Productivity and resource use in ageing tea plantations

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Productivity and resource use in ageing tea plantations

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Abstract

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The tea industry in Kenya is rural-based and provides livelihood to over three million people along the value chain. The industry which started in the first quarter of the 20th century has continued to increase in terms of production and total acreage. Tea is grown in prime agricultural and forest land and can be in production for up to 100 years if well managed. However, peak yields are obtained at 20–40 years after planting followed by a decline to a level where the plantations may become degraded and uneconomical. In the past, several hypotheses have been postulated, but the cause of this degradation largely remains unclear. The big question still lingers, is it the tea bush that degrades, the soil or both?

In this study, trends in tea yields were first assessed by analysing long-term tea production data, from 1969 to 2006, for the two sectors of the Kenyan tea industry. The plantations are characterized by differences in age and genotypes (seedling or clonal). To explore plausible management options for tea productivity improvement, a simple decision-support (DS) model for Managing Ageing Plantations of Tea (MAP-Tea) was developed and scenario analyses were done to explore some promising management interventions. It was found that uprooting and replanting of degraded old seedling tea plantations with clonal cultivars would be profitable. However, management practices that prevent degradation are most cost effective.

The experimental part of the study was carried out during two years, 2002/2003 and 2003/2004, in a chronosequence of existing tea plantations (14, 29, 43 and 76 years old), adjacent to a natural forest in Kericho, Kenya. Soil-plant-environment relations and effects on tea bush productivity, C and N-P-K stocks and soil quality traits were analysed. Younger clonal tea plantations established at high densities outyielded the older seedling plantations with a lower densities. Ageing *per se* did not reduce the N-response or the productivity of tea plantations. It was shown that seedling tea bushes acquire much higher C and N-P-K nutrient stocks with age than clonal bushes. This may enable seedling plantations to depend less on limiting nutrient(s) supply under adverse conditions, i.e. drought. The top soils of the four tea plantations showed small differences in chemical and biological characteristics, also in comparison to the natural forest. Soil pH and total organic carbon were weakly related to the productivity of the ageing tea plantations. Additions of tea prunings in incubated soils caused immobilization of N and lowered the net N-mineralization compared to the forest soil, but the differences were relatively small and unlikely to cause degradation of the ageing tea plantations. Further improvement in productivity and resource use of ageing tea plantations should come from a better timing and dosing of nitrogen, and from the transition from old low-yielding seedling plantations to modern higher-yielding clonal plantations taking into account Genotype × Environment × Management (G×E×M) relationships.

Keywords: Kenya, *Camellia sinensis* L., clones, seedlings, tea industry, management, N-P-K, biomass, made tea yields.

Preface

This dissertation illustrates the complexities associated with ageing tea agro-ecosystems in scale and time. It was written based on tea productivity data from the two sectors of the Kenyan tea industry and Plant-Soil experimental data along a chronosequence of tea plantations, backed by laboratory studies and analyses. The completion of this research took many hours, days, years and much support from many individuals and organizations that I now wish to acknowledge.

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David M. Kamau
Wageningen, November 2007

Contents

List of Abbreviations

ASNR	Apparent shoot nitrogen recovery
C	Carbon
$CaCl_2$	Calcium chloride
C.V.	Coefficient of variation (%)
DM	Dry matter
E_t	Evapotranspiration
FDA	Fluorescein diacetate
HD	High density
HI	Harvest index
ICRAF	World Agroforestry Centre (formerly, International Centre for Research in Agroforestry)
ICP	Inductively coupled plasma
IITA	International Institute of Tropical Agriculture
ITC	International Tea Committee
K	Potassium
KARI	Kenya Agricultural Research Institute
KTDA	Kenya Tea Development Agency (formerly, Kenya Tea Development Authority)
KTGA	Kenya Tea Growers Association
LD	Low density
LSD	Least significant difference
MBC	Microbial biomass carbon
MBN	Microbial biomass nitrogen
N	Nitrogen
NS	Non significant
P	Phosphorus
SD	Standard deviation
SE	Standard error
SWD	Soil water deficit
TBK	Tea Board of Kenya
TMA	Total microbial activity
TRFCA	Tea Research Foundation of Central Africa
TRFK	Tea Research Foundation of Kenya
NWO-WOTRO	Netherlands Foundation for the Advancement of Tropical Research

CHAPTER 1

General introduction

Tea production in Kenya provides an economic resource for employment of the local people and the national economy. The tea industry supports other sectors of the economy and provides livelihood to over three million people. Although overall productivity of the tea plantations is the highest in the world, a lot of concern on stagnation and/or declining yields has been raised in the last two decades especially in the older tea plantations that are 40 years and above. Some of these old tea plantations have more than 25% gaps and do not respond to known agronomic practices including nitrogen application and rejuvenation pruning. This thesis deals with the complexities associated to ageing of tea plantations by quantifying productivity trends and the plant-soil-environment relations.

Origin and distribution

Tea is an evergreen understorey shrub from the genus *Camellia* that includes some 82 species (Banerjee, 1992a). Of all the *Camellia* spp., tea is the most important both commercially and taxonomically and is cultivated to produce a stimulant brew. The two main varieties are *Camellia sinensis* var. *assamica* with relatively large, leaves, and *Camellia sinensis* var. *sinensis* with small semi-erect leaves. *Assamica* tea originated from the forests of Assam in north-eastern India and the *sinensis* tea from Sichuan province, south-western China (Van der Vossen and Wessel, 2000). These areas are normally characterized by a monsoon climate with high rainfall and high humidity during warm wet summers and cool dry winters. Following extensive selection and hybridization, most commercial tea today display vegetative characteristics intermediate between these two main types (Mondal et al., 2004).

In its wild state, the tea plant can grow up to 15 meters high and has a taproot to oblique root system (Bonheure, 1990). The tea crop has been introduced to other parts of the world with diverse climatic conditions from its native habitat ranging from a Mediterrannean-type climate to hot humid tropical and subtropical regions from as far north as Georgia (42° N), and as far south as Argentina (27° S) and between sea level and 2,460 m altitude (Carr, 1972). The main tea producing countries are: China, India, Sri Lanka, Kenya, Indonesia, Turkey, Iran, Georgia, Japan, Vietnam, Bangladesh, Argentina, Malawi, Uganda and Tanzania.

The primary crop consists of young tender leaves, which may be withered, rolled, fermented and dried to give different types of teas. Growth of the tea plant is dependent on many factors comprising of those that are inherent in the plant itself and those exerted on the tea crop by nature such as soil and climatic conditions, pest and diseases and man through crop husbandry and cultural practices. These factors are broadly described below under the headings: planting resources, abiotic factors, biotic factors, and management practices.

Plant resources

Genetic improvement

Initially, tea was grown from seed to produce seedling tea that is heterogeneous due to natural outcrossing. This resulted to numerous hybrids referred to as Assam, Cambod or China depending on the morphological proximity to the main taxa (Banerjee, 1992a). The seedling types are commonly refereed to as 'jats' depending on the origin or seed orchard. This heterogeneity resulted in a great variation in yield, quality and suitability for fermentation. The focus thereafter shifted to yield as the main selection criteria (Green, 1971). However, over the years, tea selection and breeding programmes have resulted in improved varieties that combine high-yielding ability, good quality, stress tolerance, and pest and disease resistant traits known as clone cultivars (Banerjee, 1992b). The differences associated with the use of terms 'jats', 'genotypes' and 'clones' has been addressed by several authors, e.g. Barua (1963), Rawat (1980) and Wachira (1994) and show the controversies involved. To produce clonal cultivars young plants are vegetatively propagated, i.e. raised from cuttings obtained from a mother bush in the field and carefully tended in special nursery beds until they are 12 to 18 months old. They are then planted in the field. The mother bushes are selected according to well-defined criteria, notably homogeneity, vigour of the bush, density and regular distribution of the shoots on the plucking table, weight of the shoots, suitability for fermentation and manufacture, suitability for propagation by cuttings, tolerance to drought and pests, etc. In East Africa, maximum yields of released cultivars vary considerably from 3 t ha^{-1} for the unselected seedling types (Wachira, 2001) to 11 t ha^{-1} for clone AHP S15/10 (Oyamo, 1992) while those in Central Africa show a much smaller range between the seedlings (4.2 t ha^{-1}), and the clonal cultivars (SFS 204, 5.8 t ha^{-1}) (Ellis, 1978). Cultivars released from India (Bezbaruah, 1988) and Sri-Lanka (Shanmugarajah, 1999) showed maximum yields of around 3 t ha^{-1}.

Abiotic factors

Soil

Tea is grown in a wide range of soils of different geological origin although specific soil characteristics must be met by a particular soil type for successful tea cultivation. Most soils used for tea production are highly weathered and leached soils, and moist throughout the year. The degree of leaching and hence the character of the resulting soil depends on rainfall, temperature and the age of the soil.

A common characteristic shown by soils is the acidity (pH) in which the tea plant grows best (Othieno, 1992). This condition holds not only in the top soil but also in the deeper subsoil layers. The upper limit of pH varies with the nature of the soil, especially the clay content and organic matter. However, most satisfactory pH values vary between 4.0 and 6.0 (Othieno, 1992). Soil pH is influenced by many soil chemical parameters and may change seasonally depending on the external inputs used. Whenever the soil pH range becomes undesirable for tea growth, amendment compounds are used.

The most important soil physical requirement for tea plant production is a deep and well drained soil, with a minimum depth of two metres and an aggregated or crumb soil structure with about 50% pore spaces (Dey, 1969). Tea grows on soils of practically any texture ranging from sandy loam to clays including silts and loams of all types. However, the lighter sandier soils have a lower field capacity than the heavier clay soils and require a good distribution of rainfall and nutrients. Irrigation is useful during the drier periods. Although the water requirements of the tea plant is high, pore spaces should never get saturated or waterlogged as this is harmful to plant growth.

Correlations between soil parameters and productivity are not always clear. However, the following soil properties have been linked to tea productivity in different tea-growing regions: soil pH (Goswami et al., 2001), soil depth and organic carbon (Anandacoomaraswamy et al., 2001). Most studies show that soils under tea agro-ecosystems have considerable higher organic matter and nutrient contents than those of other land use systems primarily due to differences in management and crop residue recycling (Solomon et al., 2002; Hartemink, 2003; Tchienkoua and Zech, 2004; De Costa et al., 2005).

Land preparation prior to tea establishment is essential just as good maintenance of the soil physical characteristics during its cultivation to avoid problems associated with soil compaction (Coomaraswamy et al., 1988) and soil erosion (Illukpitiya et al., 2004). The period between land preparation and tea establishment is normally the most prone to erosion (Othieno, 1975) but as the tea bush matures and attains a ground cover canopy of above 60%, soil erosion and run-off becomes negligible (Othieno and Laycock, 1977).

Rainfall

Tea grows under a wide range of climatic conditions from equatorial to humid, temperate climates. The *assamica* varieties are less hardy than the *sinensis* varieties, which can tolerate a longer dry season or lower temperatures. It is estimated that unshaded tea transpires up to 2,200 mm water per ha per year (Katikarn and Swynnerton, 1984; Anandacoomaraswamy et al., 2000) depending on the area. The tea plant thrives best under high and evenly distributed rainfall of at least 1,500 mm per annum and in the tropics, and a dry season of not more than three months. At the equator, the ideal monthly rainfall distribution will be 90 to 180 mm, and crop yields fall below 60 mm (Carr and Stephens, 1992). Occasionally, severe damage from hail occurs and results in losses in yield of 10 to 30% (Othieno et al., 1992). In regions where rainfall is less than 1,150 mm per annum and having long and hot dry spells, irrigation is recommended (Carr and Stephens, 1992).

Temperature

The rate at which tea flushes depends on temperature. Tea will grow under a wide range of temperatures provided that frost does not occur. Different workers report different ranges for optimum temperatures, i.e. while Tanton (1982a) gives the optimum as from 18 to 20 °C, Carr and Stephens (1992) have a wider range from 18 to 30 °C. For growing shoots, there are two important stages, shoot development and extension and each has a base temperature that is cultivar dependent and varies from 7 °C (Obaga et al., 1988) to 14 °C (Stephens and Carr, 1990). However, it is noted that day-time temperatures above 30 °C and night-time temperatures below 10 °C lead to reduction in the rate of leaf growth. Some cultivars like the *sinensis* varieties can however tolerate lower temperatures. In the CUPPA-tea crop growth model, Matthews and Stephens (1998a) use a base temperature for shoot development and extension of 8 °C and 10 °C, respectively with an optimum of 24 °C. Soil temperatures have also been suggested as an important variable for tea yield where shoot extension rates are reduced at soil temperatures (30 cm depth) of 16 °C and below (Carr and Stephens, 1992).

Radiation

Solar radiation (sunshine) is an important factor; the tea plant requires on average at least five sunshine hours per day (17 MJ d^{-1}). Tea yield drops significantly under cloudy conditions and with heavy and continuous rainfall, just like it does when the weather is hot, dry and sunny. For solar radiations above 350 W m^{-2}, Squire (1977) observed that single top leaves are photosynthetically light saturated while whole canopies require 700–800 W m^{-2}, a value equivalent to full sunlight in the cooler seasons of many high latitude tea areas, and about 75% of full sunlight in the warmer rainy seasons. Like in all green plants, only a very small proportion of the net available solar energy is used in the process of photosynthesis and the rest is dissipated as either latent heat or transpiration. The atmospheric humidity must be high between 70 and 90%, as shoots tend to form dormant ‘banjhi’ buds when the air is too dry. High atmospheric humidity is particularly valuable during dry seasons and when the annual rainfall is low. It is favoured by permanent shade, windbreaks, or by irrigation through spraying. Wind can damage the tea plant when it lowers the atmospheric humidity and in such exposed areas, protection by a screen of trees or an edge line of tea bushes left to grow freely is essential.

Altitude

Altitude and topography are important considerations for tea production and call for different cultural practices. In India and Indonesia, tea is grown from almost sea level while in Kenya tea grows to over 2,200 m above mean sea level. The rate of growth at high elevations is markedly lower due to lower temperatures, but these conditions are ideal for production of tea with high quality (Odhiambo et al., 1988; Owuor et al., 1990a; Robinson and Owuor, 1992).

Biotic factors

Pests

Leaf destroying pests result in weakening of the tea bush and in an immediate loss in crop production. Important pests are categorized as leaf and shoot feeders, stem and branch pests, soil pests and seed pests. The leaf and shoot feeders are the crucial pests in terms of yield reduction and include, mosquito bug (*Helopeltis* spp.), thrips (*Scirtothrips* spp.), mites, aphids (*Toxoptera* spp.), scale insects, caterpillars, and weevils. These pests are capable of causing phenomenal losses in crop yields; up to 55% annual loss by mosquito bug has been recorded in Central Africa (Rattan, 1984), while a yield loss of 30% has been reported due to spider mites in Kenya (Sudoi, 1995). The other categories of pests are not serious in mature tea and are easier to control with spot applications of insecticides using ultra low volume technology to minimize discharge. The chemical treatments are carried out during pruning periods, i.e. control of carpenter moth (*Teregra quadrangular*), termites, and cockchafer.

Fungal diseases

Most common diseases in tea plantations are caused by fungal pathogens which infect various parts of the tea plant. The economically important ones are: root diseases, stem diseases and leaf diseases. Root diseases occur wherever tea has been planted on land after clearing forests or shade trees without proper ring-barking. The diseases destroy the roots so that supplies of water and nutrients are restricted. This causes leaf wilting and defoliation above-ground and finally death of the bush. The most common is the *Armillaria* fungus. Once established root diseases are difficult to eradicate and appropriate control measures to identify and remove affected bushes in the field in the early stages is important (Onsando, 1997). Other effective methods that have been tried to control *Armillaria* are the use of *Trichoderma* species (Onsando and Waudo, 1994; Otieno, 1998) and soil solarization (Otieno, 2002).

Stem diseases are caused through infestation of pruning cuts. These offer an easy entry to fungal pathogens thus reducing the growth of the bush frame or even killing the entire bush. Preventive measures are therefore important especially during pruning periods (Otieno, 1997). The most common diseases are: stem and branch cranker (*Phomopsis theae*), and wood rot disease (*Hypoxylon serpens* and *H. investiens*).

Leaf diseases have a direct effect on the tea crop and are easily observed when the tea is being plucked. The severity of the disease is influenced by high moisture levels and is more serious when plants are recovering from prune. Its control, therefore, is to keep the maintenance foliage free from any disease and especially during the pruning period. The most common leaf diseases are grey blight (*Pestolotia* spp.), brown blight (*Colletotrichum camilleae*), anthracnose (*C. theae-sinensis*), and net blister blight (Keith et al., 2006).

Nematodes

Root knot nematodes, *Meloidogyne javanica, M. incognita, M. brevicaua* are widely distributed nematode species in tea plants, especially in India where tea has been grown for a long period of time (Glover, 1961). The first two species affect tea seedlings in the nursery and the third one affects mature tea. The infested seedlings are not always killed outright, but patches are found to be stunted, wilted, chlorotic or generally unhealthy. Sometimes root tips are devitalized and their growth is arrested. Such damage impairs root-spread, and the ability of the plants to take up moisture and nutrients is reduced. The roots of tea when infested with *M. incognito* tend to form very small galls that look like beads on a string. The infestation is generally very severe between the months of June and August in north-east India. To control nematodes in mature tea in India, neem cake is applied at the rate of 2 kg per bush and mixed with the soil (UPASI, 1987). In young tea, marigold (*Tagetes erecta*) can be grown around the tea bush (Katikarn and Swynnerton, 1984).

Management practices

Plant density

In most tea-growing countries, tea bushes are planted at spacings between 60 cm by 120 cm and 90 cm by 150 cm representing population densities of 13,448 and 7,692 bushes per hectare, respectively. The low density plantings adopted in East Africa up to the 1970s were partly dictated by costs and management problems with the belief that cultural practices like pruning and tea pluckers movement were expensive or difficult (Magambo, 1981). This has changed with the introduction of mechanical pruning as opposed to the pruning knifes. The planting is done in such a way that natural contours of the landscape are followed; sometimes, bushes are grown on specially prepared terraces to facilitate irrigation and to prevent erosion. The optimum plant spacings have been derived from expert knowledge on past plant populations and from field experiments in different countries. In Assam, dry matter yield per bush during the first six years increased with available space per bush with an average of 0.38 kg for the 60 cm by 120 cm spacing compared to 0.67 kg in a 120 cm by 120 cm spacing (Katikarn and Swynnerton, 1984). The closer spacing of 60 cm by 120 cm was found to give superior yields to other population densities in Kenya, but competition for moisture affected yields negatively during the drier months (Bore et al., 1998). However, the final conclusion was that the closer spacings will give higher annual yields per unit area (ha) in the earlier years but the yield differences will gradually diminish with age of the tea plantation.

Tea bush management: frame formation and pruning

In the field, the tea plants are trimmed into a permanent frame which is low, broad, heavily branched and capable of producing a large number of shoots, culminating in high yields in a process known as “bringing tea into bearing”. Care is taken not to force high yields too soon as this could damage the tea plant and prejudice the shaping of a solid branch frame and a strong root system, essential for high yields (Barbora, 1984; Yamashita, 1994). The plucking table rises inevitably from season to season, generally by 5 to 10 cm depending on the harvesting method. After several seasons, the plucking table rises too high to be easily harvested. Twigs form and the yields fall. It is therefore necessary to prune the plants to reduce the height and keep the tea bush within easy reach of the tea pluckers, renew the maintenance foliage and keep yield at a high level. The period for such maintenance pruning varies depending on the climatic conditions, type of vegetative material planted, and method of plucking. Pruning causes a considerable stress on the tea bushes. Recovery after pruning depends on the state of health of plant, amount of reserves present and on the process of ageing (Mwakha and Anyuka, 1990; Bore et al., 2003). In some countries/regions like Vietnam (Zeiss and denBraber, 2001) and North India (Willson, 1992b), pruning is done every year. However other countries/regions like Sri Lanka (Nissanka et al., 2004), East Africa (Ng'etich, 1996; Mwakha, 1997) and southern India (Sharma and Satyanarayana, 1994) have three to six year pruning cycles depending on the altitude. Skiffing is normally light pruning and involves removal of the green wood at about 15 cm above the pruning height and has been found to prolong the pruning cycle in Sri Lanka (Nissanka et al., 2004). After the tea plantation becomes less productive or degraded due to a combination of factors like many gaps due to bush deaths, thin and diseased branches, shoots at the base or sprouting from the soil, etc., rejuvenation pruning is recommended. This involves low pruning to remove as much unproductive bush frame as possible, removing any remaining and diseased parts of the bush, removing and replanting dead or unproductive bushes and improving soil to favour quick re-growth of shoots of feeder roots (Zeiss and denBraber, 2001). The decision to carry out rejuvenation pruning thus rests on the degree of disease infection and missing bushes. In Kenya, however, this system of managing degraded tea was found not effective due to the poor establishment and performance of the infills (Mwakha, 1989).

To maintain soil fertility and protect fields from erosion, the prunings are never removed from the field (Othieno, 1981). The prunings are also used to cover the tops of the tea bushes from sun scorch and damage caused by frost and hail. Since the pruning exercise removes all the foliage thus reducing the capacity of the tea bush to photosynthesize, the most convenient time to perform the pruning operation is when the starch reserves in the roots are high for fast recovery. The mid dry-warm season fortunately corresponds with the period when the bush is also not yielding highly.

Tea nutrition and manuring

Under normal conditions, the tea plant takes all the nutrients it needs from the soil, apart from very small quantities of nitrogen and other elements that may be absorbed by the leaves from air and rainwater. Continuous cropping rapidly exhausts the soil of its mineral supply, thus reducing plant growth and hence profitable yields. Also a possible imbalance in the relative supply of nutrients by the soil may disrupt the growth rate of the tea plant.

The main nutrient elements removed from a tea plantation via harvested tea are nitrogen (N), phosphorus (P) and potassium (K). The most important component is incurred by the inevitable removal of the young shoots. The amounts removed (kg) from the tea bush via plucking for the three major nutrients, N, P and K, are shown in Table 1. The quantities vary from one tea-producing area to another, the type of

Table 1. Macro-nutrient removal (in kg) per 1000 kg made tea.

Nitrogen (N)	Phosphorus (P)	Potassium (K)	Reference
40.2	3.7	13.3	Eden (1952)[1]
40.0	1.7	15.8	Othieno (1979a)
41.5	3.3	21.6	Tandon (1993)

[1] In Bonheure and Willson (1992).

cultivar and type of plucking. For example, the type of leaf to be plucked is determined by the factory management based on the processing method, capacity and type or grade of tea required. Thus, some regions only practice fine plucking standards where only the first two leaves and the auxiliary bud are accepted, while coarse plucking accepts more than three leaves and bud (TRFK, 2002). N-removal by plucking ranges from 40 to 160 kg N ha^{-1} assuming made tea yields of 1 to 4 t ha^{-1}.

The amounts of nutrients returned to the soil by prunings are presented in Table 2. Except for the thick wood organs which have a wide C:N ratio, other organs of normal prunings or regrowth that comprise foliage and twigs have relatively low C:N ratios and decompose readily giving relatively large quantities of mineralized N, P and K in the prune year (Ranganathan, 1973). In a normal pruning cycle once every three to five years about 4 t C ha^{-1} and 350 kg N ha^{-1} in the regrowth foliage and twigs is added to the soil surface (Table 2). The quantities of P and K in the regrowth amount to about 40 and 90 kg ha^{-1}, respectively. Thus, prunings contribute to a flow of nutrients in tea ecosystems.

Macro-nutrient uptake in tea varies between genotypes. Different regions often use different types of leaves to predict the tea bush nutritional status. Thus while the first mature leaf has been observed to be sensitive and a good predictor for most macro-nutrient deficiencies in East and Central Africa (Tolhurst, 1976; Othieno, 1988;

Table 2. Amounts and nutrients in tea prunings[1] (kg ha^{-1}). Source: Ranganathan (1973).

