recommendations for the Future of Soil Conservation

Sustainable tea cultivation is an important goal for the economic development of the Lam Dong province, because tea is the main crop providing a livelihood to fanners in the region. Declining soil quality resulting from cultivation leads to low crop productivity which, in tum, 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 fanner 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 fanners, 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 Lam Dong province. 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 Lam Dong province. 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 fanners. 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 modem 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 Lam Dong province (Table 5.1).

Table 5.1. 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	- Change in farmers' attitude towards soil management

5.3. Recommendations solutions for sustainable use of tea land

5.3.1. Basis for determining tea-growing areas

The selection of a tea-growing area is based on the following requirements:

1. *Planning plan:* based on the orientation of agricultural development to 2020 of the State in general and Lam Dong province in particular. Currently, the socio-economic development plan for the period 2011 - 2015 of the Agriculture and Rural Development sector of Lam Dong province has determined that by 2015 the tea plantation area will be planned and stabilized at 26,000 hectares in the province.
2. *Suitable area:* the area oriented to develop into a tea-growing area must first be an area with natural conditions suitable for tea plants.

Based on the results of land suitability assessment, it is possible to select priority specialized cultivation areas in the following order:

- The region has very suitable land units;
- Areas with land units of medium suitability; - Areas with less suitable land units.

3. Labor and size requirements:

- Tea cultivation in Bao Loc - Di Linh area is mainly thanks to the water of the sky, and tea after being harvested needs to be put into treatment and processing immediately, so it should be developed in densely populated and labor-intensive areas. know how to invest in intensive farming, apply advanced scientific advances.

- Layout areas Tea production requires convenient roads to facilitate directing, purchasing, processing, and improving product quality.

4. Requirements on socio-economic and environmental efficiency:

Areas selected to be prioritized for development into a tea-growing area must comprehensively reflect the effectiveness of socio-economic and environmental aspects. Based on that requirement, the order of priority for selection of the planning area is as follows:

- To develop tea-growing areas on agricultural land. Other land use purposes are: forestry land with forests, special-use land, residential land, wet-rice land for which no tea is developed.
- On agricultural land, priority should be given to developing tea growing areas on the following land use systems:

+ On the land planted with perennial industrial crops such as coffee, mulberry, cashew ...

+ Intercropping on coffee and fruit trees;

+ Planting instead of land use systems for annual crops has lower socio-economic efficiency than tea. This selection process needs to be considered because of the variation between periods of social demand for that crop and food security.

5.3.2. Economic efficiency, social and environmental sustainability of tea farming in the study area

* *Economic efficiency of tea cultivation*

The effectiveness of tea cultivation varies according to the variety of tea. For high- quality tea, the initial investment cost and regular care cost are much higher than that of branch tea, but the selling price is 9-12.5 times higher, and the profit is high. However, at present, the cultivation of high quality tea is limited to only a few enterprises and households that have contracts with the factory because this type of tea requires different care regimes and strict processing procedures *Social and environmental performance* Tea is a perennial industrial crop capable of hunger eradication and poverty alleviation along with other industrial crops such as coffee, rubber, and sugarcane. In fact, the investment in tea cultivation is not high, the harvest is fast and stable for many years. Growing tea requires a lot of labor, creating many jobs because of the long harvesting season, almost all year round, ensuring a steady income for producers. Tea development will attract a significant number of workers, not only in the production of raw materials but also in the processing and consumption of tea. Therefore, the distribution and adjustment of the planning of tea growing areas will significantly affect the ability to create jobs for local workers.

Tea is a plant that does not require very good soil like coffee, on the other hand, tea is a tree that harvests leaves, the yield is relatively stable, annual fluctuations are not large, even in years with many natural disasters, droughts do not completely disappear. like fruit trees, coffee. Tea can be grown in areas unsuitable for many annual crops. In fact, growing tea has a more positive effect on soil protection and anti-erosion than coffee. Tea can still grow well and give high economic efficiency on the slope of 20 -25 degrees. Therefore, growing tea on sloping land contributes to improving the land cover coefficient. While coffee plants require thicker soil, the slope is smaller. In some places tea is intercropped with coffee, this is also a model that needs attention. Although the average income is lower than that of coffee, tea cultivation is still considered as a model that needs to be maintained on a reasonable scale in certain areas with existing tea brands.