Plant organ	Dry matter (t ha^{-1})	C (t ha^{-1})	Nutrients (kg ha^{-1}) N	P	K	C:N ratio
Foliage	7.2	2.9	252	30	72	11
Twigs	3.6	1.4	85	10	21	17
Secondary wood	4.2	1.8	44	13	13	40
Primary wood	9.6	4.2	101	28	2	42

[1] Based on rejuvenation pruning that removes part of the woody stems. It is more severe than normal maintenance pruning.

Table 3. NPK fertilizer formulations for young and mature tea plantations in different tea-growing areas (after Bonheure, 1990).

Region	Fertilizer type	
	Young tea plants	Mature tea plants
East Africa	Ammonium sulphate, NPK(S) 25:5:5:5	NPK(S) 25:5:5:5
India	NPK 10:5:10	NPK 10:2:4
Sri Lanka	NPK(Mg) 10:8:8:3 and 14:4:8:2	NPK 28:5:14
Zimbabwe	-	NPK 25:5:5, Ammonium sulphate

TRFCA, 1990) the same mature leaf has only been found sensitive for phosphorus nutrient in Sri Lanka (Sivapalan et al., 1986) and potassium in South India (UPASI, 1987). Thus, the younger second, third or fourth leaves and even their ash are used in countries like India, Indonesia, Taiwan and USSR (Ranganathan, 1998). Nitrogen, phosphorus and potassium nutrient contents in leaves based on dry matter thus vary within the ranges 2.5–5.0% N, 0.4–1.1% P, and 1.6–3.0% K, respectively (Ranganathan, 1998). For determining the fertilizer requirements, losses such as leaching should be taken into account. The fertilizer formulations used for mature tea in different tea-growing countries are summarized in Table 3.

The doses are normally dependent on the age of the tea plantations and also vary from place to place. For example, in Kenya, the recommended N-dose amounts to 80 and 100–250 kg ha^{-1} in the first three years after planting and thereafter, respectively (Othieno, 1988). Hence, upon maturity (after the third year) the fertilizer composition/ formulation and rates remain the same. The tea industry in Kenya experienced problems caused by the use of straight N-fertilizers especially high rates of ammonium sulphate from the 1940s to the mid 1960s. Deficiencies of the other nutrients (P and K) started to be noticed (Othieno, 1994). This led to the introduction of compound NPK(S) formulations in 1967 that are still in use to date. However, the high rates previously applied in tea have been reduced to the currently recommended levels of 100–250 kg N ha^{-1} (Othieno, 1988).

The other nutrients removed from the tea plantations (in relatively smaller quantities) are the macro-nutrients sulphur, magnesium and calcium, and the micro-nutrients iron, manganese, boron, copper and zinc. With proper and timely monitoring of the tea plants nutrients status, remedial applications of some of the nutrient elements can be successfully done. For removing aluminium and manganese toxicity, application of liming materials may be required.

The use of external inputs in tea cultivation, e.g. acidic fertilizers, organic manure or liming material, is high and therefore, a continued monitoring of the soil and plant nutrient status for early problem diagnosis to take corrective measures is required. High nitrogen doses in mature tea for example results in the accumulation of theanine in the roots (Devchoudhury and Bajaj, 1988) which can lead to the destruction of the feeder root system. Long-term tea (mono)cropping has also been implicated for "soil sickness" caused by a combination of soil pathogens, mineral depletion, change in soil structure and accumulation of toxic substances, amongst others (Owuor, 1996; Fageria et al., 1997). This may lead to physical, chemical and biological soil degradation and ultimately to a decline in yield of the older tea plantations.

Tea harvesting

The tea plant grows in two phases, the productive growth or 'flushing' period and the dormant or 'banjhi' phase. Thus when the terminal leaf of a shoot reaches its maximum development, a small bud, 5 mm in length appears. At this point the shoot seems to be dormant, but the bud gradually swells and paves way for the next growth phase when the shoot grows. The rate of growth differs from one shoot to the other and varies according to climate, cultivar and type of plucking (Ellis and Grice, 1976; Tanton, 1979). Plucking is the periodic harvesting of the young shoots, normally a bud and two to three leaves, above the plucking table and is either done by hand or mechanically. This aims at striking a balance between yield and quality normally found in greater quantities in the young shoots. The growth phase, 'flushing' period, varies from 50 to 80 days depending on the altitude of area. The distribution of these days is as follows: swelling of dormant leaf, 51%; formation of pre-leaf, 30%; and, formation of the bud and two leaves, 19% (Karanuki, 1988).

To maximize on crop productivity, pruning and plucking must be synchronized, hence the pruning exercise is done either when the crop productivity is low as in the colder months, or when an impeding drought is expected thus lowering the transpiration of bushes. Both pruning and plucking stimulate the flushing of re-growth. The growth periodicity, flushing and dormancy hold both for plucked and unplucked bushes. The repeated removal of shoots stimulates the production of new shoots that tend to mask dormant periods. Shorter plucking intervals of 7–10 days in Kenya result in optimum yields and black tea quality (Owuor and Odhiambo, 1993).

Problem description and research objectives

Younger tea plantations have been associated with higher productivity in most tea-growing regions (Sivapalan, 1994; Illukpitiya et al., 2004). Since the early 1980s, some of the older tea plantations in Kenya were reported to stagnate and/or decline in yields and did not respond to known agronomic practices (Mwakha, 1989). The old tea fields were comprised of old tea bushes (over 40 years) that were weakened and had gaps (over 25% open spaces). As yet the cause of the weakening is unclear and has been indicated that some tea plantations of the same age were still productive (Mwakha, 1983; Bore, 1996). In 2006, about 20% of tea plantations in Kenya were 40 years and above and this percentage increases rapidly over time.

Suitable land for tea growing is getting exhausted due to pressure of more lucrative enterprises and tea growers have to rely more on uprooting some of the unproductive tea plantations and replant with better yielding cultivars, or expand into areas that are considered marginal for economic tea production. Other resources like availability of newly released clonal plants that are more suited to harsh environmental and tolerant to biotic factors will also encourage tea expansion and replanting. Managers of tea plantations are also faced with many questions when confronted with ageing tea plantations. Some of the questions are:

- Will the replanted tea give better returns than the current seedling tea?
- How long will it take to break even?
- Supposing the replants do not perform as well as the current seedling tea?
- What is the right age to uproot and replant? etc.

It is desirable to avail some management tool to give answers to such questions. Other notable agronomic and cultural practices that have evolved include: better pruning strategies and methods during frame formation and in mature tea that fastens recovery and reduce die-back; leaving of tea prunings *in situ* to encourage nutrient cycling; and, planting of better yielding clonal tea plants that can also withstand some biotic and abiotic stresses. All these factors are confounded in tea agro-ecosystems.

To gain a better understanding on how productivity and resource use of tea agro-ecosystems is influenced by factors associated with ageing, focussed studies based on Kenya's tea production data and a tea stand chronosequence consisting of two genotypes were used. Besides the analysis of statistical data and scenario analysis using a simple model, experimental studies were used to unravel the complexity in scale and time of yield determining and limiting factors in ageing tea plantations. The clonal tea used in the study (TRFK 6/8) is the most widely grown clone in Kenya accounting for 60% of the smallholder tea sector, while 72% of the estate plantation sector grow the seedling genotypes.

The objectives of the study were:

- To review and analyse factors associated with productivity trends in the estate and smallholder sectors and, explore options for alleviating yield stagnation and decline in ageing tea plantations;
- To study the response of tea bushes to N application rates in relation to age and genotype in association with plant density;

- To analyse the dynamics of nutrient removal by plucking in consecutive seasons, and explore options for improving N-management in relation to yield and N-losses;
- To determine temporal dynamics in standing biomass and dry matter partitioning in tea bushes varying in age and associated genotype and population density;
- To determine the stocks of carbon (C) and nitrogen (N), phosphorus (P) and potassium (K) in ageing tea plantations and thereby assess their consequences on crop productivity and ecosystem stability;
- To assess changes in soil characteristics as a possible feedback of degradation in ageing tea plantations.

Definition of terms as used in this thesis

Ageing of a tea plant/bush: The physiological state of a tea plant/bush at any time which influences its productive capacity. It is based on the length of time the tea plant/bush has been in existence since planting.

Clones: Tea plants that are derived from one bush (a mother bush) by a method of vegetative propagation. They therefore have the same genetic constitution adapted to specific environmental and cultural conditions which determine the yield potential.

Cultivars: A variety of a plant that has been purposely selected and maintained through cultivation, i.e. culti(vated) + var(iety). They differ from others of the same species in minor but heritable characteristics, e.g. clone TRFK 6/8. Cultivars are normally registered and protected under law.

Degradation: The deterioration in quality, level, or standard of performance of a functional unit. The main consequence herein is in reduction of tea yields. Units: fraction yr^{-1}, depending on scale, e.g. ha ha^{-1} yr^{-1}, number $number^{-1}$ yr^{-1}.

Genotype: The genetic constitution that is distinct from its expressed features. For ease of readership the ‘seedlings’ and ‘clones’ herein are categorized as belonging to different ‘genotypes’.

Jat: The provenance or place of origin of a tea plant. *Jat* may refer to a particular type or a particular seed orchard (from an Assamese word).

Productivity: A measure relating a quantity or quality of output to the inputs required to produce it in time and space. Consideration is given to both economic and ecological benefits.

Resource: The means available to grow tea; i.e. tea plant (genotypes), soil constituents, weather (temperature, water, radiation, etc), and farm inputs (fertilizers, labour).

Seedlings: Tea plants that are derived from seeds, consisting of a broad spectrum of genotypes. Generally more adapted to adverse growing conditions.

Outline of the thesis

Chapter 1 is the general introduction, presenting some background on tea (*Camellia sinensis* L.) agro-ecology; its origin and distribution, and factors that affect tea productivity and ageing. Finally, the general introduction provides details of the problem description and research objectives, an outline of the thesis, definition of terms used in this thesis and, the limitations of and constraints to the experimental work.

Chapter 2 covers a literature review on factors and processes that are related to ageing of tea plantations. Tea yields and area data from the two main sectors of the Kenyan tea industry are analysed to show the extent of the ageing problem. A simple model for Managing Ageing Plantations of Tea (MAP-Tea) is developed as a tool for research to identify promising interventions for tea productivity improvement.

Chapter 3 covers the results of field experiments in tea plantations differing in age, genotype and planting density and their productivity and nitrogen use in terms of total N-uptake and apparent N-recovery. It explores options for improving N-management in relation to yield and N-losses.

In Chapter 4, carbon and nutrient (NPK) stocks in ageing tea plantations are evaluated as a measure for storage in the whole tea plant, an important factor in nutrient budgeting and hence crop yield stability and C sequestration.

Chapter 5 reports on changes in soil characteristics as a possible feedback of degradation in ageing tea plantations using results of aerobic incubation studies and analyses of soils sampled from a natural forest and a tea chronosequence.

Chapter 6, which incorporates the general discussion and conclusions of the study, gives a synthesis of the results of the different chapters of the thesis.

Limitations of and constraints to the experimental work

For a perennial crop like tea, it is important to use long term experiments to resolve most of the agronomic issues. Tea is highly demanding in terms of external inputs because of the high nutrient removal from the harvested crop. Therefore, all field experimental sites were selected based on a known history of the tea plantations and the field data for the purpose of the thesis work collected for three consecutive years. The selected sites comprised a chronosequence of tea plantations planted in 1988, 1973, 1959 and 1926, on one soil type and with similar cultivation history. Cultural practices adopted to maintain the tea bush to an acceptable height like pruning and subsequent return of the pruning’s mulch every three to five years introduces another important nutrition factor. This implies that past application of inorganic fertilizers and last pruning may still have significant residual effects even after several years. In this study, although the sites were selected such that they were all pruned within the same period and last fertilizer had been applied at least three months prior to demarcation of the trial plots done in December 2001, this could introduce some error. However, to reduce such errors, the first 10 months (January 2002 to October 2002) were used to monitor the individual plot tea yields before introducing the fertilizer treatments in November 2002 and subsequently in November 2003. Analysis of the 10 months individual plot yields showed no significant differences ($P<0.05$) within plots, hence a normal one-way ANOVA was used in yield data analysis per site.

Seasonal and annual yield responses due to N-fertilizer application and N-uptake and recovery were studied over a period of two years. The study sites were also used to estimate carbon and nutrient (NPK) stocks and also test the extent carbon and NPK may accumulate in tea plantations with the age class. The latter study was limited to uprooting and partitioning of randomly selected individual tea bushes in terms of dry mass of the organs and their nutrient contents.

With time, plant population density or spacing has been changing arising from technology development. Similarly, there has been a shift in genotype choice from the seedling varieties to clonal plants that are improved cultivars with better attributes like yielding, quality, and tolerance to drought, pests and diseases. Prior to the 1970s wider plant spacings resulting to low population densities (LD) often below 8,000 plants per ha were used partly due to high establishment costs and management related problems. However, the 1970s saw the introduction of clonal cultivars at closer spacings, or high density (HD) of greater than 10,000 plants per ha across the Kenyan tea industry. Subsequently, most tea planted after the 1970s have a density ranging from 10,000 to 14,000 plants per ha. This resulted in introducing genotype choice confounded by planting density as a second factor on top of ageing which is covered in Chapters 3 and 4 of this thesis.

CHAPTER 2

Productivity and prospects of tea production in Kenya: Data analysis and scenarios

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Abstract

The current tea industry plays a significant role to the Kenyan economy and contributes 25% of the country's export earnings and 4% of the Gross Domestic Product (GDP). Tea farming is a stable long-term rural based enterprise that provides livelihood to over three million Kenyans along the value chain. The vibrant industry is characterized by two sectors that have different structures: estate plantations established in the early 1920s with production units larger than 20 ha and, smallholders established after independence in 1964 with smaller units averaging only 0.25 ha per farmer.

Tea production trends of the two main sectors of the Kenyan tea industry were analysed, and factors that contribute to their performance in relation to ageing of tea plantations reviewed. The analysis showed stagnation of total tea production in the estate plantations sector at ~120,000 t yr^{-1}, whereas the smallholder sector continued to increase the production. Over the last three decades from 1972 to 2006, yield levels varied from about 1.7–3.7 t ha^{-1} in the estate plantations and from about 0.7–2.3 t ha^{-1} in the smallholder sectors, respectively. The total area under tea increased from 23,300–51,300 ha and from 26,500–95,800 ha in the estate plantations and smallholder sectors, respectively over the same period. However, yields in the estate sector have remained stagnant and/or declined during the last decade, whereas the smallholder sector has continued to experience a steady rise in both yields and area, though made tea yields per ha are still lower than in the estate sector.

Scenario analysis using a simple decision-support (DS) model showed that replanting is vital if tea productivity in the ageing tea plantations is to be improved. Estimated net returns will double by replanting with high-yielding clonal cultivars within a period of 20 years. Further improvement of tea productivity in both sectors should take into account Genotype × Environment × Management (G×E×M) relationships. Based on a better understanding of factors that determine yield, the right strategic and tactical management decisions can be made. It is recommended that before large scale uprooting programmes are implemented, soil quality assessment and genotype screening need to be carried out.

Keywords: *Camellia sinensis* L., tea industry, estate plantations, smallholder farms, management, made tea yield, ageing.

Introduction

Tea, *Camellia sinensis* (L.) belongs to the plant family Theaceae. Cultivated tea varieties are natural hybrids of the original tea species *C. sinensis* (L.) O. Kuntze, *C. assamica* (Masters) and *C. assamica* subsp. *lasiocalyx* (Planchon ex Watt) (Mondal et al., 2004). The variety *sinensis,* also called 'China tea' is suitable for growing in marginal areas of the subtropics and is more drought-tolerant and can survive short frost periods. The variety *assamica* also called 'Assam tea' is a tropical variety sensitive to dry and cold weather conditions (Banerjee, 1992b). The tea plant in its wild state can grow up to 15 metres tall and has a taproot to oblique root system (Bonheure, 1990).

Tea grows on a wide range of soils of different geological origin, but for economic cultivation, specific characteristics must be met. Soils need to be well drained and deep with a minimum depth of two meters, and having and aggregated or crumb structure with about 50% pore spaces (Othieno, 1992). Soil acidity (pH) is a critical chemical characteristic with optimum values between 4 and 6 in both top soil and subsoil layers. The upper limit of the pH varies with the nature of the soil, especially the clay content and organic matter, and is considered as 5.6 in East Africa (Anonymous, 1986) and 6.0 in southern India (UPASI, 1987). The lower pH limit is not well defined. Liming of acidic mature tea stands has been tried, but often has resulted in decreases of tea crop yields, which has been associated with low potassium uptake (Othieno, 1992).

In most tea-growing areas, younger tea bushes have been associated with high productivity and conversely, old tea bushes with declining productivity (Illukpitiya et al., 2004). Since the early 1980s, some of the older tea plantations in Kenya were observed to stagnate and/or decline in yields and did not respond to known agronomic practices (Mwakha, 1983; Mwakha, 1989). The tea industry in Kenya has experienced changes in the manuring practice from the use of straight N-fertilizers especially sulphate of ammonia at high rates of about 400 kg N ha^{-1} in the 1960s which led to lack of yield response due to potassium deficiency, to the currently used compound NPK(S) formulations introduced between 1967 and 1969 (Othieno, 1994; Wanyoko, 1997). Thus, the leap in yields in the estate sector from 1000 to 2000 kg made tea ha^{-1} in the mid 1970s was attributed mainly to the use of NPK compound fertilizers although improvement in tea husbandry practices like non-removal of prunings and herbicide weeding also played an important role (Wanyoko, 1997).

Under cultivation, tea is managed so as to maximize the production of young tender leaves that form the useful product. Quality restraints restrict the size of shoots that can be harvested to young ones with up to three leaves. In manual harvesting, the shoots are harvested at intervals ranging from one to three weeks while longer periods of up to seven weeks are observed in mechanical harvesting (Bore and Ng'etich, 2000). Harvesting frequency is influenced mainly by air temperature and the rainfall distribution under rainfed conditions in the tropics (Othieno et al., 1992).

Yields of crops are determined mainly by the strength of the sources or sinks (source-limited or sink-limited). In the past, attempts were made to correlate photosynthesis and associated factors (radiation interception, canopy light interception, leaf area index, base temperatures) with crop yield, using un-harvested tea bushes as controls (Squire, 1977). Interpretations of the results were wanting since climatic conditions that increase photosynthesis also favour shoot growth. It was concluded that yield is limited by management practices, since the tea plant can produce high yields if the sink strength (two leaves and a bud) is not limited by harvesting practices. Unlike many source-limited vegetative crops, tea growth is sink-limited (Tanton, 1979). Thus, yield is determined by the growth characteristics of the shoots in terms of rate of extension, mass and number per unit area and factors that influence them (Matthews and Stephens, 1998a). Sources and sinks are functionally related and tea plucking removes part of both components (Magambo and Cannell, 1981). Knowledge of potential yields, defined as yields that can be obtained when factors such as water, nutrients, and pests and diseases are not restricting the growth of the crop, is important. Tea managers want to know the potential yield of a particular site is in order to take appropriate actions and improve on actual yields. Factors such as temperature, sunlight, daylength, and genotypic characteristics affect the potential yield (Corley, 1983). 'Yield-gap' analyses show that if there is only a small difference between the potential yields and actual yields, then any resources spent to improve yields are likely to be wasted (Matthews and Stephens, 1998b). On the other hand, if there are large differences between potential and actual yields, then it is possible to improve management practices provided that the factor(s) limiting the yields are correctly identified. Factors documented to limit yield include: removal of young shoots (Tanton, 1979), air temperature (Tanton, 1982a; Carr and Stephens, 1992), soil temperature confounded with dry air (Tanton, 1982a; Othieno et al., 1992; Odhiambo et al., 1993; Chen and Fong, 1994; Nixon et al., 2001); hail (Ng'etich et al., 2001; Othieno et al., 1992), daylength (Tanton, 1982b), and solar radiation (Squire, 1977).

Generally, age classes of tea plantations can be described as: *young tea,* normally assumed to be tea soon after field out-planting and the first pruning; *mature tea,* normally after the first pruning until the yields show signs of stagnation; and, *old tea,* that shows stagnation/decline in productivity, hence becomes uneconomic. Unfortunately, it is difficult to determine when stagnation or decline in tea productivity starts since the phenomenon is confounded with strategic and tactical management decisions by the farmer. Often, the farmer gives more attention to sections of the tea farm with the highest yields, hence returns.

The development of the tea plant is defined by four growth stages: the *seedling or cutting* stage, the *frame formation* stage, the *mature/commercial* stage and, the *degraded/moribund* stage (Zeiss and denBraber, 2001; TRFK, 2002). The duration of each growth stage is determined by the genotype and growing conditions. Seedling plants take 2 to 3 years to germinate and grow, using the starch and oil in the seed for energy. Vegetatively propagated cuttings take about one year in the nursery and require careful tending until the roots and shoots are well developed. The frame formation stage starts with the first tipping of the apical dominance and ends at the formation pruning stage. Tipping shapes the way the main frame of the large branches grow so that the bush develops strong and big branches with a large canopy capable of producing many shoots. Plucking table is usually established at 70 cm height. Although the bushes require nitrogen (N) and other essential nutrients for growth of stems, leaves and increased branches at this stage, a trade off in N-fertilization is required since depriving of N to young tea plants increases assimilate partitioning towards the roots at the expense of the shoots, hence developing a better and deeper root system that is desirable (Anandacoomaraswamy et al., 2002). Mulching is useful especially before ground cover is attained. The frame formation stage takes 18 to 36 months depending on cultivar, weather, altitude, cultural practice and management. The commercial/mature stage begins after the first pruning and continues for as long as the tea bush is growing vigorously. The highest yields are usually attained in this phase, hence it is most profitable. Regular pruning is performed periodically to maintain bush size in pluckable height and to keep the growth vigour of the plant in a condition most conducive for maximum vegetative production. In most tea-growing countries, this is done after 3 to 5 years depending on plucking intensity and subsequent rate of the plucking table rise. The degraded/moribund stage is associated with several problems, including; low yields, gaps in tea fields due to death of weak and diseased branches, high rate of above-ground and root diseases, increase in the proportion of unproductive tissues in the tea plants, few and small buds and crown buds, and many shoots at the base of the bush. These problems may be caused by poor management rather than the actual age of the tea bush. Normally, when tea plantations become degraded/moribund, rejuvenation pruning close to the ground to grow completely new frames of young healthy branches or uprooting and replanting are recommended (Willson, 1992a; Zeiss and denBraber, 2001). Hence, even with rejuvenation pruning, some degraded/moribund tea plants continue to produce low yields.

The objectives of this study were to review and analyse factors associated with productivity trends in the estate and smallholder sectors of the Kenyan tea industry and, explore options for alleviating yield stagnation and decline in ageing tea plantations.

Analyses of trends in tea production

Tea industry in Kenya

Kenya is the third largest producer of tea in the world after China and India (ITC, 2006). The country specializes in black tea production and processing. Unlike other leading tea producers, Kenya relies mainly on the export market where 95% of the total tea produced is sold in bulk accounting for over 20% of the global market (ITC, 2006). Currently, tea is the second leading foreign exchange earner and export commodity amongst agricultural produces after the horticulture industry. Tea-growing areas are divided into two regions defined by the Great Rift Valley, which is a natural geographical phenomenon that divides the country almost asymmetrically; the Aberdare highlands, Mt. Kenya region and Nyabene hills forming the East of Rift block, and in the west of the Rift block comprising of the highlands of Mau escarpment around Kericho, Nandi Hills, Mt. Elgon and the Kisii highlands (Figure 1).

Kenya's actual average tea yields per unit area basis were the highest in the world in 2005 at 2,350 kg made tea ha^{-1} (Table 1) in 2005. Whereas some countries like China have increased the land under tea with a growth rate of 19.2% between 2002 and 2005, some other countries like Indonesia, Taiwan and Zimbabwe have been uprooting tea and probably replacing these areas with other alternative crops. Kenya on the other hand has exhausted the good areas for tea expansion and aerial growth was only 1% between 2002 and 2005. Tea production in Kenya is characterized by two sectors often having different structures; estate plantations with production units larger than 20 ha, and smallholder production with smaller units averaging 0.25 ha per farmer. When well-managed, the crop can remain in production for over 100 years although productivity gradually declines over time. This means that unlike annual cropping systems, tea plantations require long-term investment in activities that are influenced by political and socio-economic factors at various levels. For instance, fear of nationalization may induce estate plantation owners to discount long-term investment as risky and opt for short-term profit maximization strategies. Similarly, land tenure systems can affect smallholder tea farms due to ownership wrangles or family land fragmentation through inheritance. Furthermore, a combination of rising

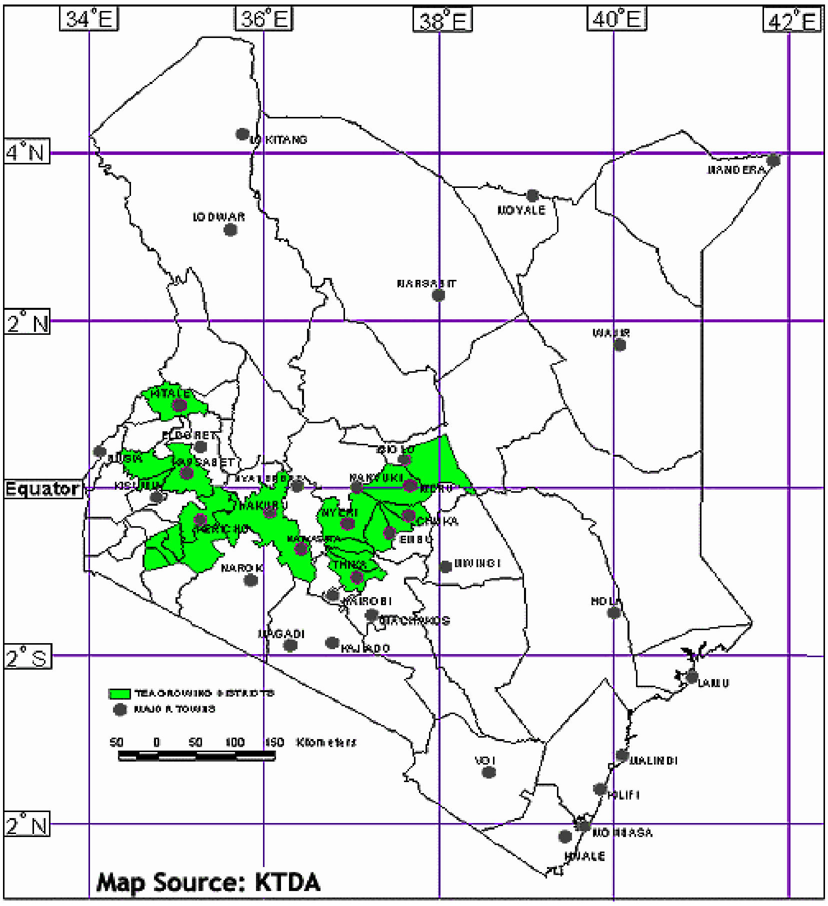

Figure 1. Tea-growing regions of Kenya.

production costs, stagnating/ downward trend in prices, and higher opportunity costs of capital may discourage transitions and long-term investment (Iqbal et al., 2006).

Estate plantations (KTGA) and smallholders (KTDA) sectors in Kenya

Tea in Kenya was introduced in 1903, but commercial cultivation did not start until 1924 by the estate plantations sector, under the umbrella of Kenya Tea Growers Association (KTGA). The smallholder sector, managed by the Kenya Tea Development Agency (KTDA) formerly Kenya Tea Development Authority was started in 1964 after Kenya gained her independence. Currently, the estate plantations comprise of 18 private companies running 39 tea-processing factories, while the smallholder farmers number over 400,000 and have 57 black tea-processing factories situated within the tea-growing zones (TBK, 2007). The KTGA sector has large plantations which are intensively managed by trained personnel while the farmers in the smallholder sector rely on a limited number of agricultural extension staff who offer advisory service in managing their small tea fields that average 0.25 ha per farmer (Ogola and Kibiku, 2004).

Table 1. Tea production figures and area in major tea-growing countries in 2005 (source, ITC, 2006).

Country	Amount in 1000 metric tons	Area under tea in ha		% change in tea area	Yield in kg made tea ha^{-1} 2005[1]
		2002	2005		
China	935	1,134,200	1,351,900	19.2	824
India	928	515,832	523,000	1.4	1,799
Kenya	329	139,976	141,315	1.0	2,350
Sri-Lanka	317	187,971	188,480	0.3	1,686
Indonesia	166	150,723	142,782	–5.3	1,163
Turkey	135	76,600	78,000	1.8	1,762
Vietnam	109	85,000	91,000	7.1	1,282
Japan	100	49,700	50,000	0.6	1,690
Argentina	73	36,600	36,900	0.8	2,012
Bangladesh	59	49,500	51,000	3.0	1,192
Malawi	38	18,800	18,700	–0.5	2,032
Uganda	38	21,170	21,500	1.6	1,795
Tanzania	30	21,316	22,715	6.6	1,407
Iran	25	34,500	34,500	0.0	725
Taiwan	19	18,329	17,620	–3.9	1,078
Myanmar	18	73,000	77,700	6.4	412
Georgia	16	34,000	35,000	2.9	471
Rwanda	15	12,862	13,000	1.1	1,166
Zimbabwe	15	6,850	6,500	–5.1	2,308
Totals	3,365	2,608,933	2,645,107	1.4	-

[1] Average yield per ha based on area planted, i.e. for countries with large tea extension areas, yields based on the 2002 area to allow commencement of harvesting normally three years after planting, unless tea area decreased due to uprooting of the tea.

By 2006, the total area planted by the smallholder tea sector by was 95,780 ha against a production of 191,180 t made tea while the estate plantations had 51,300 ha against a production of 119,400 t made tea (TBK, 2007). This translates to smallholder plantations accounting for 65% of total planted area and producing 62% of the made tea. However, the smallholder production may be slightly higher because of “illegal green leaf tea trade” colloquially known as ‘soko huru’ or ‘mang’irito’ depending on the area practiced. The leaf is normally purchased directly from the smallholder farms and sold to the estate sector factories by middlemen (Ontita, 2007). There has been a marked improvement in Kenyan tea production over the years with notable replacement of the pioneer seedling teas with improved clonal cultivars that are better yielding, are of good quality, take about one year from propagation to planting unlike seed plants that take up to three year, have better attributes like tolerance to drought, pests and diseases (Owuor et al., 2007a). A comparison of observed yields of the seedling genotypes grown in Kericho compared to the different clonal cultivars and their selection criteria is presented in Table 2. The introduction of clonal cultivars commenced in mid 1960s in the estate plantations sector such that all materials planted in the tea farms after 1970 are clonal, whether in new plantings or by replanting in ex-tea areas. Therefore, the smallholder sector has had the benefit of growing of improved vegetatively produced (clonal) cultivars in their expansion programme. In contrast, the estate sector relies predominantly on old seedling tea plantations and on small areas of clonal tea planted in uprooted seedling tea areas and in limited ex-forest plantations formerly reserved for fuelwood trees used in the tea factories. A survey conducted in 1998 established that in the estate plantations and smallholder sectors, seedling tea accounted for 72% and 20% of the planted material, respectively, while the remaining were clonal cultivars (Wachira, 2002).

To establish the performance of the two tea sectors in Kenya in terms of total production per unit area (ha), data from 1972 to 2006 were used. A tea bush normally starts producing in the third year, hence yields per ha were calculated based on the land area backdated three years for the period 1969–2003. The annual yields from 1972 to 2006 for KTDA and KTGA sectors are shown in Figure 2a, while Figure 2b shows the trends in area from 1969 to 2006. There were year to year variations in both sectors and yields ranged from 0.7 to 2.3 t ha^{-1} (mean, 1.5 t ha^{-1}) and from 1.7 to 3.7 t ha^{-1} (mean, 2.7 t ha^{-1}) in the smallholder and estate plantations, respectively. Although it is not possible to determine factors contributing to year to year variations in yields due to big differences in biophysical features in the tea-growing areas of Kenya, rainfall and air temperature (Othieno et al., 1992; Odhiambo et al., 1993; Ng'etich

Table 2. Some tea genotype/cultivars grown in Kenya and recorded highest yields in Kericho.

Genotype/Cultivar	Selection criteria(s)	Maximum yield (t mt ha^{-1} yr^{-1})	Year of release	Reference
Seedling	Unselected	3.1	1920s	Wachira (2001)
TRFK 6/8	Quality	4.4	1964	Wachira (2001)
TRFK 31/8	Yield	5.1	1964	Wachira (2001)
TRFK 303/577	Yield/drought	7.8	1989	Njuguna (1989)
AHP S15/10	Yield	11.0	1970s	Oyamo (1992)

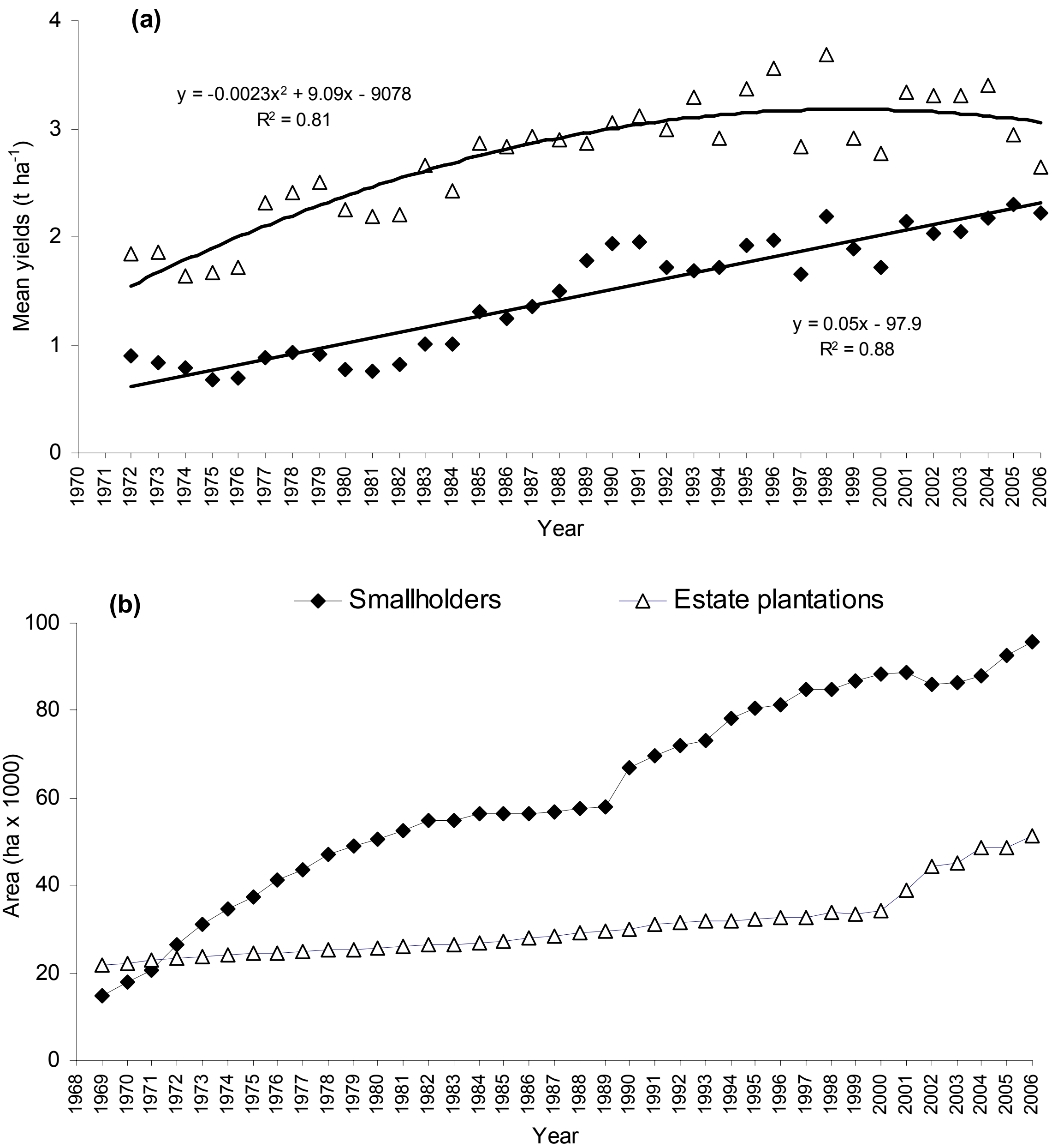

Figure 2. Tea production trends (1969–2006) of the two tea sectors in Kenya, (a) expressed as mean yields, and (b) total area.

et al., 2001) are considered to be main factors. In a field experiment that monitored seedling stand yields for 16 years in Kericho, Othieno et al. (1992) reported variations in annual yields from less than 0.9 to 2.0 t ha^{-1} over the period 1971–1986. An analysis revealed that 50% of the year to year variation was attributed to soil water deficits while 16% was due to hail damage. Kericho has a unimodal rainfall pattern with a peak during April–June (Stephens et al., 1992) unlike other tea-growing areas of Kenya that have bimodal rainfall with long rains in April–June and short rains in

September–October (Jaetzold and Schmidt, 1982) which implies that rainfall distribution is much poorer in these other tea-growing areas than in Kericho.

The smallholder sector realized a linear growth trend with time (years) while the estate plantations sector showed a quadratic trend where stagnation of yields appear to have started from the late 1980s (Figure 2a). The smallholder sector showed a steep increase in planted area over the period compared to the estate plantations sector whose area under tea increased gradually until 2000 (Figure 2b). In 2000, the private companies took over the management of some tea farms previously run by a parastatal, Nyayo Tea Zones, that was set up to prevent forest encroachment in the mid 1980s.

When total annual production is plotted vs total area for the two sectors over the period, 1972–2006 (Figure 3) the smallholder sector showed a quadratic growth pattern, while the estate sector reached a peak at 120,000 t demonstrating that there is yield stagnation/decline in the estate sector. It is postulated that since the estate sector has run out of land for new development, the newly replanted tea in formerly old tea lands are unable to produce good yields even under optimized agronomic practices compared to the same tea in virgin forest areas (Mwakha, 1989). To assess changes in productivity by the two sectors, i.e. turning points as seen in Figure 2a, the period 1972–2006 was split into two, first 15 years (1972–1986) and recent 20 years (1987–2006). Total production and total area regressions for the two periods (1972–1986 and 1987–2006) in the smallholder and estate plantations sectors are presented in Figures 4 and 5, respectively. The smallholder sector showed linear relationships in both periods although the growth rate was steeper during 1987–2006 (Figure 4b). There was a

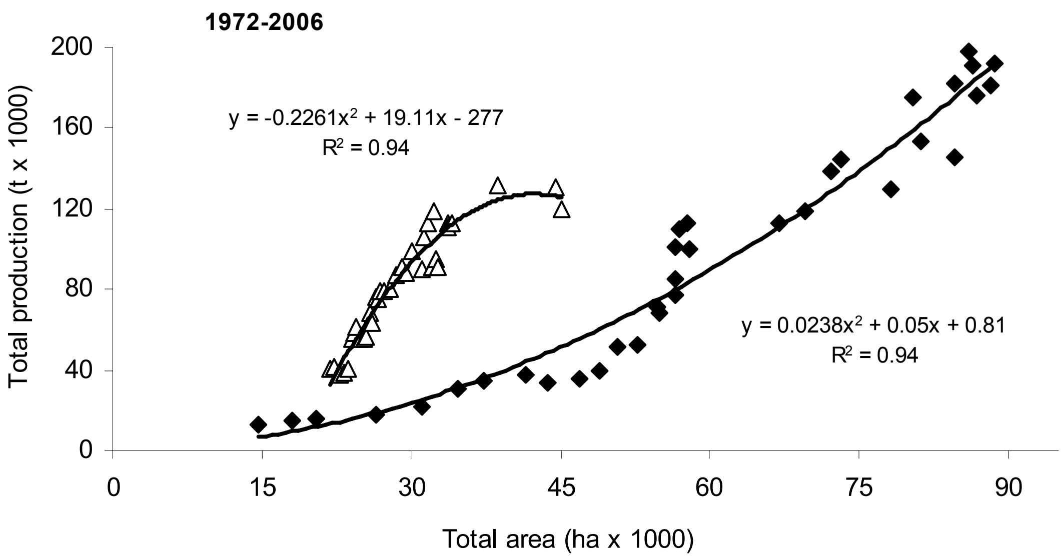

Figure 3. Dynamics of production trends in the smallholders (♦) and estate plantations (Δ) sectors.

linear increase in the productivity in the estate plantations during 1972–1986, that changed to a quadratic trend during 1987–2006, showing that indeed there has been yield stagnation. Thus the estate plantations sector had a good productivity up to the late 1980s. It is expected that the rapid growth being realized by the smallholder sector will change with time and eventually level off and stagnate, unless a new intervention to increase yields is found.

The quality of management in the two sectors can be deduced from the higher yields per unit area in the estate plantations sector compared to the smallholder sector. The main factors that contribute to the differences in yields per unit area include; nutrient management (farm inputs), human resource and labour, processing factory capacities especially during peak seasons, proximity to farms thereby maximizing on harvesting in the estate sector and lowering costs of transportation, road infrastructure and maintenance (M'Imwere, 1997; Owuor et al., 2005). These factors have affected

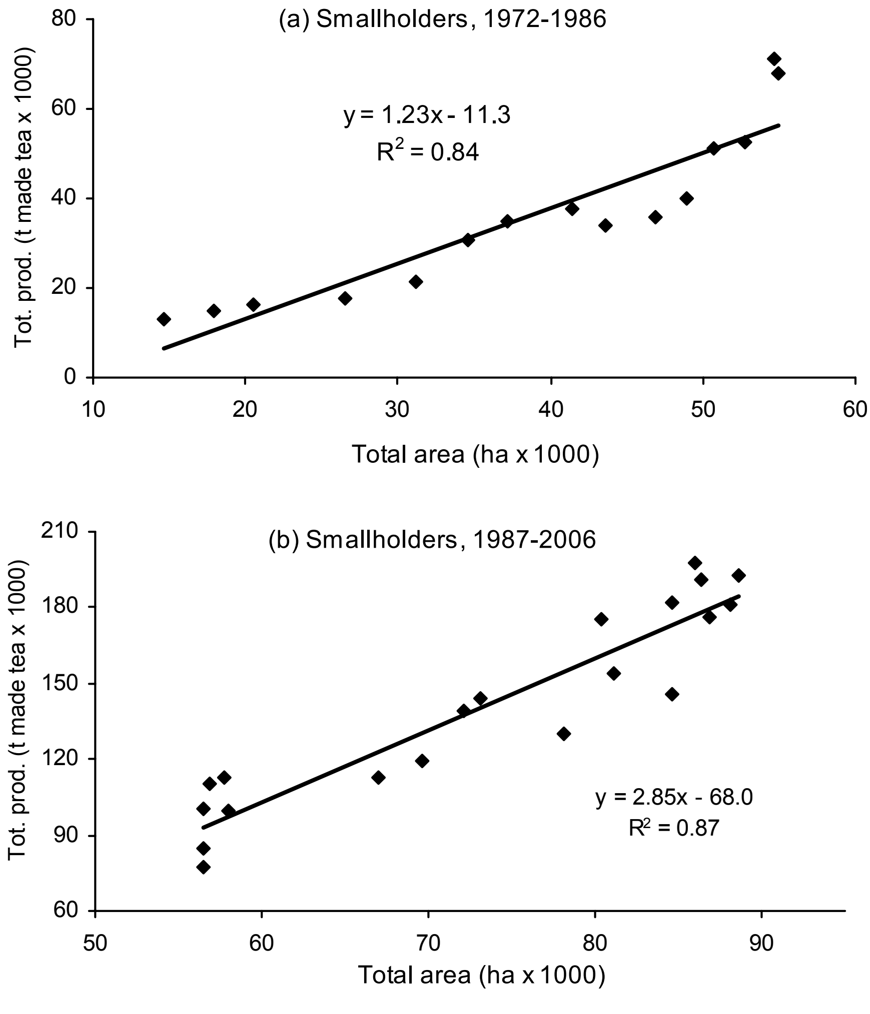

Figure 4. Dynamics of production trends in the smallholders sector over different periods.

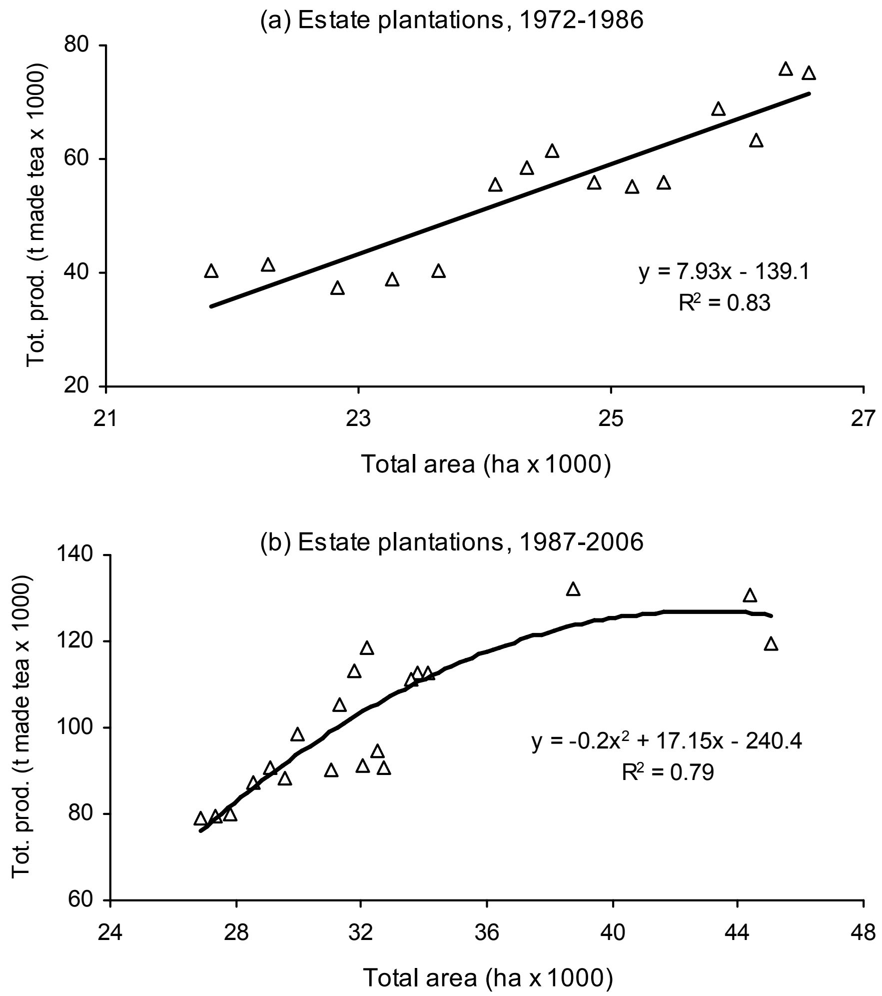

Figure 5. Dynamics of production trends in the estate plantations sector over different periods.

production in the smallholder sector more than the estate plantation sector (Owuor et al., 2007a). It is, however, important to establish effective nutrient management programmes in tea plantations with clear economic and environmental targets so as to lower the variance in nutrient balances between the different farms (e.g., Oenema and Pietrzak, 2002). We speculate that the stagnation in tea yields in the estate sector is closely associated to lack of innovations (choice of clonal material for infilling and for replanting in old uprooted tea lands, optimum planting densities) than ageing of the tea plantations as such (Chapter 3).