5.3.3. Development orientation of tea growing areas

On the basis of synthesizing the results of land degradation research, assessing the appropriateness, the current status of tea cultivation in 2010, analyzing the requirements for selecting a concentrated tea development area, showing the potential of the land in the study area. quite abundant research for the purpose of growing tea. The project proposes a plan for planning a tea-growing area in the study area as follows:

The tea-growing area is defined in Bao Loc city, Di Linh district and Bao Lam district. The proposed areas belong to the land units that are assessed as suitable for tea plants, distributed along the main roads connecting to the production zones, creating a convenient traffic network for production development. transportation of raw materials and products. The population distributed in these areas is quite concentrated and the labor force is abundant. Particularly for Di Linh district, although currently the tea cultivation area is very small, the research results can serve to change the crop structure in the future when coffee prices are often unstable.

On the basis of the selection and identification of tea-growing areas analyzed above, excluding areas unsuitable for growing tea but some types of land use such as residential land, forestry land, and rice-growing land. … area of areas suitable for tea cultivation in the study area as shown in the table. At the same time, the topic also proposes to expand the tea area according to 2 options.

Table 5.2. Proposed area of tea area in the study area

Unit: ha

Suitable area		**Bao Lam**	**Bao Loc**	**Di Linh**
Well suitable		25,795.42	10,130.78	12,809.08
Average suitable		3.201.83	2,373.90	15,341.79
Less suitable		3,913.09	19.53	13,543.61
Current status of farming		13,246,00	8,208.00	886.00
Open plan wide	first	12,549.42	1,922.78	11,923.08
	2	19,664.34	4,316.22	40,808.48

Option 1: This is the top priority area for tea development in the area that is assessed to have most favorable conditions, meeting the growth characteristics of tea plants. At the same time, with the planning orientation of about 26,000 hectares of tea growing land in Lam Dong province, Bao Loc - Di Linh completely meets this requirement with the best land conditions. Tea growing areas can be selected in Bao Lam with 12,549.42 ha, in Bao Loc with 1,922.78 ha, or 11,923.08 ha in Di Linh.

Option 2: showing the full potential of expanding the tea growing area on the basis of the synthesis of all three regions with different suitability levels. In which, forming a key tea growing area, a satellite area and a backup area. Thus, Bao Lam district has the potential to develop tea growing land by 19,664.34 ha, Bao Loc 4,316.22 ha, Bao Lam 40,808.48 ha. The less suitable area is the last priority reserve area in the planning of tea areas, or gradually improving the limited conditions for tea plants for future use.

5.3.4. Some solutions for sustainable use of tea land

Based on the analysis of soil degradation for tea cultivation and the assessment of land suitability for tea plants above, it is shown that tea production has 5 main objectives to be achieved: high yield, high yield, good quality, safe tea, sustainable tea growing land. To achieve the above goal, intensive cultivation of the existing tea garden, renovating the old tea garden, and planting new tea are three contents that need to be carried out at the same time.