Factors contributing to productivity of ageing tea bushes

The factors and processes are discussed in relation to the following identified classes: genotype traits, crop husbandry practices (agronomic and cultural), ecological factors (abiotic and biotic) and soil fertility/land degradation.

Genotype traits

Vegetative propagation offers a large choice of improved clonal tea varieties targeted to desired attributes (Othieno, 1981; Seurei, 1996). A clonal stand is predictable regarding its phenotypic characteristics and, therefore, gives a uniform stand. The harvested shoots when expressed as a percentage of the total dry matter produced by the plant known as harvest index is important for yield potential and is dependent on genotype. Clonal cultivars often have a higher harvest index than the seedling genotypes. Another way of manipulating the harvest index is by increasing plant population densities that changes the way the plant partitions it's assimilates more into the harvestable portion at the expense of secondary thickening (Njuguna and Magambo, 1993). The most planted clonal cultivars combine a high yield potential and good quality. The total yield of the tea plant depends on individual contributions from the components of yield such as the rate of shoot extension, individual shoot weight and shoot density that depend more on moisture (Odhiambo et al., 1993; Burgess and Carr, 1997) and temperature (Odhiambo, 1986; Stephens and Carr, 1990). Although the estate plantation sector in Kenya comprises over 70% of the lower yielding seedling genotypes, as opposed to the smallholder sector where over 80% are improved clonal cultivars, productivity per unit area in the sector is higher (Figure 2a) due to improved management. The genetic defined yielding ability of the seedling plants may have been attained, hence causing stagnation and decline in productivity. A major gain in productivity of tea plantations could be achieved by a transition from low-yielding seedling genotypes to high-yielding clonal cultivars. Indeed, although clonal tea plants when planted on former tea lands do not produce yields equivalent to those produced from the same cultivars on virgin lands, they nonetheless produce yields much higher than the old seedling tea fields (Mwakha, 1989).

Crop husbandry practices: Pruning and infilling

Cultivation of tea involves various cultural practices that ensure the tea bush is maintained at a low table height to enable harvesting, stimulate vegetative growth and maintain a healthy frame (Willson, 1992a). This involves regular pruning which in Kenya is done every 3 to 5 years. Pruning causes stress to the tea bush as there is time the plant must survive without photosynthesis. When pruning is done at the same height, it introduces knots that reduces branching points, hence the recommendation of pruning 5 cm above last prune at every pruning time. However, after 70 cm that is considered maximum pruning table height for tea pluckers, down-pruning to 45 cm is done and the cycle continues. Eventually, rejuvenation pruning above the root collar (10–15 cm) is recommended when the bush frame becomes un-productive (Ventaka Ram, 1974). This results in high shoot weights, but low shoot numbers (Bore, 1996).

To lower the stress introduced by pruning, rim-lung pruning has been recommended, which involves first pruning two-thirds of the leaf bearing branches, and eventual removal of the other remaining one-third upon appearance of new leaves (Mwakha and Anyuka, 1990). Recovery after pruning depends on the state of health of plant, amount of carbohydrates reserves present and on the process of ageing (Ng'etich, 1996; Bore et al., 2003). When off-season pruning is done, or there is drastic drought after pruning, the tea bushes recover poorly or even die creating gaps in the tea stand. Most of the ageing tea fields have many gaps. Unfortunately, the older plantations had also lower plant densities, implying bigger open patches when plants die. The large gaps are a source of weeds due to low ground cover and also increase the risk of erosion and of soil fertility decline. The gaps also reduce light interception, hence a lower rate of photosynthesis that causes a decline in productivity. In north-east India about 10% open patches in mature tea plantations comprising a total area of 285,000 ha resulted in an estimated annual crop loss of 40 million kg made tea (Jain, 1980). Infilling of the gaps immediately after pruning is the recommended practice in most tea-growing regions like East Africa (TRFK, 2002), Central Africa (TRFCA, 1990), India (UPASI, 1987) and Sri Lanka (Sandanam, 1986). However, the infilled tea plants in Kenya showed a poor establishment and did not perform as well as those planted in former forest sites implying a need for soil reconditioning (Mwakha, 1989; Njuguna and Magambo, 1993; Bore, 1996). Since uprooting and replanting is seen as a long-term and expensive investment, the tea plantations with many gaps are kept in production, hence resulting in decline in productivity of such plantations.

Ecological factors

Weather conditions and plant adaptation

The recent events in global climate change have seen weather patterns change in all areas of the world, including tea-growing regions. In Kenya, frequent and longer droughts, heavy rainfall, hailstorm damage, high and low temperature variations leading to frosts incidences, etc are being experienced (e.g., Anonymous, 2000; TRFK, 2006). This has led to a push of breeding programmes focussing more on clonal plants that can withstand longer periods of drought, frost incidences, and pest and disease tolerance (Wachira and Ronno, 2005). Although the older seedling teas were unselected and have diverse genetic variation among tea bushes (Wachira, 2002; Illukpitiya et al., 2004), they have better rooting systems to enable them withstand long periods of drought and higher carbon and nutrient stocks to withstand adverse weather (Chapter 4). This is unlike clonal tea plants which have superior yields but cannot withstand adverse weather. Before the breeding programmes are successful in releasing clonal tea plants with a combined yield-quality-drought tolerance attributes, the current diversity offered by the seedling tea stands though lower yielding is desirable.

Susceptibility to biotic factors

Diversity in the forest environment provides a stable micro-climate and continuous supply of food for many pests and diseases. Tea, being a monocrop, loses the diversity and becomes prone to pests and disease infestation, especially after long periods of cultivation. Pests and diseases in commercial tea plantations are increasingly being studied especially to assess their damage potential and to devise appropriate control measures (Agnihothrudu, 1999). Common diseases in tea plantations are caused by fungal pathogens that infect various parts of the plant. However, some occur as a result of poor husbandry practices especially during land preparation and pruning. The economically important ones are stem, root, and leaf diseases. The three major diseases associated with decline in productivity of ageing of tea plantations in Kenya, are stem and branch cranker (*Phomopsis theae*), wood rot disease (*Hypoxylon serpens* and *H. investiens*) and root rot (*Armillaria* spp.) (Mwakha, 1989).

Stem and wood rot

Stem and branch cranker (*Phomopsis theae*) is a stem disease caused by pruning cuts exposed to sun-scorch. This offers an easy entry to fungal pathogens thus reducing the bush frame or even killing the entire bush. Similarly, wood rot diseases like *Hypoxylon serpens* and *H. investiens* are caused by deep pruning of bushes with big pruning cuts creating wounds that make the fungal pathogens have access to the woody tissue. Rain drops from a heavy downpour is known to also scatter the fungus onto the cut wounds. Preventive measures are therefore important especially during pruning periods and use of correct tools and methods (Otieno, 1997). Fortunately, the use of pruning knifes that cause big wounds has been discouraged in favour of the mechanized pruning machine that offers uniform prune above a certain height thus avoiding the woody branches.

Root rot

Armillaria fungus occurs wherever tea has been planted on land after clearing forests or shade trees without properly ring-barking and/or removing all roots of the trees. The inoculum from which the primary infection starts in tea is normally present in root residues and can remain viable in the lower soil depths for many years (Otieno, 2002). The fungus spreads rapidly by root to root contact within a plantation and destroys the tea roots so that supplies of water and nutrients are restricted. This causes leaf wilting and defoliation of above-ground and finally death of the bush. Once established, root diseases are difficult to eradicate and appropriate control measures to identify and remove affected bushes in the field in the early stages is important (Onsando, 1997). For the older tea bushes that are also deep rooted, uprooting to remove all roots is difficult and expensive and most often several neighboring tea bushes will have been infected through root contact. Other effective methods that have been tried in the control of the *Armillaria* fungus is use of *Trichoderma* species (Onsando and Waudo, 1994; Otieno, 1998) and combining *Trichoderma* species with soil solarization (Otieno, 2002). However, these methods are time consuming whereby isolation of the affected area by use of deep trenches is done.

Soil fertility and land degradation

The effects of forest clearing and long-term cultivation of annual crops on soil fertility and yields are well documented (Sanchez et al., 1983). Unlike annual crops, soils under perennial crops are believed to be adequately protected by crop canopy and surface litter so that soil degradation is minimal (Hartemink, 2005). However, tea is grown on high rainfall areas, in most cases on sloping to steep land, and the soils under tea are variably exposed depending on crop husbandry activities like, periodic pruning, uprooting and replanting, or gaps that arise from plant deaths. Exposure of bare soils to heavy showers may results to soil loss and land degradation that ultimately leads to decline in productivity of the tea plantations. It was reported that deterioration of soil structure caused poor yields in replanted tea in India (George and Singh, 1990) and Japan (Ikegaya and Hiramine, 1978), but so far not in Kenya (Obaga and Othieno, 1986; Owino-Gerroh, 1995). Jayasuriya (2003) speculated that the positive impacts of technological progress by the tea sectors outweighs the negative effect of land degradation in Sri Lanka.

Yield stagnation in old tea plantations has also been associated with the presence of allelopathic chemicals in the soils arising from the prunings and leaf litter mulch that hinder nutrient uptake (Owuor, 1996; George and Singh, 1990). The presence of allelochemicals in tea plant parts and soils has been suggested through laboratory based studies showing inhibition of seed germination and subsequent radical growth and *in vitro* growth of tea plants (Owuor et al., 2007b). Plant specific soil-borne diseases as in coastal foredunes vegetation could also contribute to the allelopathic interactions (Van der Putten et al., 1993). Investigations on the management of uprooted and replanted tea areas are still on-going in many tea-growing countries, including Kenya.

Exploring management options

A simple decision-support model for Managing Ageing Plantations of Tea (MAP-Tea) was developed to explore the most promising interventions for productivity improvement. The MAP-Tea model calculates net economic returns of tea production over time (up to 100 years) using estimates of costs and yields for plantations for contrasting genotypes, e.g. low-yielding seedling tea and a high-yielding clonal cultivar. The model distinguishes four phases of tea cultivation in plantations, i.e. seedling/cuttings establishment, frame formation, mature/commercial, and degraded/ moribund. Each phase has fixed costs of inputs and/or tea prices that can be varied under different scenarios. In the simulations explained below, it is assumed that the low-yielding seedling genotype will remain productive until the age of 35 years after which the degradation stage commences at constant rate (constant aerial fraction, i.e. ha ha^{-1} yr^{-1}; 'zero-order kinetics'). A high-yielding clonal tea cultivar is used for re-planting purposes, which is also subjective to degradation. The degradation rate of clonal tea was assumed to be proportional to the number of planted clonal tea bushes (fraction of number of clonal tea bushes per year; 'first-order kinetics'). It is important to note that the model assumes that uprooting of the old tea bushes is carried out as they reach the degraded age and replanting is done to fill in the empty spaces (gaps). However, the field situation is different given that the older tea plantations are wider spaced (< 8,000 bushes per ha) while the optimal planting density found in clonal fields is above 10,000 bushes per ha. Hence, replanting can best be done by either removing and replanting whole tea bush rows or by uprooting blocks of tea plantations that have more gaps and are more degraded. The details of the parameters applied in the model are presented in Table 3. To assess the impacts of replanting of degrading tea plantations, two simulations were carried out using different scenarios as described below.

Simulation 1: Scenarios for tea plantation management with and without replanting

Two levels of tea plantation management, 'poor' and 'good' were distinguished: 'poor' management where there is no replacement of old degrading seedling bushes, and 'good' management where gradual replacement of degrading seedling bushes takes place. Calculations were done for two rates of tea bush degradation: k=0.02 and k=0.06 yr^{-1}. It was assumed that the newly planted clonal tea bushes also degraded at rates of (first-order kinetics) k=0.02 and k=0.06 yr^{-1}, respectively and that the gaps are replanted again by clonal tea bushes. The simulations showed that the net returns were negative during establishment phase. Annual constant positive financial returns were obtained during the mature/commercial phase, from 5 to 35 years, as expected (Figure 6a). Thereafter annual returns started to decline due to degradation of seedling tea bushes. Under poor management the net returns decreased to zero at an age of 52 and 85 years for degradation rates of k=0.06 and 0.02 yr^{-1}, respectively (Figure 6a). However, assuming good management, maximum net returns of Ksh 242,900 and

Table 3. Parameters, costs and prices (Ksh × 1,000)[1] used in the model Management of Ageing Plantations (MAP–Tea).

Operation or Factor	Seedling/cuttings (establishment)	Frame formation	Mature/ Commercial	Degraded/ Moribund
Land (Ksh ha^{-1})	600	-	-	-
Forest/land clearance (Ksh ha^{-1})	80	-	-	80
Planting materials (Ksh ha^{-1})	700	-	-	700
Planting (mandays ha^{-1})	10	-	-	10
Weeding (mandays yr^{-1})	4	4	-	4
Fertilizer costs (Ksh yr^{-1})	6	6	24	24
Formation pruning (mandays ha^{-1})	6	6	-	-
Rent of investments (Ksh yr^{-1})	55.2	55.2	55.2	55.2
Yield (kg made tea ha^{-1} yr^{-1})	-	-	2,000 (seedling) 4,000 (clonal)	
Price of tea (Ksh kg^{-1} made tea)	-	-	0.11	0.11
Factory processing costs (Ksh kg^{-1} made tea)	-	-	0.03	0.03
Plucking costs (Ksh kg^{-1} green leaf)	-	-	0.005	0.005
Pruning costs (mandays ha^{-1} yr^{-1})	-	-	3.5	3.5
Seedlings degradation rate (fraction yr^{-1})	-	-	-	0.02, 0.06
Clonal replants degradation rate (fraction yr^{-1})	-	-	-	0.1, 0.2, 0.3, 0.4

[1] 90 Ksh equivalent to 1 euro.

Ksh 271,700 are achieved by 56 and 89 years, for degradation rates of 0.06 and 0.02 yr^{-1}, respectively. The break-even point is attained after 14 years (Figure 6b). It shows that replanting is vital to maintain a high productivity in ageing tea plantations and that replanting of seedling by clonal tea is profitable.

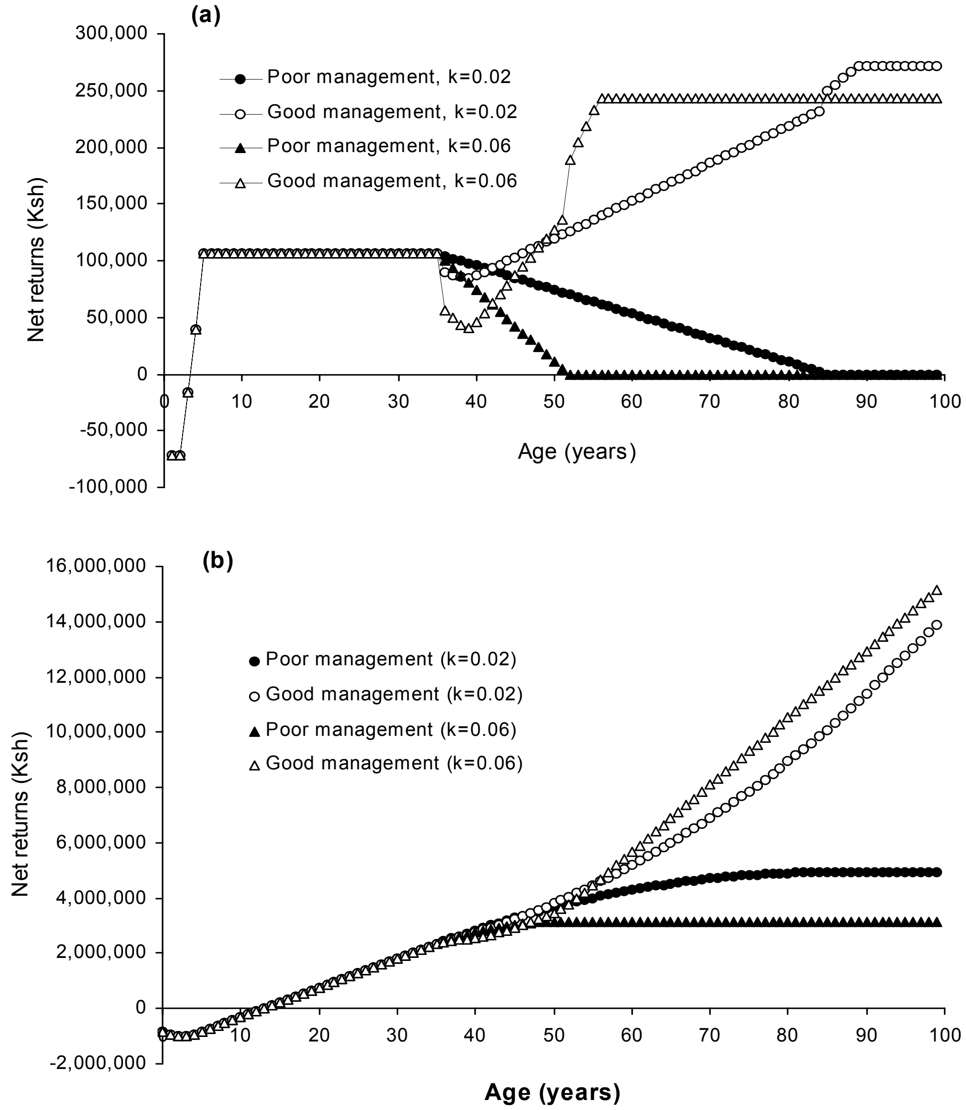

Figure 6. Simulated net annual (a) and cumulative (b) financial returns (in Ksh ha^{-1}) of tea plantations under poor management (not replanting degrading seedling tea) and good management (replanting degrading seedling tea bushes by clonal tea bushes) of tea plantations that start to degrade at constant rates of 0.02 and 0.06 yr^{-1} at the age of 35 years (see text and Table 3 for explanations).

Simulation 2: Scenarios for replanting at different degradation rates

In the previous simulation, it was assumed that the degradation of clonal tea was similar to that of seedling tea. However, there is evidence that clonal tea bushes do not establish well in degrading seedling tea plantations, and that degradation rates of the young clonal tea bushes are high sometimes. The simulations presented here were made to explore the effects of variations in the establishment (degradation) of clonal tea bushes in degrading seedling tea plantation on net financial returns. Using the 'good management' practice where replanting with clonal cultivars is done, four rates of clonal tea bush degradation were considered. The first two years after uprooting were assumed to be rehabilitation years and replanting was carried out during the third year. Hence yields from clonal tea were obtained from the beginning of the fifth year after uprooting of the old seedling tea bushes. Degradation rates were arbitrarily set at 0.1, 0.2, 0.3 and 0.4 yr^{-1} to represent different site qualities (Willson, 1992b) and/or reduction due to presence of toxic allelochemicals (Owuor, 1996), that may arise from infection by some tea-specific soil borne pathogens (Van der Putten et al., 1993).

We found that differences in the degradation rate of clonal tea bushes have a big effect on annual net financial returns. Similar or higher net returns from clonal tea plantations than from seedling tea bushes during the mature/commercial phase can only be obtained from replanted clonal tea bushes with degradation rates of about k=0.2 yr^{-1} or less (Figure 7). As the degradation rate of the seedling tea bushes was set at constant rate of 0.05 yr^{-1}, it will take about 20 years to reach a new equilibrium of constant net annual returns. Note that the upward shift in net returns at about 55 years is caused by the fact that all seedling tea bushes have been replanted by that time and that costs associated by replanting decreased thereafter.

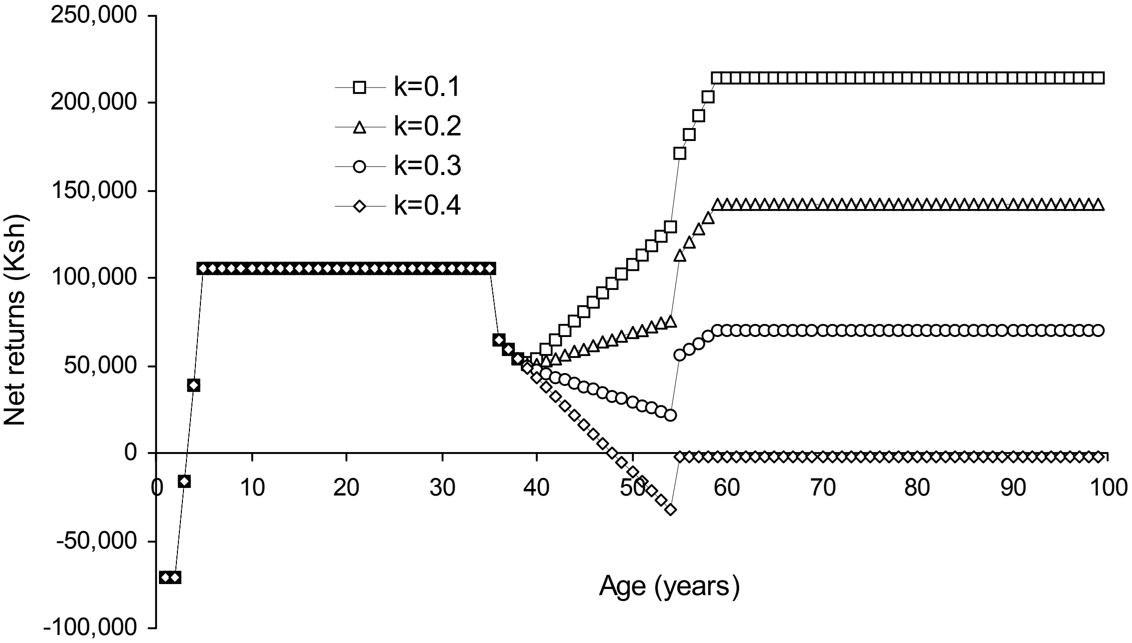

Figure 7. Simulated net annual financial returns (in Ksh ha^{-1}) of tea plantations that start to degrade at constant rates of 0.05 yr^{-1} at the age of 35 years and where the degrading seedling bushes are replanted by higher-yielding clonal tea bushes, which subsequently also degrade at 0.1, 0.2, 0.3 and 0.4 yr^{-1} (see text and Table 3 for explanations).

Conclusions

Tea is an important crop in Kenya as it provides livelihood to some three million people. Average productivity of the tea plantations is high compared to that of other tea producing countries. Results from breeding experiments indicate that there is a wide scope for increasing productivity, as new clonal tea genotypes have a much higher potential yield than seedling tea bushes. However, the cost of replanting tea bushes is high (about Ksh 800,000 per ha), while no tea can be harvested for 3–5 years. The establishment of the new clonal plants is also highly variable in degraded tea plantations. This shows the importance of knowing site quality, the need for soil rehabilitation and choice of genotypes that can perform well in ex-tea areas. These factors should be comprehensively addressed before large scale uprooting programs are implemented.

There are significant differences in mean yield between the two tea sectors in Kenya, which are mainly related to differences in management practices, the use of tea genotypes and age of tea plantations. While the annual mean tea yield in the small-holder sector still increases over time, the mean annual yield in the estate sector is stagnating and/or declining. Our results suggest that uprooting seedling tea bushes and replanting by high-yielding clonal tea is financially attractive when the degradation rate of the newly planted clonal tea bushes is less than 0.2 yr^{-1}. The cause of degradation and the variations in degradation of seedling tea bushes and of newly planted clonal tea bushes is still unclear, and as a result remedial measures are still unknown.

In conclusion, further improvement in tea productivity should take into account Genotype × Environment × Management (G×E×M) relationships as was found in food crops (Spiertz et al., 2007). To assist tea growers maximize on net returns, new genotypes including those that perform well on ex-tea areas should be selected under agro-ecological conditions that mimic future changes in weather patterns. The possibility of soil pathogen-driven degradation of ageing tea plantations has to be explored so as to improve the establishment of newly planted high-yield clonal tea bushes. Furthermore, management practices should be tuned to site-specific and seasonal dynamics in tea growth and production.

CHAPTER 3

Productivity and nitrogen use of tea in relation to plant age and genotype-density combinations

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Abstract

Lack of science-based knowledge on responses of tea bushes to nitrogen (N) in ageing tea plantations hampers ecologically and economic sound N-management. It is hypothesized that ageing of plantations results in a lower productivity and a lower response to N application. To get more insight, seasonal and annual yield responses to N were studied in field experiments superimposed on a chronosequence of tea plantations (14-, 29-, 43-, and 76-years). The two youngest plantations comprised of a clonal cultivar planted at a density of 10,766 and 13,448 plants ha^{-1} and the two oldest plantations of seedlings at a density of 6,730 and 7,179 plants ha^{-1}, respectively. N was applied as urea at 0, 50, 100, 200 and 400 kg N ha^{-1} yr^{-1}.

Mean annual made tea (mt) yields were higher for the clonal tea compared to the seedling tea and increased with age within genotypes. The clonal bushes out-yielded the seedlings by about 800 kg mt ha^{-1} under favourable weather conditions in 2003/04, while yield differences between the genotypes were minimal under stress conditions in 2002/03. The clonal 14- and 29-year old plantations showed a positive yield response to N-fertilizer, whereas the 43-and 76-year old plantations did not. Apparent shoot N-recovery (ASNR) based on N-uptake by 'two leaves and bud' was higher in tea plantations with clonal cultivars than with seedlings. The ASNR amounted to 0.40 and 0.38 kg kg^{-1} in 2002/03, and 0.36 and 0.50 kg kg^{-1} in 2003/04, for the 14- and 29-year clonal tea plantations, respectively. Seedling plantations had much lower ASNR values.

N-removal by plucking followed the yield pattern. Because of the relative low variation in N-removal there was a strong increase in N-excess with rate of N-application. Biomass increase and N-uptake were closely associated within the clonal cultivar, but not in the seedlings. The impact of plant genotype-density combinations on productivity, N-use and N-excess was greater than the effect of age as such. It is concluded that (1) genotype choice combined with plant density to a great extent determines the yield response to N, and (2) ageing does increase the yielding ability within the same genotype. Future N-management should be based on the yielding ability of tea bushes as defined by plant genotype-density combinations and age of plantations.

Keywords: *Camellia sinensis* (L.), clones, seedlings, N removal, N uptake-biomass relationship.

Introduction

Tea is a perennial monocrop that can be in economic production for up to 100 years if well managed. Cultivated tea (*Camellia sinensis* (L.) O. Kuntze) is maintained as a low bush in a continuous vegetative phase by pruning every 3–5 years to form a plucking table that facilitates easy removal of the young shoots. The pruned material is left on the soil which favours recycling of nutrients and organic matter, thus contributing to the mineral balance of the soil-plant system, and preventing erosion in young plantations (Willson, 1992a) amongst other benefits. Nitrogen is the most important nutrient and the highest content is contained in young harvestable tea shoots. Use of nitrogen fertilizers in tea plantations is widely practiced and improved productivity per unit area under good management in commercial tea plantations with rates ranging from 100 kg N ha^{-1} yr^{-1} in India and Kenya (Bonheure and Willson, 1992) to 1200 kg N ha^{-1} yr^{-1} for green tea in Japan (Watanabe, 1995). Recommendations on fertilizer composition and rates are based on the ratio and amounts of nutrients removed. Those data are obtained through long-term field experimentation, and supplemented by soil and leaf tissue analyses to cater for losses like leaching, volatilization, fixation (Bonheure and Willson, 1992), and accumulation (Dang, 2005). The nutrient ratios of the major fertilizers, N:P_2O_5:K_2O, reported for most tea-growing countries vary with region and cultivar; such as: 10:1:5 (Othieno, 1979), 12:1:6 (Verma, 1997) and 7:1:4 (Hettiarachchi et al., 2003). N-recommendations for mature tea is normally implied by the genotype planted in different tea-growing regions like Central Africa (Grice et al., 1988), India (Ranganathan and Natesan, 1983), Kenya (Othieno, 1988), and Sri Lanka (Wickremasinhe and Krishnapillai, 1986). Thus, recommendations on fertilizer type and rate for younger clonal and much older seedling tea plantations vary between regions.

The growing conditions in various seasons are described by Stephens et al. (1992) as: (1) a warm-dry season (Dec–Mar); (2) a cool-wet season (April–Aug); and (3) a warm-wet season (Sep–Nov). It is well established that tea growth is affected by these differences in weather patterns. To maximize crop yields and seasonal distribution of shoot growth, tea growers sometimes use split N-dressings. Whereas, splitting fertilizer in areas with non-limiting rainfall or under irrigation has been found to be important and is recommended in parts of South India (Ranganathan and Natesan, 1987) and Malawi (Mkwaila, 1993), long-term field experiments in Kenya have shown that split applications of fertilizers are not beneficial in terms of increasing annual yields; the variations in yield were attributed more to weather than to splitting N-fertilizer (Owuor et al., 1992; Owuor, 1997; Kamau et al., 2000).

N-fertilizer requirement of tea bushes was found not to change with the plant population density. An experiment conducted on a 27-year old seedling tea stand established at different plant densities in Kenya demonstrated that mean yields increased with higher plant population density only during the first pruning cycle, April 1988 – January 1991; the highest density of 10,766 plants ha^{-1} yielded significantly more than lower densities of 8,611, 7,179 and 5,883 plants ha^{-1}, but not during the second pruning cycle, May 1991 – December 1994 (Wanyoko and Owuor, 1995). Similar observations were also reported in India for younger clonal plants aged 3 to 12 years and plant population ranging from 6,944 to 37,040 plants ha^{-1} (Chakravorty and Awashi, 1981). In these experiments, effects of differences in genotype and age were not taken into account. Furthermore, most trials assessing high plant population density cannot be monitored for long periods since the rows of the higher density population (> 18,520 plants ha^{-1}) close up after canopy cover to an extent that tea pluckers are unable to pass in between during harvesting, unless pruning is done annually. The introduction of higher yielding clonal cultivars with a better harvest index (HI) and increase in planting density resulted to higher productivities. The harvest index, expressed as the percentage of the total dry matter partitioned to harvestable shoots, also depends on weather, management and cultural practices (Carr and Stephens, 1992). In younger clonal tea plantations, the HI was found to decrease with age (Magambo and Waithaka, 1983) arising from the increase in allocation of dry matter to the frame of the bush. Other studies have shown an increase of HI with plant population, and this has been attributed to more partitioning of dry matter to the leaves than the roots and bush frame in the closer-spaced plants (Bore et al., 1998; Magambo and Cannell, 1981).

When considering the economics of any fertilizer application rate, tea quality and sustainability of the cropping system are important. Whereas high N-application rates lower the sensory evaluation and black tea chemical quality parameters (Cloughley, 1983; Owuor et al., 1987; Owuor et al., 1990b; Owuor and Othieno, 1996), the economic benefit of higher quality of unfertilized teas was not large enough to offset the benefits of higher yields at modest N-rates (Abeysinhe, 2003). Economic optimum N-rates in tea rarely exceed 350 kg N ha^{-1} (Owuor and Othieno, 1996; Kamau et al., 1998; Li, 2005) even for regions where high rates are used in green tea cultivation. It was also found that high N-application rates caused higher acidification and nutrient imbalance (Owino-Gerroh, 1991; Bonheure and Willson, 1992) and increased N-emissions thus threatening ecological sustainability of tea production (Newbould, 1989).

Knowledge about annual and seasonal responses to N-management of ageing tea stands is scarce, despite the vast amount of literature available on the effects of N-fertilizer use on yield and tea quality. N-management practices for mature tea plantations are often similar and the decisions are left to managers or extension workers who largely use their expert knowledge rather then science-based insights. This lack of science-based knowledge hampers tactical (e.g. N-timing and N-dosing) and strategic (e.g. uprooting, cultivar choice, population density) measures in tea crop management. We hypothesize that ageing of tea plantations results in a lower productivity and a lower response to N application. The objectives of this study are to (i) study the response of tea bushes to N application rates in relation to age and genotype in association with plant density, (ii) analyse the dynamics of nutrient removal by plucking in consecutive seasons, and (iii) explore options for improving N-management in relation to yield and N-losses.

Materials and methods

The field study was conducted at Kericho, located in the western highlands of Kenya, and situated at an elevation of 2,180 m above sea level, latitude 0°22′ S, and longitude 35°21′ E. The climate of Kericho area is influenced by onshore winds from Lake Victoria that tend to give the area rainfall throughout the year. The sites are located within a radius of four km from the Tea Research Foundation of Kenya (TRFK) agro-meteorology station where the weather data parameters as described by Stephens et al. (1992) were obtained. Based on age profile, four sites with uniformly managed tea plantations for commercial production planted in 1988, 1973, 1959 and 1926 and with known past cultivation history were selected. At the start of the experiment in 2002, the tea plantations were 14-, 29-, 43-, and 76-years old. Two sites had an average yielding clone TRFK 6/8, planted at densities of 10,766 and 13,448 plants ha^{-1}, and the other two sites seedling genotypes with densities of 6,730 and 7,179 plants ha^{-1}, respectively. Prior to the 1970s, tea plantations were established at lower plant population densities. Thus, genotype and plant densities are strongly associated when considering tea plantations of different age. In this experiment there were two age classes within the genotypes, either seedling or clonal. Lung-pruning in all the sites was done between August and October 2001.

The soils in the study area are characterised as Nitisols with a friable clay texture derived from volcanic origin and are deep, free draining and acidic. The available water content is 150 to 200 mm m^{-1} between –10 and –1,500 kPa soil water potential (Ng'etich and Stephens, 2001a). Site description of the four tea plantations and some soil properties of the 0–20 cm top layer are presented in Table 1.

The experimental design comprised of a split-plot block design with age and genotypes as main treatments and five N-rates (0, 50, 100, 200 and 400 kg N ha^{-1}) each replicated three times as sub-treatments. Urea fertilizer was first applied in November 2002 by broadcasting in between the tea bush rows. N-application was subsequently repeated in November 2003 and November 2004. Phosphorus and

Table 1. Tea plantations characteristics and some soil parameters.

Tea plantation characteristics				Soil parameters		
Genotype	Age (years)	Spacing (m)	Plants per ha	pH^1 (1:1 H_2O)	Total Org C^2 ($g\ kg^{-1}$)	Total-N^2 ($g\ kg^{-1}$)
Clonal	14	1.22 × 0.76	10,766	4.01 ± 0.18	35.9 ± 1.4	3.3 ± 0.5
	29	1.22 × 0.61	13,448	4.50 ± 0.23	36.5 ± 1.2	3.9 ± 0.4
Seedlings	43	1.22 × 1.22	6,730	3.93 ± 0.13	35.4 ± 1.0	3.6 ± 0.7
	76	1.52 × 0.91	7,179	3.85 ± 0.13	32.9 ± 1.8	3.3 ± 0.5

[1] Samples from all plots (n = 15);

[2] Samples from control plots only (n = 3);

± Standard deviation.

potassium were also uniformly applied in November each year at rates of 100 kg P_2O_5 and 100 kg K_2O, respectively. The plots consisted of 55 tea bushes arranged in 5 × 11 bushes for the 14-, 29-, and 43-year old tea plantations while the plots of the 76-year old tea plantation had 48 bushes in a 6 × 8 rectangular arrangement. Plots were surrounded by a line of tea bushes that served as guard rows as required in fertilizer field experiments (Kamau, 2000).

Uniform yield recording of the harvestable shoots comprising two leaves and an apical bud at the four sites was done between January and October 2002. Thereafter, yield recording was carried out every 7 to 14 days depending on shoot growth for the entire duration of the experiment. The yields were converted to kg made tea ha^{-1} (kg mt ha^{-1}) by multiplying the green leaf weight by a factor of 0.225 (Anonymous, 1986). The moisture content of made tea in black tea is about 3% (KTDA, 2004).

In 2003, leaf samples of the 1st mature leaves were taken from about tea 25 bushes per plot in February, July, and October representing the average of three distinct growing seasons in one year. In 2004, two leaves and a bud as well as the 1st mature leaf were sampled. The samples were oven-dried at 105 °C for 4.5 h and total nitrogen was determined by Kjeldahl digestion, distillation and titration (Anderson and Ingram, 1996).

To analyse the data various parameters were used, such as: evapotranspiration (E_t), apparent shoot N-recovery (ASNR), the relationship between biomass and N-uptake, N-excess, and heat-load. These were calculated as follows:

$$E_t = 0.85 \times E_0, \quad (1)$$

where, E_0 is the Penman potential evaporation in mm.

$$ASNR = (N_{uptake,i} - N_{uptake,0}) / N_{applied,i} \quad (2)$$

where, $N_{uptake,i}$ is uptake at a specific fertilizer N rate by the harvestable shoot; $N_{uptake,0}$ represents the control without fertilizer N. ASNR is expressed as a fraction. The N-excess is calculated as:

$$\text{N-excess} = (N_{\text{fertilizer applied},i} + N_{soil}) - \text{N-removal} \quad (3)$$

where, $N_{\text{fertilizer applied},i}$ is the specific N-fertilizer rate assuming no changes in soil N-reserves and no other N-input and output within one year. N_{soil} is derived from the N-uptake in the control plots. N-excess is expressed as kg N ha^{-1}. The biomass and N-uptake relationship for non-limiting N-conditions was defined by Lemaire and Gastal (1997) as:

$$N_{uptake} = a\, W^{b} \quad (4)$$

where, a in kg ha^{-1} represents amount of N-accumulated by the crop for W = 1 t ha^{-1}; b is a coefficient representing ratio between relative accumulation ratio N and biomass. Average daily heat-load was defined as

$$\sum (T_{mean} - T_{critical}) / \text{number of days}, \quad (5)$$

where, $T_{critical}$ is the average base temperature of 9 °C for tea shoot development and extension (Matthews and Stephens, 1998a). The daily heat-load is expressed in °C.

An analysis of variance (ANOVA) was used to compute means and least significant differences (LSD) for the four sites with age and genotype as main factors and N-treatment as sub-factor using MSTAT-C (1993) statistical software. To estimate the N-content of ‘two leaves and bud’ in 2003, a regression analysis per season was done on the data for 2004 between ‘two leaves and bud’ (Y) and ‘1st mature leaf’ (X). The equations were as follows:

Season 1 (December–March): Y= 0.807 X + 1.28, (n = 60, R^2 = 0.25 ***P<0.001)
Season 2 (April–August): Y= 0.714 X + 1.64, (n = 60, R^2 = 0.22*** P<0.001)
Season 3 (September–November): Y= 0.662 X + 2.05, (n = 60, R^2 = 0.23*** P<0.001)

Estimates of N-uptake were obtained by multiplying the nitrogen content of ‘two leaves and bud’ sample with the yields in kg mt ha^{-1}. The measured and calculated seasonal N-content in the ‘two leaves and bud’ and ‘1st mature leaf’ are presented in Table 2.

Table 2. N-content (g kg^{-1}) in '1st mature leaf' and 'two leaves and a bud' in 2002/03 and 2003/04.

	1st Mature leaf			Two leaves and a bud[1]		
Year	Dec - Mar	Apr - Aug	Sep - Nov	Dec - Mar	Apr - Aug	Sep - Nov
2002/03	36.3 ± 3.7	33.2 ± 2.8	34.5 ± 2.5	42.5 ± 0.33	40.1 ± 2.0	43.3 ± 1.6
2003/04	33.0 ± 4.3	33.5 ± 3.9	29.1 ± 4.4	39.6 ± 0.73	40.3 ± 5.9	39.7 ± 6.1

[1] Values 2002/03 for 'two leaves and a bud' are calculated as described in section Materials and methods.

Results

Annual and seasonal weather pattern

Contrasting weather patterns occurred between years and seasons with 2002/03 experiencing an extended dry and hot spell between February and March, while 2003/04 had a well distributed rainfall pattern and optimum temperatures (Tables 3 and 4). Annual mean temperatures and solar radiation did not differ much between the two years, 2002/03 and 2003/04. However, there were differences within seasons and higher diurnal temperatures were seen in season 1 of 2002/03, while season 2 showed lower temperatures than in 2003/04. Similarly, solar radiation was lower during season 2 in 2002/03 with a mean of 18.2 MJ m^{-2} compared to 19.8 MJ m^{-2} in 2003/04. Although rainfall was higher in 2002/03 (2,338 mm) compared to 2003/04 (1,851 mm), the distribution was poor as shown by the higher total soil water deficit (SWD) of 252 mm in season 1 compared to 107 mm in 2002/03 and 2003/04, respectively (Table 4). Similarly, season 3 of the second year had relatively lower rainfall but its distribution as seen by the number of rainy days was even. A simple annual water balance was derived from the observed monthly rainfall and the calculated evapotranspiration (E_t). Excess water amounted to 791 mm in season 2 (April–August) of 2002/03 compared to 468 mm in 2003/04.

Annual yield response to nitrogen

The yield responses in kg made tea ha^{-1} to N-fertilizer in 2002/03 and 2003/04 are shown in Figures 1a and 1b, respectively. In the first year, only the 29-year old clonal plantation showed a significant response to N-application. Maximum yields of 3080 kg made tea were found at a rate of 200 kg N ha^{-1}. In 2003/04 both the 14- and 29-year old tea plantations with the clonal cultivar responded significantly to N (*P*-values of 0.016 and 0.010, respectively); maximum yields amounting to 3,800 and 4,200 kg

Table 3. Monthly temperatures, diurnal temperature range and solar radiation at Kericho in 2002/03 and 2003/04.

	Maximum temperature (°C)		Minimum temperature (°C)		Diurnal temp. range (°C)		Mean air temperature (°C)		Solar radiation (MJ m^{-2})	
Month/Year	2002/03	2003/04	2002/03	2003/04	2002/03	2003/04	2002/03	2003/04	2002/03	2003/04
December	23.4	24.4	10.2	8.3	13.1	16.2	16.8	16.4	18.8	23.9
January	24.3	24.7	7.8	9.3	17.2	15.3	16.0	17.0	24.7	22.4
February	26.2	25.0	8.9	9.7	18.2	15.4	17.6	17.4	25.4	23.5
March	26.4	25.3	8.9	9.7	17.9	15.7	17.7	17.5	23.8	23.0
April	24.3	23.2	10.2	10.0	14.1	13.2	17.3	16.6	19.3	20.3
May	23.5	23.8	10.9	9.7	12.6	14.2	17.2	16.8	18.3	22.2
June	21.8	22.4	10.3	9.1	12.3	13.4	16.1	15.8	16.3	17.3
July	21.5	22.6	10.2	8.0	11.3	14.6	15.9	15.3	18.6	19.9
August	22.2	22.5	10.4	9.0	11.8	13.6	16.3	15.8	18.4	19.4
September	23.8	23.3	8.9	8.9	14.9	14.5	16.4	16.1	20.3	21.4
October	24.2	22.8	9.7	9.0	14.5	14.8	17.0	15.9	19.7	20.8
November	23.9	22.0	10.4	9.1	13.5	13.7	17.2	15.6	20.3	19.9
Mean	24.0	23.7	9.7	9.1	14.3	14.6	16.9	16.4	20.3	21.2

Table 4. Monthly rainfall, evapotranspiration and soil water deficits at Kericho in 2002/03 and 2003/04.

	Rainfall (mm)		Rainfall LTA[2]	Evapotranspiration, E_t (mm)		SWD[1] (mm)	
Month/Year	2002/03 (n)	2003/4 (n)	(mm)	2002/03	2003/04	2002/03	2003/04
December	190 (17)	68 (7)	91	120	139	Nil	71
January	87 (6)	132 (8)	96	145	138	48	6
February	20 (4)	107 (11)	92	148	137	128	30
March	81 (9)	158 (12)	158	157	148	76	Nil
April	321 (21)	325 (24)	260	118	116	Nil	Nil
May	368 (24)	152 (14)	285	113	131	Nil	Nil
June	160 (22)	126 (15)	255	96	104	Nil	Nil
July	227 (23)	222 (19)	187	110	112	Nil	Nil
August	264 (18)	223 (20)	214	112	117	Nil	Nil
September	261 (20)	169 (21)	181	123	123	Nil	Nil
October	223 (17)	57 (15)	161	124	125	Nil	68
November	72 (12)	112 (12)	144	124	111	52	Nil
Totals	2338 (193)	1851 (178)	2124	1490	1501	304	175

[1] SWD, Soil water deficit is difference between potential evapotranspiration (E_t) and rainfall.
[2] LTA, Long-term average based on 53-years data (1952–2004).
(n), number of rainy days during the month/period.

made tea ha^{-1}, respectively, were attained at an N-rate of 200 kg ha^{-1}. The 43-year old seedling plantation showed mean yields of 2037 and 2619 kg made tea ha^{-1} in 2002/03 and 2003/04, respectively. The 76-year old seedling tea plantation had a slightly negative response to N-rate in the two consecutive years; yields were relatively stable at a mean of 2958 kg made tea ha^{-1} in the two consecutive years, showing that drought stress experienced in 2002/03 did not affect yield. The response to N in the clonal tea plantation varied with age as shown by the 14-year tea plantation giving a maximum yield at 100 kg N ha^{-1} compared to the 29-year old where the peaks are obtained at 200 kg N ha^{-1}. Although the 43-year seedling tea plantation gave consistently better yields at 100 kg N ha^{-1}, the yields were not significantly different at $P \leq 0.05$. Averaged for N-treatments, a strong effect of age was shown in 2002/03 for seedling bushes, while for clonal bushes the effect was clearer in 2003/04. For similar genotypes, clone or seedlings, yields increased with age.

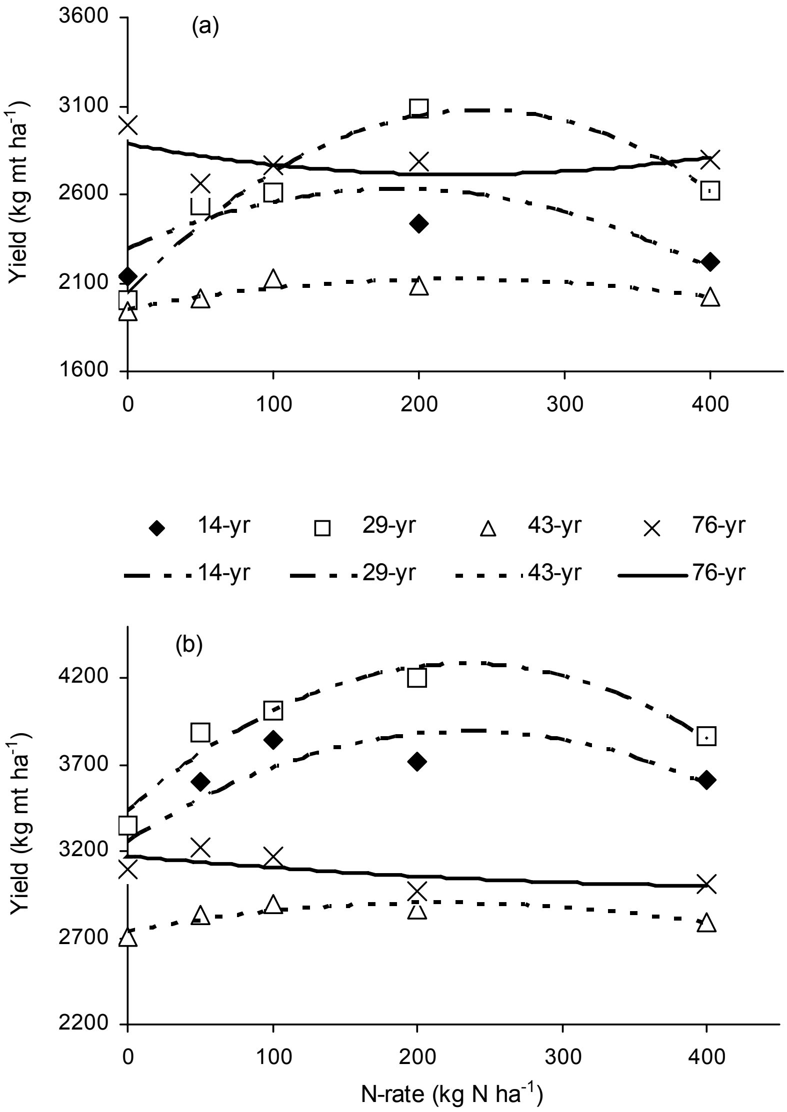

Figure 1. Annual yield responses in kg made tea ha^{-1} to N-application in (a) 2002/03, and (b) 2003/04.