5.3.4.1. Solutions for tea growing areas

- The area is very suitable for tea plants, so it should be built into a key area of tea intensification, investing in high-quality tea varieties. Where the average spectral slope is less than ^{8o} , it is designed to plant tea in a straight line along the main line to facilitate care. Compare with soil degradation levels to have a plan to maintain the quality of tea land on weak soil degraded areas, improve soil and prevent land degradation on medium and strongly degraded areas. . The main type of soil here is the soil developed on basalt, which has quite ideal physico-chemical properties for crops, so the cause of the increase in soil degradation is the formula of fertilizing and compacting the soil due to trampling. pedaling during tea care and harvesting.
- The medium suitability zone forms a satellite tea growing area around the key area. This area focuses on developing tea varieties for mass planting, intercropping with suitable plants in different growth periods of tea to increase economic efficiency and take advantage of arable land.
- Less suitable areas should still maintain a certain area of tea at garden scale in households, intercropping with coffee and some other plants. Most of the less suitable areas have a common slope of 15-25 ^{o} , prone to soil degradation due to surface erosion, and bioclimatic conditions with less rainfall and long dry seasons, and barren soils due to low rainfall. lack of water. Thus, it is necessary to design tea plantations according to the model of terraced fields to prevent soil erosion in the rainy season, to design a system of canals and reservoirs for irrigation in the dry season.Especially, for less suitable and medium suitable areas on strong synthetic soil degradation, the plant structure should be changed to production forests or fruit trees for long-term soil improvement.
- For the old tea growing areas, it is necessary to determine which areas need to be improved and upgraded, which areas need to be cleared to rotate other crops. The tea plantations are good but old, have been exploited for a long time, do not invest in intensive farming from the beginning, should not be demolished, so reinvest to renovate because the cost is low but the output increases faster than investing in the gardens. Tea has a high yield.

5.3.4.2. Building models of tea growing

* The arrangement of the tea rows affects the production efficiency and longevity of the tea fields, the arrangement method depends on the slope of the tea hill.

- Slope below 8 ^{o} arranged straight rows of tea;
- Slope from 8 - 15 ^{o} arranged tea rows according to contour lines;
- Growing tea on terraced fields for areas with slopes above 15 ^{o} .

The design of tea plantation should ensure: convenient for travel, care, reduce soil hardness, prevent erosion and protect the environment. With bare lands and bare hills, it is possible to design tea areas, tea plots, and tea bands. With a good land with many secondary plants growing like sacrificial, got, myrtle, it is absolutely not allowed to destroy the fields and burn the fields, but need to spread the tape along the contour lines to protect the soil against erosion. Areas with large slopes (over ^{15o}) for convenience in boundary management, need to be based on natural topography such as streams, streams, and waterways to divide the tea area. , tea plantation for easy management. The complete tea plantation design makes it easy to transport seeds, fertilizers, and harvested products, reducing labor intensity. Reasonable design also reduces leaching and erosion, contributing to protecting tea land.

* Agroforestry is a model of intercropping tea with some other tree species with a multi-layered structure as follows:

Tea intercropped with green manure crops. During the basic construction phase, use the yellow flower basket as a temporary overhead shade tree. Legumes such as peanuts, soybeans, green beans, etc. provide shade in the lower floor to take advantage of the land gap between two rows of undissected tea, to keep the soil moist in the dry season, to increase the harvest of by-products, control weeds, cover the soil and have a source of green manure to add organic matter to the soil.Windshield: all kinds of black cassava, acacia leaves, acacia tai... are planted with the role of windbreak around the tea area.

Tea intercropped with short- and long-term shade trees with strong growth, not with the same pests and diseases such as acacia acacia, acacia, black cassava, lily of the valley, etc. In addition, fruit trees such as durian can be intercropped. grafting, jackfruit with a density of about 60 trees/ha to limit erosion in the rainy season and at the same time increase economic efficiency per unit area.

The technique of making tea soil will have a long-term effect on the growth and development of tea plants, which is the first decisive step to the soil structure of tea plants. Good soil preparation will improve the physical and chemical properties of the cultivation layer, have the effect of eliminating weeds, preventing erosion, retaining water, and keeping color. Specifically, it is necessary to have a plan to dig a thin layer of soil 2-3 cm between the rows of tea to reduce the possibility of physical soil degradation such as soil compaction, soil hardening, increase porosity and water permeability. … In addition, it also kills weeds and some tea pests that often hide in the surface soil layer of tea fields (pseudo-pupation of silkworm beetles,

5.3.4.3. Solutions for seeds, fertilizers and pesticides

caterpillar pupae, cluster worms, ...). Tilling can be done twice a year: the first time is in February-March after spring rains and weeds have grown; 2nd time in September-November before the weeds flower.

Planning to replace midland tea and seed tea varieties with low yield and low income with high quality tea varieties such as: BP14, LDP2, PH1, PH8... top Shan tea and imported varieties in each concentrated area. at least 30 hectares or more. For areas with altitude above 800 m, it is possible to produce high quality green tea such as Kim Tuyen, Tu Quy Xuan, Thanh Tam..., Oolong tea.

Reasonable use of fertilizers must adhere to 4 principles. One is to apply the correct dose and rate of fertilizer, which is equivalent to the number of kg/unit area, the ratio N:P:K. Select the dosage, rate as well as the method of fertilizing each tea variety in accordance with the ecological zone conditions to meet the requirements of sufficient and highly effective fertilizer in tea production. For example, for high-yield tea with the norm of 30 kg N/ton of product, NPK fertilizer with the ratio 3:1:1, high-quality Taiwanese tea with the norm of 120 kgN/ton of product, the NPK ratio is 3. :1:1. In tea cultivation, it is necessary to study the production of organic and bio-organic fertilizers in situ according to standards and suitable for tea plants to provide fertilizer for tea, minimizing the use of chemical inorganic fertilizers.

Second, the correct type of fertilizer, with each period or tea variety using foliar fertilizer or root fertilizer, choose between organic and inorganic fertilizers. In addition to fertilizing with organic fertilizers or rotted manure, the tea plants need to be fertilized with additional weights such as magnesium sulphate, zinc sulphate, etc., foliar fertilizer after 2-3 batches of picking and spraying once for high yielding tea. , 2 times/lot for high quality tea.

The third is to fertilize at the right time, to meet the nutritional needs of each period of the crop. Pay attention to the timing of fertilizing such as fertilizing in the dry season months, the fertilizer efficiency will be low, causing a lot of fertilizer waste, should be applied at the beginning of the rainy season, or applied periodically from April to May. XI. Do not apply mineral fertilizers in the dry season and during heavy rain, avoid fertilizing in the area 3-4 m from the river or ditch. Minimize loss of nutrients due to weeds or leaching.

Fourthly, apply fertilizer properly, with the right technique to improve the effectiveness and efficiency of fertilizers. The method of fertilizing tea is to mix all kinds of fertilizers in proportion, apply 15-20 cm deep in the middle of the tea row, cover the amount of fertilizer applied, avoid spreading fertilizer to limit surface washing.

To treat pests on tea plants, some biological solutions can be used as follows:

- Protect and develop natural enemy populations available on tea fields:

Allow the pests to exist at low densities below the level of economic harm, without affecting tea yield. Applying reasonable farming methods creates favorable conditions for tea plants to grow and develop, increases the resistance to pests and diseases of tea plants, creates favorable conditions for natural enemies to reside, and contributes to reducing demand for tea. requires the use of chemical drugs.

Ensure plant diversity in the tea tree ecosystem. Shade trees and intercropping trees create conditions for natural enemies to have a richer species composition. Maintain nectarine flowers around the tea fields to attract natural enemies to reside and develop.

Do not use chemical drugs indiscriminately, only use chemical drugs when necessary, use specific or narrow-spectrum drugs, are less toxic to natural enemies but highly effective against pests, only spray where there is honey. The depth and severity of the disease is higher than the threshold of economic harm.

- Increased use of probiotics and herbs:

Using herbal and biological preparations to control major pests on tea plants. The study applies the rearing of some predatory predatory species (lady beetles, short beetles, small spiders.,...) and releasing them into the tea tree ecosystem to eliminate green planthoppers, mosquito bugs, silk beetles. , small spider. Thereby reducing the amount of pesticides, avoiding residues of these drugs in the soil and in tea buds.