Seasonal yield response to nitrogen

The seasonal responses to N are presented in Figures 2a and 2b where yields are expressed as kg mt ha^{-1} month^{-1}; the average seasonal yield responses are shown for both years in Table 5. In 2002/03, only the 29-year old plantation responded significantly to N-rate in season 2 (*P*=0.048) and season 3 (*P*=0.045). However, in 2003/04, the 14-year old tea plantation showed a strong response to N-rates in season 2 (*P*=0.003), while the 29-year plantation responded significantly in season 1 (*P*=0.025) as well as season 2 (*P*=0.013). A comparison of the monthly data (kg mt ha^{-1} month^{-1}) shows that season 1 had the lowest and season 3 the highest yields, apart from the seedling plantations in 2003/04.

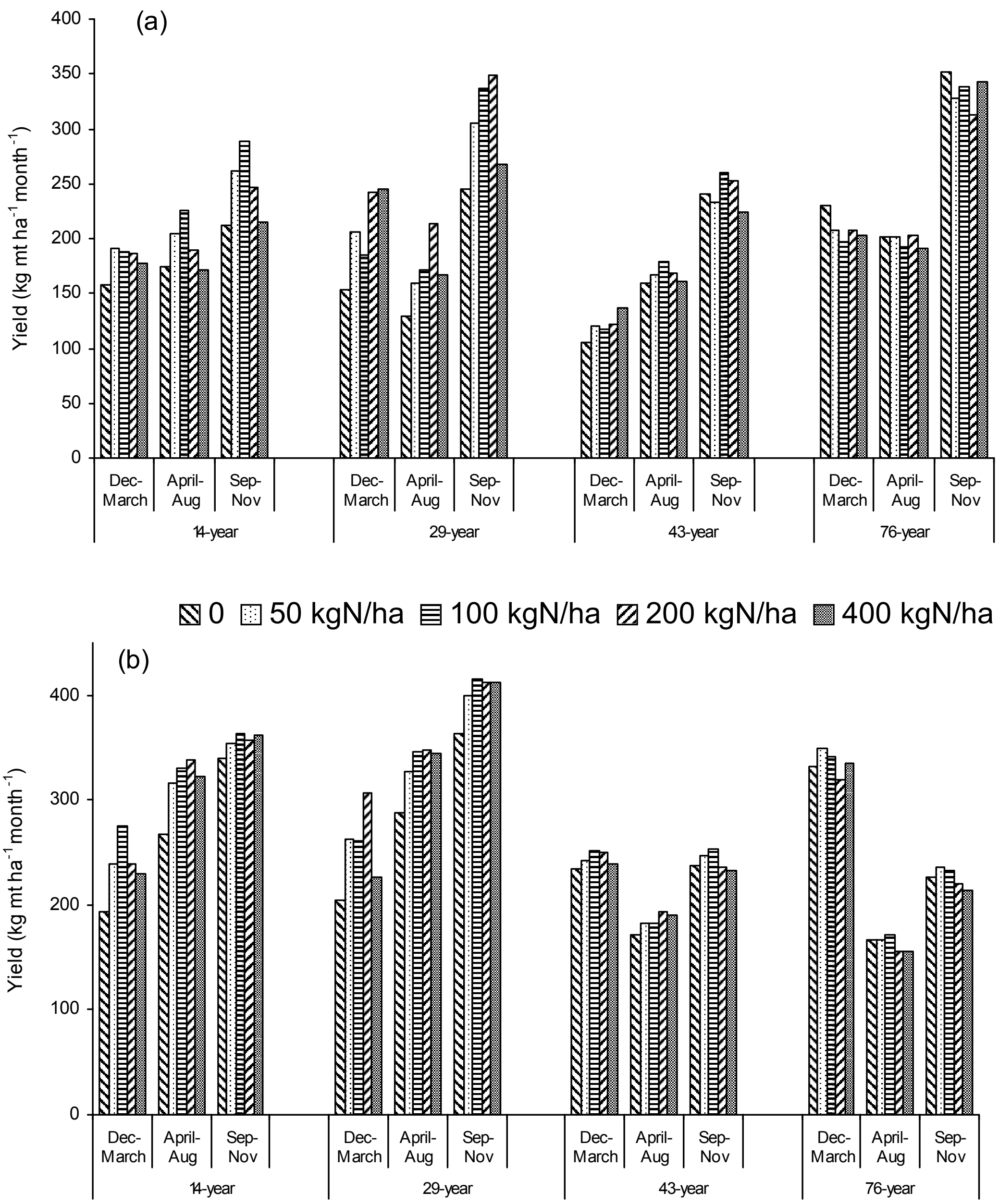

Figure 2. Average seasonal made tea yields per month (in kg mt ha^{-1}) for three seasons and five N-rates in (a) 2002/03, and (b) 2003/04.

The dynamics of monthly yield (kg mt ha^{-1}) trends in both years are shown in Figures 3a, b. The strongest decline in yield was found from February to April in 2002/03 while the yields in 2003/04 were relatively constant apart from a few outliers. As a consequence of the drought in February–March 2003, there was a decline in yields followed by a recovery of yields from April onwards for all genotypes, whereas the effect of low temperatures in June–July in 2003/04 resulted in a decline of yields. Seedlings were also not affected much by drought and plucking was still done during the entire warm-dry season in 2002/03.

Table 5. Observed mean seasonal and annual yields (kg mt ha^{-1}) in 2002/03 and 2003/04.

Year	Genotype	Age (years)	Season Dec–Mar	Apr–Aug	Sep–Nov	Annual yield (kg mt ha^{-1})
2002/03	Clonal	14	721	966	734	2422
	Clonal	29	825	841	902	2568
	Seedling	43	483	833	721	2037
	Seedling	76	834	986	1000	2819
2003/04	Clonal	14	941	1575	1067	3582
	Clonal	29	1009	1655	1201	3866
	Seedling	43	973	1120	724	2817
	Seedling	76	1341	1078	677	3096

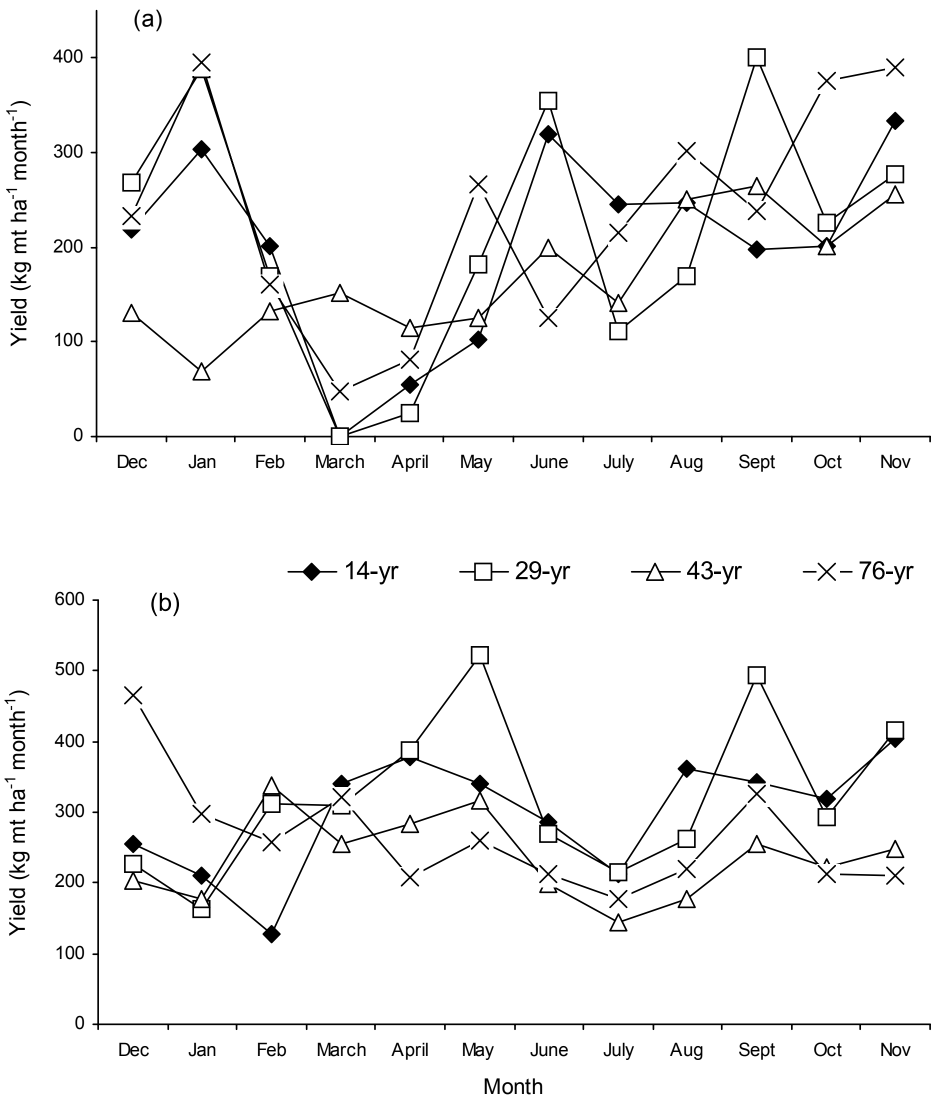

Figure 3. Trends in made tea yields (kg mt ha^{-1} month^{-1}) in (a) 2002/03, and (b) 2003/04.

Seasonal variations in yield related to temperature, rainfall and solar radiation

The seasonal variations in made tea yields indicate that yields differ irrespective of N-application rate. Seasonal yield variations are associated to shoot development and extension. The effects of temperature, i.e. average daily heat-load (°C), rainfall amount (mm d^{-1}) and solar radiation (MJ m^{-2} d^{-1}) were investigated. Temperature effects are illustrated by the relationship between mean yield per week and daily heat-load in Figures 4a and 4b for 2002/03 and 2003/04, respectively. Daily heat-loads varied between 6.8 and 9.2 °C and between 6.3 and 8.5 °C in 2002/03 and 2003/04, respectively. However, the variances in heat-load between years were low at 0.5 and 0.7 in 2002/03 and 2003/04, respectively. No significant effects were found for the seedlings and clonal cultivar in 2002/03 and 2003/04, respectively. The trends suggest that the optimum daily heat load varies between 6.5 and 8.0 °C corresponding to actual temperatures of 15.5 and 17.0 °C.

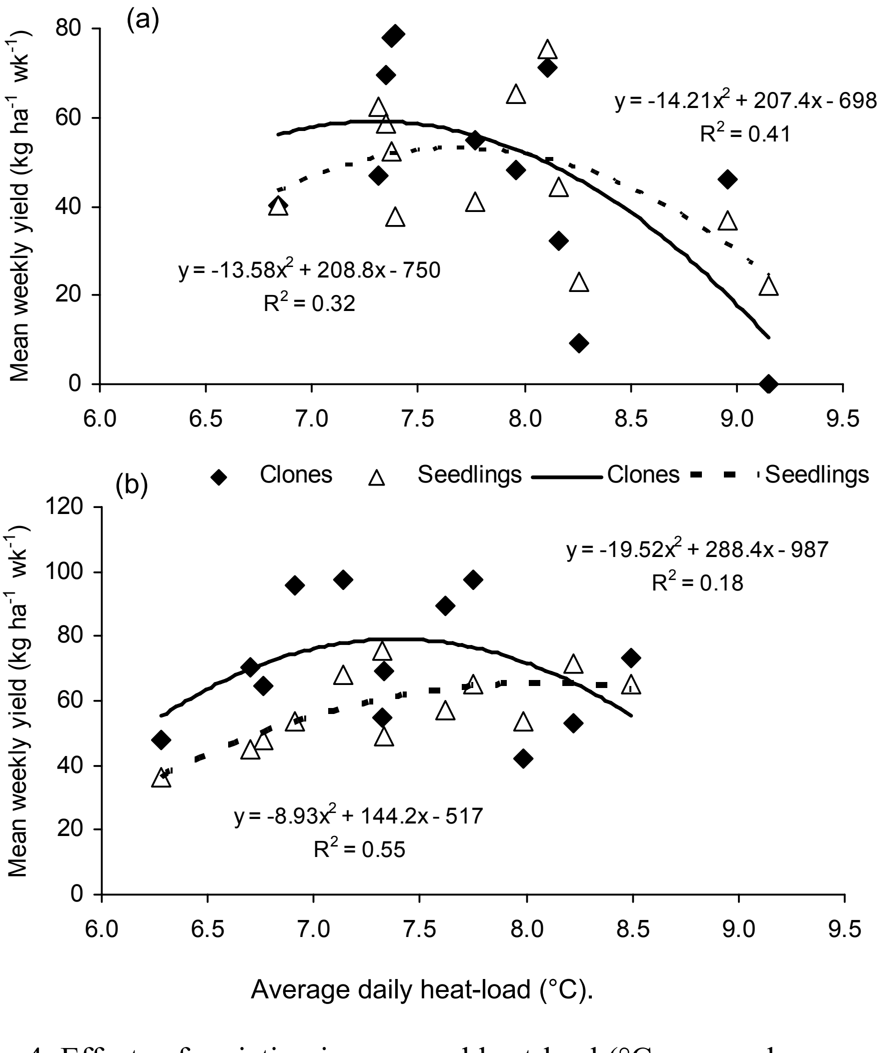

Figure 4. Effects of variation in averaged heat-load (°C, grouped per month) on tea yields (kg made tea ha^{-1} wk^{-1}) in (a) 2002/03, and (b) 2003/04.

Table 6. Total N-uptake in 'two leaves and a bud' (kg N ha^{-1}), apparent shoot N-recovery (kg kg^{-1}), and N-excess (kg ha^{-1}) in 2002/03 and 2003/04.

Genotype	Age	Fertilizer	2002/03			2003/04		
		N-applied	Total N-uptake	App. N-recovery	N-excess	Total N-uptake	App. N-recovery	N-excess (kg N ha^{-1})
	(yrs)	(kg N ha^{-1})	(kg N ha^{-1})	(kg kg^{-1})	(kg N ha^{-1})	(kg N ha^{-1})	(kg kg^{-1})	
Clonal	14	0	86	-	-	104	-	-
		50	106	0.40	30	122	0.36	32
		100	113	0.27	73	137	0.33	67
		200	102	0.08	184	142	0.19	162
		400	95	0.02	391	133	0.07	371
Clonal	29	0	76	-	-	101	-	-
		50	95	0.38	31	126	0.50	25
		100	100	0.24	76	129	0.28	72
		200	119	0.22	157	139	0.19	162
		400	103	0.07	373	132	0.08	369
Seedling	43	0	82	-	-	103	-	-
		50	85	0.06	47	116	0.26	37
		100	90	0.08	92	117	0.14	86
		200	88	0.03	194	118	0.08	185
		400	88	0.02	394	110	0.02	393
Seedling	76	0	124	-	-	143	-	-
		50	117	–0.14	54	153	0.20	40
		100	118	–0.06	106	145	0.02	98
		200	119	–0.03	205	140	–0.02	203
		400	120	–0.01	404	133	–0.03	410

Seasonal variations in mean weekly yield due to rainfall and solar radiation are shown in Figures 5a, 5b and Figures 6a, 6b for both years, respectively. The daily rainfall distribution ranged 0.7 to 12 (mean 6.2, SD 3.5) and 1.8 to 10.8 (mean 5.1, SD 2.4) in 2002/03 and 2003/04, respectively. Thus, the distribution of rainfall was poor in the first year when compared to the second year. Under the more favourable conditions in 2003/04 the clonal bushes showed higher yields per unit rainfall, which will result in higher water productivity (WP). Solar radiation did not appear to have a clear influence on yields in both years. The big scatter shown by the clonal cultivars suggest a higher sensitivity to adverse weather conditions like extreme temperatures (cold, heat), drought and bright sunshine compared to the seedling cultivars.

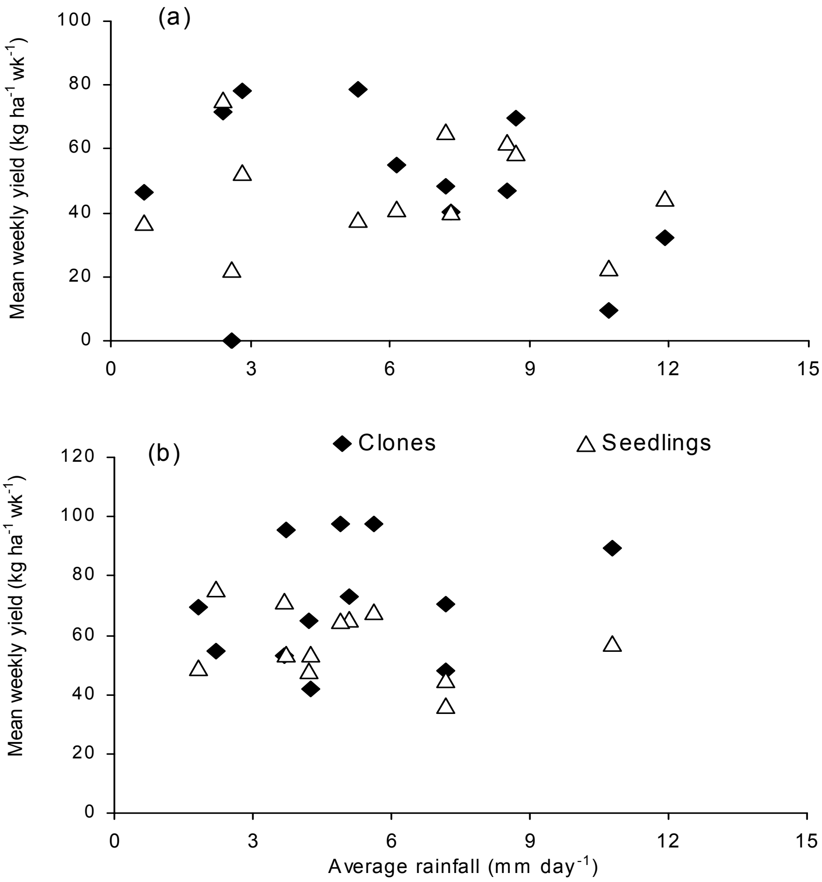

Figure 5. Effects of variation in averaged rainfall (mm d^{-1}, grouped per month) on tea yields (kg made tea ha^{-1} wk^{-1}) in (a) 2002/03, and (b) 2003/04.

Seasonal and annual N-uptake

The patterns in total N-uptake were similar to the seasonal yield trends. The total N-uptake at various N-rates by harvesting 'two leaves and bud' varied between the two years and also among seasons for the seedling cultivars (Figures 7a, 7b). The clonal tea plantations had the highest mean N-uptake in season 3 of both years, while it applied for the seedling stands only in 2002/03. In contrast, seedling stands had the highest N-uptake during the warm-dry season (1) of 2003/04. The total N-uptake amounted to 100, 99, 87, 120 kg N ha^{-1} yr^{-1} in 2002/03, and 128, 125, 113, 143 kg N ha^{-1} yr^{-1} in 2003/04, for the 14-, 29-, 43-, and 76-year tea plantation, respectively. There was a noted similarity in N-uptake for the seedlings between season 3 of 2002/03 and season 1 of 2003/04.

A strong relationship was found between N-uptake and harvested crop biomass (made tea yields) under non-limiting N conditions. These relationships are presented as power functions in Figure 8. Yields from the control treatments in the 14- and 29-year old clonal plantations were assumed to be N-limited, hence were omitted from the

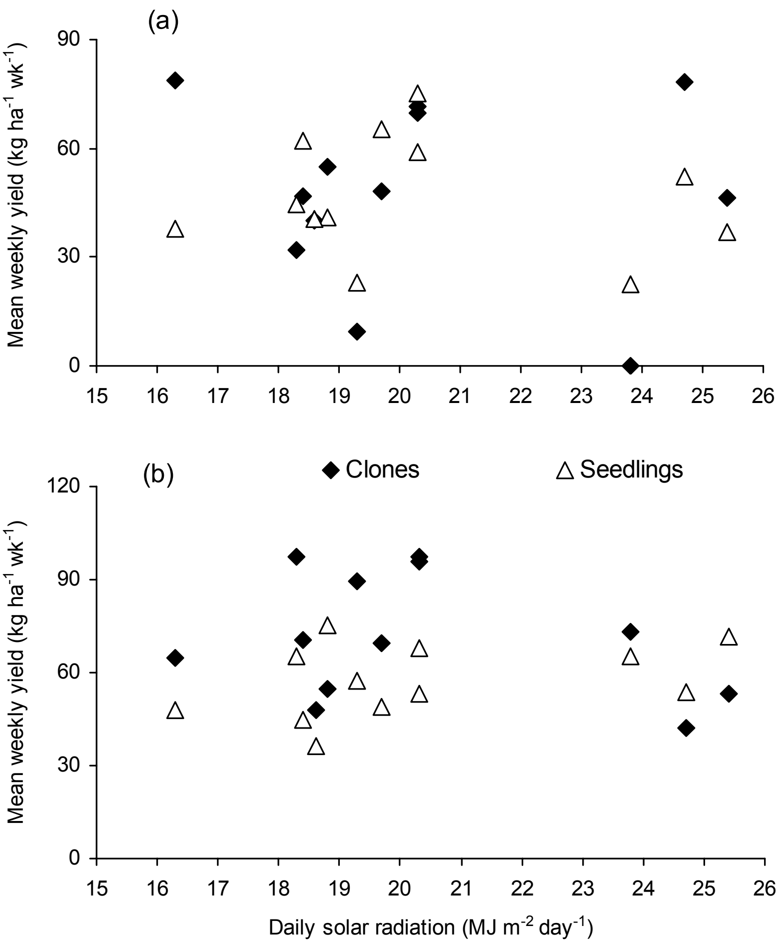

Figure 6. Effects of variation in solar radiation (MJ m^{-2} d^{-1}, grouped per month) on tea yields (kg made tea ha^{-1} wk^{-1}) in (a) 2002/03, and (b) 2003/04.

regression analyses. The regression on yield data were not significantly different between the individual years, hence the data for two years were merged (Figure 8a). Significant relationships were also found for the clonal tea plantations (Figure 8b) but not for the seedlings. To analyse the effect of age, the individual clonal tea plantations were separately fitted. Similar regression equations were obtained with the clonal tea cultivar for different age classes (Figure 8c). The parameter values for the relationship between critical N-uptake and biomass yield of tea plantations are summarized in Table 7.