5.3.4.5. Some recommendations

In order for the assessment of land degradation and the appropriate zoning of land to be more effective with tea trees, thereby dividing into a group of specific solutions for each area of the current status or expansion, we realize that there are The next research work on building a map of tea growing status. In which, a map of the current status of tea plantations is established using remote sensing technology - GIS to classify, survey and verify and put into the old tea growing areas that have been cut down for restoration.

From the map of the current situation of tea cultivation, to determine in detail the distribution of tea in the regions, specifically the existing tea varieties, which will serve as a basis for predicting tea production in the following years to have a processing plan. and balance the consumption market.

Bao Loc - Di Linh is one of the large and good quality tea regions of Lam Dong as well as the whole country, at present, the tea area is always fluctuating due to the market price of the tea industry and a number of agricultural commodities. A typical competitive product is coffee. Therefore, it is necessary to make adjustments to the tea cultivation area in a timely manner with the long-term orientation of the State and local authorities based on research results associated with practice. After stabilizing the tea area, continue to invest in depth from cultivation to processing to improve the quality of finished tea, maintain and promote Bao Loc - Di Linh tea brand.

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Appendix 1. 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. Ifnot 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 (sandi 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 ofN-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 ofP-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/IOOQm2 ifpossible):

- 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 *lor* 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 enterpriselcooperative 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 2. Correlation Analysis Among Dynamic Soil Properties

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

Indicator	Org.C	TotalN	Total S	Total P	Total K	Avail. K	Avai I.P	pH
TotalN	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	SoilC	Bulk densi	MWD	PAWC
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 3. Effects of Slope and Fertilization on Soil Quality

Table A3.1. The t-test for difference of means of soil properties between upper and lower back slope positions (0- to to-cm depth).

Slope position	Forest	l-yr	5-yr	10-yr	20-yr
Total e (mg g-I)					
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 gO1)					
Upper	1.91a	1.90a	1.53a	1.63a	1.76a
Lower	2.12a	1.97a	2.08b	1.74a	1.55a
Total P (p,g g-I)					
Upper	224.67a	237.21a	312.38a	348.65a	320.12a
Lower	224.90a	247.80a	374.00a	358.35a	392.94a
j\"ailable P (p,g g-I)					
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-I)					
Upper	14.84a	13.59a	11.47a	11.07a	10.13a
Lower	14.07a	14.55a	12.35a	12.06a	10.57a
j\"ailable K (p,g g-I)					
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	Nj\2	3.03a	3.53a	3.64a
Lower	4.76a	Nj\	2.75a	3.23a	3.71a
Pj\We (% Vol.)[3]					
Upper	13.40a	Nj\	12.98a	12.26a	8.98a
Lower	13.38a	Nj\	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 p AWe-plant available water capacity, MWD-mean weight diameter of agreegates.

Table A3.2. Comparison of soil properties in 20 yr-old tea plantations with different fertilizer inputs.

Soil properties	Depth (cm)	High fertilizer inputs	Low fertilizer inputs	Significance level[l]
Total C (mg got)	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 got)	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 (J.lg gol)	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-I)	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 (J.lg g-I)	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 (J.lg got)	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 -I)	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	0-10	1.24	1.22	0.48
(g cm -3)	10-20	1.30	1.36	0.06
PAWC(%i	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

l Significance levels of t-test for difference of means of soil properties.

2 PAWe-plant available water capacity, MWD-mean weight diameter of agreegates.

Appendix 4. Economic Analysis for 20 -yr-old Tea Plantations with Different Fertilizer Application (by VND)l.

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 5. Sources of Living and Literacy Rate of farmers

Table A5.1. 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 A5.2. 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] Fonnal education accounted for those who have attended in at least primary school.

Appendix 6. Farmers' Perception about Changes in Crop Yields

Table A6.1. Recognition by farmers about the change in yield with length of continuous cropping.

Year after cultivation	Percentage of farmers (n=45)		
	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 A6.2. 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