Apparent shoot N-recovery (ASNR) and N-pools prone to losses

Data on ASNR and N-excess prone are presented in Table 6. The estimates of apparent shoot N-fertilizer recovery derived from the harvested leaf N and the N-applied during 2002/03 and 2003/04 showed that the fraction N-recovered decreased for the N-applied in the order: 50 > 100 > 200 > 400 kg ha^{-1} irrespective of genotype and age. The highest ASNR of 0.40 and 0.38 kg kg^{-1} in 2002/03, and 0.36 and 0.50 kg kg^{-1} in

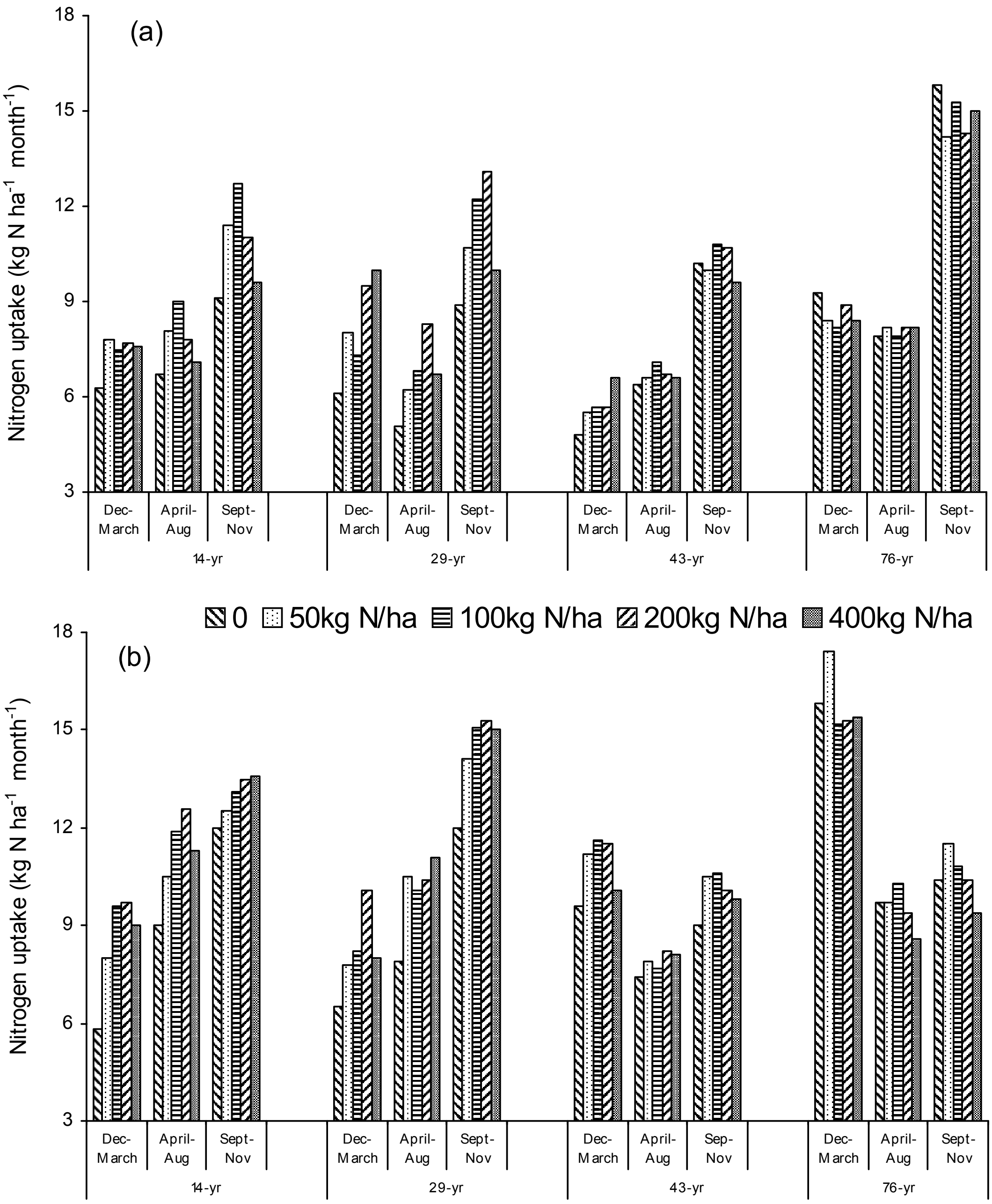

Figure 7. Total N-uptake (kg N ha^{-1} month^{-1}) in 'two leaves and bud' during three seasons in (a) 2002/03, and (b) 2003/04.

2003/04 were recorded in the 14- and 29-year clonal tea plantations, respectively compared to 0.08 and –0.01 kg kg^{-1} in 2002/03, and 0.26 and 0.20 kg kg^{-1} in 2003/04 in the 43- and 76-year seedling cultivars, respectively.

A simple N balance sheet was used to estimate N-excess. N-excess increased with the rate of N-application; at the lowest rate (50 kg N ha^{-1}) ranging from 25 to 54 kg ha^{-1} and at the highest rate (400 kg N ha^{-1}) from 369 to 410 kg ha^{-1}. Higher N-pools

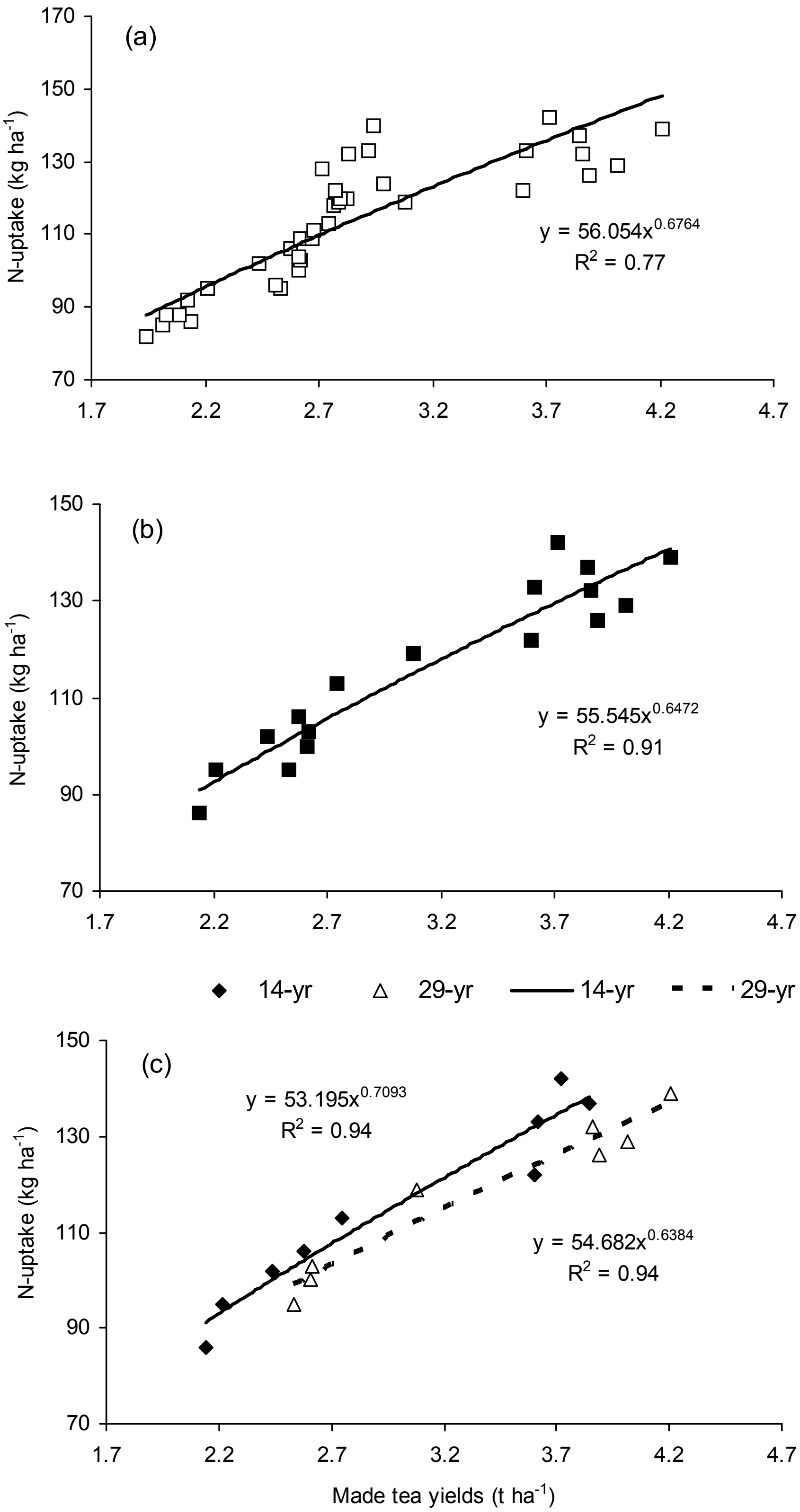

Figure 8. The relationship between total N-uptake and made tea yields under non-limiting N conditions for (a) all plantations, (b) clonal plantations, and (c) 14- and 29-year old clonal plantations.

prone to losses were obtained in the older plantations with seedling genotypes. In the younger plantations with clonal cultivars, the differences due to age were fairly small. In 2002/03 the 76-year old tea plantation had an N-excess of 54, 106, 205 and 404 kg ha^{-1} at the 50, 100, 200, and 400 kg N ha^{-1} rate, respectively, while in 2003/04, the N-excess amounted to 203 and 410 kg N ha^{-1} at the 200 and 400 kg N ha^{-1} rates, respectively. The magnitude of the pools prone to N-losses was associated with the rate of fertilizer and age of plantations.

Discussion and conclusions

Seasonal and annual yield responses

In our study, yield response to N-rates in clonal tea plantations increased with age; however, seedling tea plantations did not respond. The response within seasons showed that yields in the cold-wet season (2) are most crucial in determining annual yield responses to N. Despite the warm-wet season 3 having the highest monthly productivity, the yields hardly responded to N. In the clonal cultivars, lower yields were found at the highest rate of 400 kg N ha^{-1} compared to the 200 kg N ha^{-1} rate. Similar trends have been reported in long-term field experiments; Wanyoko (2002) found higher tea feeder root density of 8 cm cm^{-3} in the non N-applied tea bushes compared to 2 cm cm^{-3} of tea bushes applied with 150 kg N ha^{-1} rates for 20 years; hardly any feeder roots were observed at the 400 kg N ha^{-1} rate (Wanyoko, 2003). Tea feeder roots occur as a mat on the tea surface where the fertilizer is spread along the rows. The long dry and hot period in February–March 2003, could have contributed to a high percentage of death of feeder roots in bushes applied with high rates of urea (400 kg N ha^{-1}), leading to lower yields in the following seasons 2 and 3. The seedling tea cultivars did not respond to N either per season or per annum and therefore do not require N-fertilizer. Moreover, the yield benefit to N dwindles with age as is illustrated with a fairly small but positive N-response curve in the younger 43-year old seedling tea to a negative N-response curve in the much older 76-year seedling plantation.

A comparison of the total made tea yields reveals that in 2003/04, yields were 48%, 51%, 29% and 0.1% higher than in 2002/03 for the 14-, 29-, 43-, and 76-year old tea plantations. Although all tea plantations were affected by unfavourable weather conditions including critical drought in season 1 of 2002/03, the seedling tea genotypes could be plucked even during the drought period compared to the clonal cultivars that were not plucked from mid February to the end of April 2003 (Figure 3). Othieno et al. (1992) found that 50% of the annual variation in younger seedling tea yields of up to 24 years old was attributed to drought and 16% to damage by hailstorm(s). Willat (1971) suggested that exceeding a critical SWD value would cause a yield decline. Based on studies in southern Tanzania, Nixon et al. (2001) reported that at a SWD > 100 mm yield loss per unit of water deficit was 0.3 kg mt ha^{-1}, but increased to 1.0 kg mt ha^{-1} at SWD > 300 mm in mature 22-year old clonal tea plants. No yield loss owing to hail damage was observed during the entire period of this study, though a few light hailstorms were experienced in May–August 2003.

The adaptive response of older tea plantations can be attributed to deeper rooting and higher carbon stocks (Chapter 4). This agrees with the findings of a study using a crop growth model CUPPA-Tea, that in irrigated tea-growing areas, water saving irrigation in mature-deep rooted tea for economic reasons will not have detrimental effects on long-term bush health (Matthews and Stephens, 1998b). Whereas all other tea plantations improved yields in 2003/04, the 76-year old showed constant yields implying that the genetic yielding ability could have been attained. The findings herein are similar to those reported by Dang (2005), who compared 10-, 25-, and 40-year old tea plantations in the highlands of Vietnam. He found similar mean yields in 10- and 25-year old plantations but significant lower yields in the 40-year old tea plantation. The yield of tea plantations in Vietnam however appear to stagnate at a relatively younger age compared to the Kenyan tea plantations, where an increase in yield and response to N is still being shown after 30-years by clonal tea cultivars.

Tea growers in most regions of Kenya including those that have a bimodal type of rainfall, long rains from mid March to June, and short rains from mid September–mid-November, traditionally apply N-fertilizers either at the beginning of season 2 in April/May or the second half of season 3 in October/November. In this study, although N-fertilizer effects are most clear in season 2, the small yield benefits to N application in the different cultivars appear to spread through all seasons (Figure 2). The prevailing weather conditions as seen in the different seasons during two contrasting study years, also determine yields per season (Matthews and Stephens, 1998b). The effects of N-rates are only seen in the 29-year old plantation in season 3 of 2002/03 and not in others. This is unexpected considering that the warm-wet weather experienced in season 3 is at optimum for tea growth, suggesting that one dose of N-fertilizer application does not match with crop demand in a long-growing season. Thus to optimize on fertilizer N-response, there is need for split applications that will also reduce the N-excess pool prone to N-losses.

Estimates of total N-uptake and apparent shoot N-recovery

In this study, we found that the N-concentrations in 'two leaves and a bud' are similar within genotypes and age class and are not influenced by seasons but this was not the case in the older first mature leaves. This implies that there is fast relocation of N from the older leaves of the tea plant to the younger shoots. Other researchers have also shown that plants allocate N to the top-leaves in order to maintain a high rate of crop photosynthesis (Hirose and Werger, 1987; Lemaire and Gastal, 1997). Indeed, the "two leaves and bud' has been observed to be insensitive to N nutrition of the tea bush and hence the recommendation on use of the youngest mature leaf for nutrient diagnosis in East Africa (Othieno, 1988).

Favourable environmental conditions experienced in 2003/04 led to better total N-uptake and apparent shoot N-recovery at all sites. Age of tea plantation in clonal cultivars had little effect on the total-N uptake (Table 6). With seedling tea, however, the 43-year old plantation showed lower N-uptake at all N-rates in 2002/03 and 2003/04 compared with the 76-year old plantation which is attributed to higher yields by the latter. Seedling tea plants showed much lower apparent N-recovery compared to clonal tea cultivars. Apart from the 43- and 76-year seedling tea plantations that had low apparent shoot N-recovery in 2002/3, the figures for the tea plantations are well within the range of other quoted values ranging from 0.20–0.70 kg kg^{-1} (Sanchez, 1976), 0.35 kg kg^{-1} for young clonal tea plants in India (Kumar et al., 1999), and 0.50 kg kg^{-1} for high yielding clonal tea plantations in Malawi (Malenga and Wilkie, 1994). The great variability in apparent N-recovery shown by the seedling tea plantations during the two year study imply a wider genetic variability in the seedlings, compared to the clonal cultivar. Wachira (2002) reported that seedling populations have a wider genetic base compared to clonal tea cultivars. The observed total N-uptake by the tea plantations was generally higher than those reported by De Costa et al. (2005) ranging from 47 to 105 kg N ha^{-1} yr^{-1} with a mean of 69 kg N ha^{-1} yr^{-1}.

N-uptake and biomass relationship

Cultivated tea is maintained as a low bush in a continuous vegetative phase with regular removal of the young shoots. For annual crops, Lemaire et al. (2007) showed that the crop N-uptake is feed-back regulated by the crop mass accumulation potential under non-limiting N-supply within species and across environments. The parameter values we found for the 14- and 29-year old clonal tea plantations in this study (Table 7) correspond with those reported for C_3 crops (Lemaire et al., 2007). It demonstrates that N-uptake – biomass curves can also be applied for perennial crops like tea. The *a*-value that represents the amount of N-required to produce leaf biomass of 1 t ha^{-1} was 53 and 55 kg N ha^{-1} for the 14- and 29-year tea plantations, respectively, showing that both the two tea plantations have similar N-use efficiency.

Potential N-pools prone to losses in relation to age and N-management

The results presented here show that at similar N-rates, higher yields result in lower N-excess from the available N-pool. Similarly, the N-pool prone to losses was

Table 7. Parameter values for the relationship between N-uptake and biomass compared with reported values in literature, using the power function $N_{uptake} = a\ W^b$ under non-limiting N conditions (see also text).

Category	Age (years) / Area grown	Parameter values			Reference
		a	b	R^2	
Tea	(a) All plantations / tropical	56	0.68	0.77 (n=39)	This chapter
Tea	(b) Clonal (14, 29) / tropical	56	0.65	0.91 (n=18)	This chapter
Tea	(c) Clonal (14) / tropical	53	0.71	0.94 (n=9)	This chapter
	Clonal (29) / tropical	55	0.64	0.94 (n=8)	This chapter
Lucerne	Temperate	48	0.67	-	Lemaire et al. (2007)
Wheat	Subtropical	53	0.56	-	Lemaire et al. (2007)
Rice	Tropical	52	0.52	-	Lemaire et al. (2007)

proportional to the applied N-rates in all cases demonstrating the risk of applying high N-rates. For the seedling genotypes, rates above 100 kg N ha^{-1} show that over 88% of the N is prone to losses. The clonal cultivars planted at a denser spacing had relatively smaller N-pools prone to losses compared to the older seedling plantations planted a wider spacing showing the importance of choice of genotype and associated planting densities. The period between April and September is most prone to leaching losses hence fertilizer application should be delayed until October. Unfortunately, June, July and August are also relatively cold and, therefore, slow-down tea growth rate; hence, farmers are often reluctant to apply fertilizers during the second season. The third season from mid-October to the end November has optimum temperatures and rainfall. However, to avoid the risk of a drought in February to March, it is recommended to have split fertilizer applications like 50–100 kg N ha^{-1} in early June (season 2) and the remaining half in October during the third season. Fertilizer applications should be applied at modest levels to coincide with the growth of the tea plant and when potential N-losses are at minimum. The response of tea bushes to N increases up to an age of about 30 years and then seems to stagnate. Hence higher rates of up to 200 kg N ha^{-1} yr^{-1} should be confined to the more productive tea plantations of up to 30 years while younger plantations should receive not more than 150 kg N ha^{-1} yr^{-1}. Older tea plantations do not respond to N-fertilizer and, therefore, applications should be restricted to low levels (about 50 kg N ha^{-1} yr^{-1}) required to maintain tea quality (Owuor and Odhiambo, 1994) and to safeguard against damage by pests during stress periods (Sudoi et al., 1996).

We conclude that clonal tea cultivars respond better to nitrogen irrespective of age, while old seedling genotypes do not, but are affected less by adverse weather.

Productivity is influenced by seasonal weather conditions in both the clonal and seedling tea genotypes; an optimum heat-load and an even rainfall distribution result in high yields. Future N-management should be based on the yielding ability of tea bushes as defined by plant genotype-density combinations and the age class. Ageing as such does not reduce productivity and the response to N.

CHAPTER 4

Carbon and nutrient stocks of tea plantations differing in age, genotype and plant population density

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Abstract
Tea (*Camellia sinensis* L.) is a perennial evergreen shrub managed intensively for continuous growth of young shoots. The extent to which carbon (C) and nutrient (N-P-K) accumulation in bushes varies with age, genotype and plant density, and the effects on tea bush productivity have not been reported yet in literature. To get a better insight in these relationships, the effects of age and the associated change in genotype (clone or seedling) and density on carbon and N-P-K stocks in tea bushes and on the partitioning within bushes were analysed by destructive sampling of whole tea bushes.

A chronosequence of plantations differing in age and genotype-density combinations was selected. The 76- and 43-year old plantations were composed of seedling tea planted at a relative low density: a spacing of 1.52 × 0.91 m and 1.22 × 1.22 m, respectively, whereas in the 29- and 14-year old plantations the clonal tea was grown at higher plant densities: a spacing of 1.22 × 0.61 m and 1.22 × 0.76 m, respectively. Total dry matter weights (DM) of tea bushes increased with age from 9.0 to 11.5 kg in clonal bushes and from 13.5 and 19.9 kg per seedling bush for the 14- and 29-year, and the 43- and 76-year old plantations, respectively. Most DM was stored in the woody tissue of the tea bush frame. Total C-stocks expressed per unit area (ha) amounted to 44 and 72, and 43 and 69 t C ha^{-1}, respectively. The total nutrient stocks ranged for N from 732 to 995 and from 734 to 1,200 kg ha^{-1}, for P from 78 to 120 and from 67 to 92 kg ha^{-1}, and for K from 775 to 901 and from 646 to 1,120 kg K ha^{-1}, in correspondence with age and genotype-density combinations. Although tea plantations accumulate less biomass than tropical forests and mature plantation trees, these perennial agro-ecosystems contribute to a sustained carbon sequestration in fragile areas. It is concluded that ageing in tea plantations results in high C and N, P, and K stocks that might be functional in maintaining yield stability under adverse weather conditions. Plantations with higher nutrient stocks are less responsive to nutrients and therefore will require lower fertilizer applications.

Keywords: Biomass, nitrogen, phosphorus, potassium, clonal, seedling.

Introduction

Tea (*Camellia sinensis* L.) is a perennial evergreen shrub managed intensively by periodically lopping to form a table facilitating plucking, either by hand or machine. Tea plantations in Kenya occupy a large acreage of agricultural land measuring over 136,700 ha in 2004. The plantations are mainly located in high-potential areas categorized as Lower Highland Zone – LH1, and Upper Middle Zone – UM1 (Jaetzold and Schmidt, 1982; Sombroek et al., 1980). These zones have fragile soils and comprise of the 10% of total area under indigenous forest (Oglethorpe and Oliech, 1992) representing a large fraction of the forest area in Kenya (Anonymous, 2004). The forest area continues to decrease as a result of the expansion in land used for agriculture, overgrazing, commercial timber harvesting, over-exploitation for fuel wood and fencing poles, and general industrial and settlement development. An example is the Kakamega Forest in western Kenya where 50% (14,000 ha) of the indigenous forest cover was cleared in a time-span of 30 years (Wass, 1995). On a global scale, an estimated 13 million ha of forests in the tropics are lost each year (FAO, 1999).

Pastures store most of their carbon and nitrogen below-ground as soil organic matter. In contrast, temperate conifer forests often store large amounts of organic matter above-ground in woody plant tissue and fibrous litter (Sharrow and Ismail, 2004). Reported data on carbon and nutrients storage are mostly based on allometric relationships equations (Brown, 1997; Malhi and Grace, 2000; Jepsen, 2006; Lecointe et al., 2006; Green et al., 2007). Young forests are favoured for carbon sequestration, because of their ability to accumulate large amounts of organic matter in woody biomass and resistant litter (Thuille et al., 2000). Nutrients, especially nitrogen are known to be key determinants of carbon sequestration in various forest ecosystems (Kimmins, 1996; San Jose, 1995). Little information is available on the quantification of carbon storage in tea plantations, which would fill the gap for comparison with the native forest vegetation or other agricultural use in line with change in land use. Information based on *in situ* measurements in tea plantations of above-ground biomass (foliage and bush frame) and below-ground biomass (tea root system) benchmark tea plantations with forests.

No studies assessing carbon and nutrients allocation and stocks in tea plantations have been carried out in Kenya, yet these stocks could be an important carbon and nutrient source for maintaining crop productivity under variable weather conditions. It is postulated here that ageing of tea plantations can enhance adaptation of bushes to abiotic stress conditions (drought, cold, nutrient limitations). Quantifying budgets for C- and nutrient stocks will assist to explore the response of tea plantations to such abiotic stresses, and offer new insights for management interventions (uprooting, fertilization, irrigation). Indeed, the tea growers in Kenya have expressed much concern of the changing weather patterns in the prime tea-growing areas, where harsh conditions like serious frost incidences and extended dry spells have become common (Anonymous, 2000). The vulnerability of the tea industry in Sri Lanka to global warming and climate change has been reported by Wijerante (1996).

To quantify carbon and nutrient stocks and test the hypothesis that carbon and nutrient accumulation in tea plantations vary with age, we selected and examined a stand chronosequence of the tea plantations (14-, 29-, 43-, and 76-year old) with similar cultivation history, with the primary objectives of (a) determining temporal dynamics in standing biomass and dry matter partitioning in tea bushes varying in age and associated tea type and population density, (b) determining the stocks of carbon (C) and nitrogen (N), phosphorus (P) and potassium (K) in the tea plantations and thereby (c) assessing the consequences of carbon and nutrient stocks for tea crop productivity and ecosystem stability.

Materials and methods

Study area and experimental sites

The study was conducted in the Kericho region, the main tea-growing area in the western highlands of Kenya. Four sites with uniformly managed tea plantations planted in 1988, 1973, 1959 and 1926 and with known past cultivation history were selected in January 2002. The age of these plantations is based on 2002 as a reference year. Genotype choice (seedling or clone) and plant density were determined by a change in management practices, lower yielding seedlings were replaced by higher yielding clones. In the older plantations, 43- and 76-years, seedlings were planted at relatively low densities (LD): 6,730 and 7,179 plants ha^{-1}, respectively. In the younger plantations,14- and 29-years, an average yielding clone – TRFK 6/8 – was planted at relatively high densities (HD): 10,766 and 13,448 plants ha^{-1}, respectively. All tea plantations were managed according to best practices.

The four sites are located within a radius of four kilometres from the Tea Research Foundation of Kenya (TRFK) Headquarters at Timbilil Estate, Kericho, at an elevation of 2,110–2,180 m above sea level, latitude 0°22′ S, and longitude 35°21′ E. The daily mean air temperatures ranged from 15.5 to 18 °C and a mean annual rainfall of 2,150 mm (Stephens et al., 1992). The monthly radiation, temperature, rainfall, evapotranspiration and soil water deficits at Kericho between December 2002 and November 2004 and the detailed experimental design and treatments are reported in Chapter3. In brief, the field experiments in each site were laid out in a randomized block design consisting of five N-fertilizer rates (0, 50, 100, 200 and 400 kg ha^{-1}) replicated three times. P and K were applied uniformly at 100 kg P_2O_5 ha^{-1} yr^{-1} and 100 kg K_2O ha^{-1} yr^{-1}, respectively.

Sampling procedure and measurements

From February to April 2003 the experimental sites experienced a severe drought affecting shoot growth in most tea bushes. Subsequently, at least 5 bushes per plot at all the four sites were tagged depending on the visual symptoms as 'non-affected', 'mildly affected' and 'severely affected'. To avoid the extremes in terms of drought effects, one 'mildly affected' tea bush per plot in all the 15 plots per site was randomly selected and uprooted. These tea bushes were cut at the base of the stem and the excavation of all the roots done by hand based on the plant spacing area (Table 1) e.g. 1.22 × 0.76 m for the 14-year plantation with 10,766 plants ha^{-1} density. Each tea bush was partitioned into 'two leaves and a bud', maintenance foliage, twigs, stem, thick woody roots and thin feeder roots. Samples of all plant components were oven-dried at 105 °C for 24 hours to determine the dry matter content. For the "two leaves and a bud" material, the samples of three replicates were merged to obtain an adequate sample size for further analyses. All other plant samples were analysed separately using procedures and analyses outlined in the next section.

Laboratory methods

In the dried and ground samples, organic C was determined using Walkley-Black method (IITA, 1979a) while total N was determined by Kjeldahl digestion, distillation and titration method (Anderson and Ingram, 1996). For total P, dried sub-samples were ashed in a muffle furnace at 450 °C for four and a half hours and P determined colorimetrically with Spectronic20 at 400 nm after complexing with a mixture of ammonium molybdate and ammonium metavanadate in concentrated nitric acid (IITA, 1979b). For K, the ashed samples were digested with a mixture of double acid (HCl and HNO_3) and hydrogen peroxide in a ratio of 2:3 and extracted with 0.05 M HCl (IITA, 1979a) and K determined by flame photometry.

Table 1. Characteristics of the tea plantations varying in age and genotype-planting density combinations.

Acronym	Genotype	Age (yr)	Spacing (m)	Plants per ha
14HD	Clonal	14	1.22 × 0.76	10,766
29HD	Clonal	29	1.22 × 0.61	13,448
43LD	Seedling	43	1.22 × 1.22	6,730
76LD	Seedling	76	1.52 × 0.91	7,179

Above- and below-ground components

The above- and below-ground biomass and C-stocks per bush were combined into three different classes, i.e. (i) *Foliage* consisting of the plucked two leaves and bud and maintenance foliage, (ii) *Frame* consisting of the woody twigs and stem, and, (iii) *Roots* consisting of woody thick roots and thin feeder roots. To determine the C-stocks of the combined classes per bush, a weighted average from the individual organic carbon contents and dry mass in the plant parts was used.

Data analysis and statistics

The data obtained were subjected to an ANOVA analysis using MSTAT-C (1993) statistical software package with age and genotype as main treatments and nitrogen fertilization as sub-treatments. Mean separation of the various effects was done using the least significant difference (LSD). Nitrogen application rates did not have significant effects on the dry matter as shown in Table 2; therefore, only the effects of age and genotype-density combinations are presented, thereafter.

Results

Above- and below-ground biomass accumulation

More dry mass was accumulated in plant parts of seedlings (LD) compared to the clonal (HD) plantations (Table 3). The total biomass of the differently aged tea

Table 2. Total dry weights (kg DM bush^{-1}) of tea bushes for clones and seedlings at 5 N-rates.

Genotype	Age	N-rates (kg ha^{-1})					Mean
	(yr)	0	50	100	200	400	N-rates
Clonal	14	8.7	9.1	9.3	8.2	9.4	9.0
	29	10.8	8.9	12.8	13.4	11.7	11.5
Clonal mean		9.7	9.0	11.1	10.8	10.6	10.2
Seedling	43	17.8	12.5	11.1	13.6	12.4	13.5
	76	18.9	19.5	20.6	21.3	19.2	19.9
Seedling mean		18.4	16.0	15.9	17.5	15.8	16.7
Overall mean		14.0	12.5	13.5	14.1	13.2	13.5
		Genotype	Age	N-rates			
C.V. (%)		33	33	27			
LSD (P=0.05)		0.8	0.8	NS			

C.V., Coefficient of Variation.

NS, non significant.

Table 3. Dry mass of plant parts (kg DM bush^{-1}) for tea plantations differing in genotype and age class.

Plant part(s)	Clonal			Seedling		
	14-yr[1]	29-yr	Mean[2]	43-yr	76-yr	Mean
Foliage	0.58a	0.58a	0.58A	0.71a	0.94a	0.83B
Frame	7.21a	9.74b	8.48A	11.40a	16.00b	13.70B
Roots	1.17a	1.19a	1.18A	1.45a	2.92b	2.19B
Total	8.96a	11.51b	10.24A	13.56a	19.86b	16.72B

[1] Values connected horizontally by the same lower-case letter are not significantly different at $P<0.05$.

[2] Means connected horizontally by the same upper-case letter are not significantly different at $P<0.05$.

plantations amounted to 9.0, 11.5, 13.5 and 19.9 kg DM per bush for the 14-, 29-, 43- and 76-year old plantations, respectively. Thus, there is a general increase in dry mass per bush with age in the different genotype-density combinations (Figure 1). The increase was still found after conversion to kg ha^{-1} but the trend existed only for similar tea types, e.g. clonal or seedling (Figure 2).

The tea bushes in all plantations partitioned most dry mass in the woody tissue of the bush frame, i.e. the twigs and stem, representing 81–85% of whole tea bush, compared to roots and foliage with 10–15%, and, 5–6%, respectively (Figure 3). Whereas the younger clonal tea plants had a similar root biomass (Table 3), the older seedling tea plants showed a difference. Tea root biomass of the 76-year old bushes was significantly higher than of the 43-year old bushes:. 2.92 kg plant^{-1} and 1.45 kg plant^{-1}, respectively.

Carbon stocks

The C contents of the plant parts per age class ranged 390–460 g kg^{-1}, 460–480 g kg^{-1}, and 410–510 g kg^{-1}, in foliage, frame, and roots, respectively (Table 4) showing that the variations with age were minimal. However, the carbon storage per age class differed; especially, the amount of C in the frame which increased with age from 3.4 to 7.7 kg C per bush (Figure 4a). By calculating C stocks per unit of area (t C ha^{-1}), the effect of plant density on differences in carbon stocks between the clonal and seedling types was levelled out. However, the age effect still existed within the same plant populations (Figure 4b). The C storage levels in the frame alone ranged from 37 to 62 t C ha^{-1} and from 35 to 55 t C ha^{-1} for the clonal and seedling types, respectively.

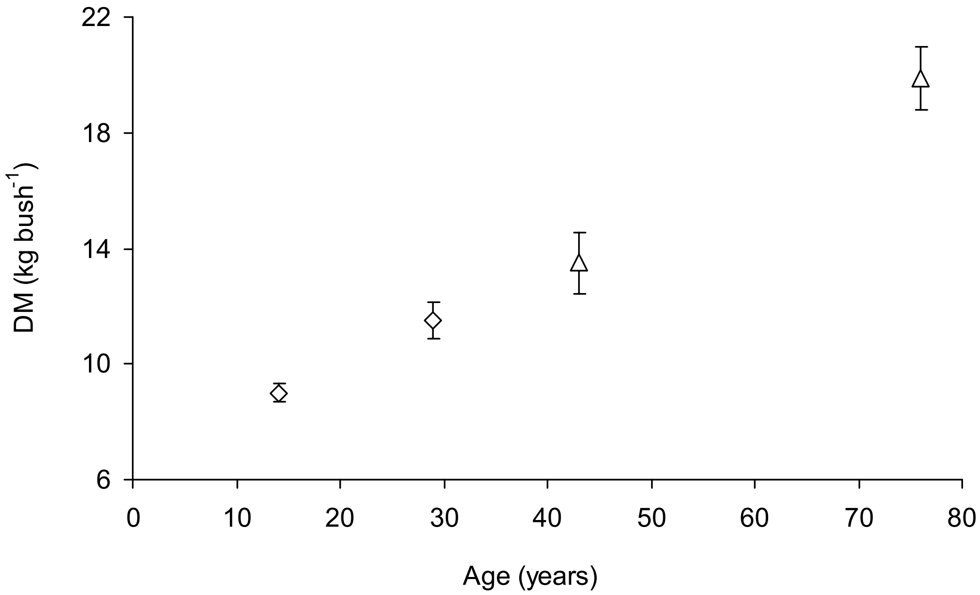

Figure 1. Total dry matter weight per bush in relation to age and genotype-density combinations. Error bars are s.e. of the means, n = 15.

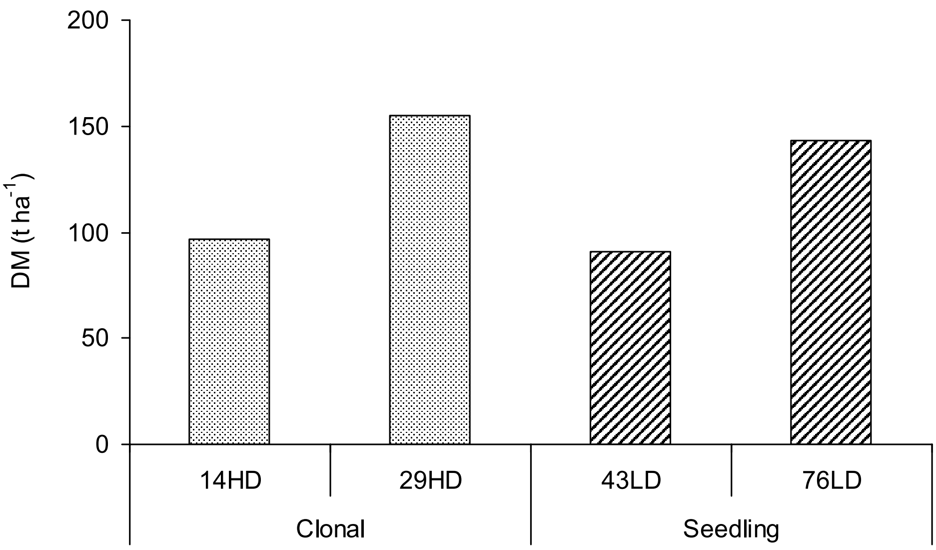

Figure 2. Total dry matter weight per ha in relation to age and genotype-density combinations.

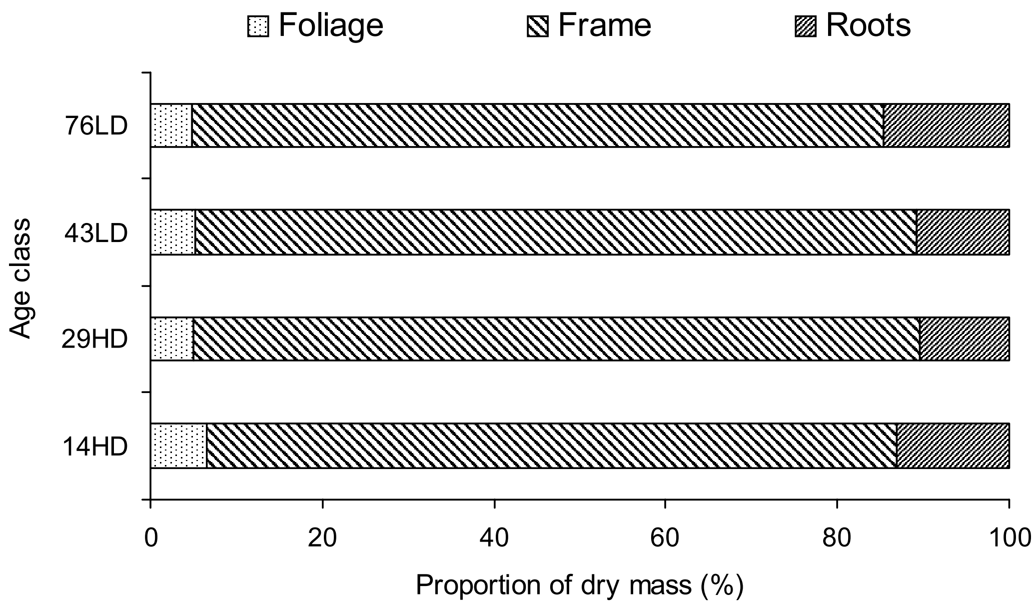

Figure 3. Partitioning of dry mass per tea bush over foliage, frame and roots.

Nutrient contents

N-contents were highest in the seedling plantations, while P and K were not affected much by age × planting density combination (Table 5). Genotype appeared to have a bigger influence on the nutrient contents than the age of the tea bush. Thus, the bushes of the two clonal tea plantations of 14- and 29-years had comparable N-, P-, K-contents; the same applied for the 43- and 76-year old plantations with seedlings. For the above-ground parts, the highest NPK concentration levels were found in the harvestable component of two leaves and a bud, followed by the maintenance foliage, twigs and stem. Similarly, the thin feeder roots had higher NPK nutrient concentrations than the thick woody roots. Whereas the twigs had higher P and K concentrations than in the stem part in the clonal tea bushes, the differences were not significant for P in the older 43- and 76-year seedlings, and K showed the opposite trend. Indeed some twigs in the older tea bushes were almost as thick and woody as the stems, and closer NPK nutrient concentrations were found in these parts.

Nutrient stocks

The N, P, and K stocks per bush and unit area of land are presented in Tables 6 and 7, respectively. The bush frame accounted for most of the NPK stocks compared to foliage and roots. NPK stocks in the tea bush parts generally increased with age especially for the frame and roots. However, when the nutrient contents are converted to kg ha^{-1}, the pattern changed (Table 7) and only within tea types is an increase of the nutrient stocks associated with age. The clonal cultivar planted at higher densities stored considerably more nutrients in the frame per unit of land (ha).

Table 4. Weighted carbon contents (g kg^{-1}) of plant parts in tea bushes differing in age and genotype-density combinations.

Plant part(s)	Clonal		Seedling	
	14-yr	29-yr	43-yr	76-yr
Foliage	390	420	460	440
Frame	470	470	460	480
Roots	410	430	510	500

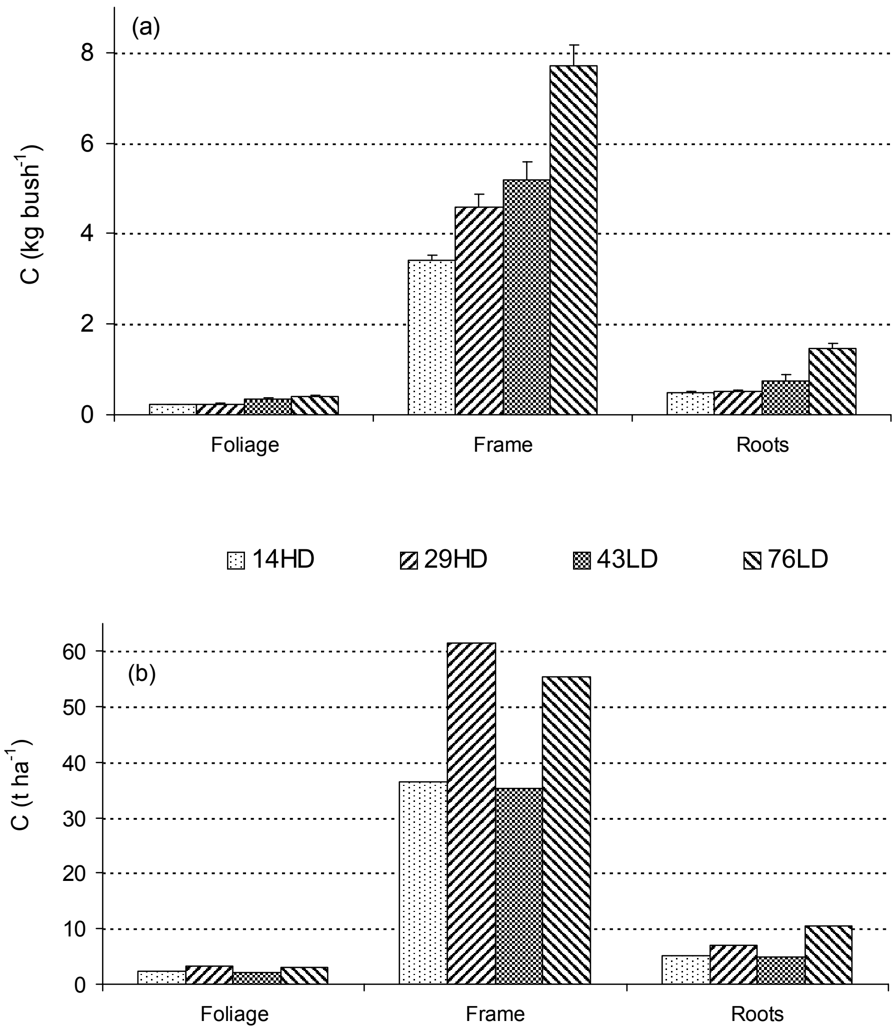

Figure 4. Carbon stocks and distribution in tea plantations differing in age and genotype × density combinations; (a) kg C bush^{-1} and (b) t C ha^{-1}. Error bars are s.e. of the means, n=15.

Table 5. NPK contents (g kg^{-1}) in above- and below-ground plant parts of tea bushes, associated with age and genotype-density combinations.

Nutrient	Plant part	Clonal			Seedling		
		14-yr	29-yr	Mean	43-yr	76-yr	Mean
N	Two leaves and bud	34.5a	34.4a	34.5A	45.0a	44.4a	44.7B
	Maintenance foliage	30.6a	26.7a	28.6A	29.4a	27.4a	28.4A
	Twigs	8.1a	7.2a	7.6A	7.6a	9.3a	8.4B
	Stems	4.1a	4.1a	4.1A	6.4a	6.0a	6.2B
	Thick woody roots	5.6a	4.8a	5.2A	9.3a	8.1a	8.7B
	Thin feeder roots	12.1a	14.3a	13.2A	14.3a	16.1a	15.2B
P	Two leaves and bud	2.69a	2.99a	2.84A	2.82a	2.87a	2.85A
	Maintenance foliage	1.87a	1.94a	1.91B	1.44a	1.53a	1.49A
	Twigs	0.99a	0.83a	0.91B	0.56a	0.63a	0.60A
	Stems	0.53a	0.64a	0.59A	0.57a	0.58a	0.58A
	Thick woody roots	0.71a	0.71a	0.71A	0.77a	0.79a	0.78B
	Thin feeder roots	1.05a	1.03a	1.04B	0.89a	0.88a	0.88A
K	Two leaves and bud	21.9b	20.4a	21.2B	19.5b	17.2a	18.4A
	Maintenance foliage	18.2b	17.8a	18.0B	18.4b	16.8a	17.6A
	Twigs	7.7b	5.4a	6.6B	5.9a	5.7a	5.8A
	Stems	6.9b	4.4a	5.7A	7.3a	8.1b	7.7B
	Thick woody roots	6.1a	8.2b	7.2A	7.0a	10.1b	8.6B
	Thin feeder roots	8.5b	7.4a	8.0A	10.7b	9.8a	10.3B

[1] Values connected horizontally by the same lower-case letter are not significantly different at P<0.05.

[2] Means connected horizontally by the same upper-case letter are not significantly different at P<0.05.

Nitrogen

The total N-stocks for the whole tea bush amounted to 67.6, 74.3, 108.6, and 166.6 g N bush^{-1}, for the 14-, 29-, 43- and 76-year old plantations, respectively. The proportion of N in the foliage decreased with age accounting for 26%, 22%, 19%, and 16% in the 14-, 29-, 43- and 76-year old plantations, respectively (Table 6). However, the frame still showed the highest fraction of N-storage amounting to 63–69%. The N stock per unit area of the clonal population (HD) increased from 732 to 995 kg N ha^{-1} with age from 14- to 29-year old plantations (Table 7). The increase for the seedling population (LD) amounted from 734 to 1,199 kg N ha^{-1}, showing that N stocks increase with age for similar tea types in plantations.

Table 6. NPK distribution (g bush^{-1}) in foliage, frame and roots of tea bushes differing in age and genotype-density combinations.

Nutrient	Age class	Plant part: Foliage	Frame	Roots	Total
N	14HD	17.6 ± 0.8 (26)	42.7 ± 2.6 (63)	7.3 ± 0.4 (10)	67.6
	29HD	15.7 ± 1.4 (22)	51.3 ± 4.1 (69)	7.3 ± 0.5 (9)	74.3
	43LD	20.9 ± 3.1 (19)	74.4 ± 6.0 (68)	13.3 ± 2.6 (12)	108.6
	76LD	25.7 ± 1.8 (16)	114.0 ± 10.8 (68)	26.9 ± 2.5 (16)	166.6
P	14HD	1.1 ± 0.1 (14)	5.3 ± 0.2 (74)	0.9 ± 0.1 (12)	7.2
	29HD	1.2 ± 0.1 (12)	6.9 ± 0.6 (78)	0.9 ± 0.1 (10)	8.9
	43LD	1.1 ± 0.2 (11)	7.9 ± 0.8 (79)	1.0 ± 0.1 (10)	10.0
	76LD	1.5 ± 0.1 (12)	9.2 ± 1.0 (72)	2.1 ± 0.3 (17)	12.8
K	14HD	10.6 ± 0.5 (15)	52.7 ± 2.6 (74)	8.0 ± 0.7 (11)	71.3
	29HD	10.2 ± 0.7 (15)	46.5 ± 3.2 (70)	9.6 ± 0.8 (15)	66.3
	43LD	12.2 ± 1.5 (13)	73.9 ± 7.4 (77)	10.3 ± 1.6 (10)	96.4
	76LD	15.4 ± 1.2 (10)	113.0 ± 12.8 (72)	28.0 ± 2.9 (18)	156.4

± indicates standard errors of the mean, n = 15.

Figures in parenthesis are percentages of the plant parts to total bush dry mass.

Table 7. Distribution of NPK stocks (kg ha^{-1}) in tea plantations differing in age and genotype-density combinations.

Nutrient	Age class	Plant part: Foliage	Frame	Roots	Total
N	14HD	194	463	75	732
	29HD	215	686	94	995
	43LD	141	498	87	734
	76LD	187	818	194	1200
P	14HD	11	57	10	78
	29HD	15	93	12	120
	43LD	7	53	7	67
	76LD	11	66	15	92
K	14HD	118	571	86	775
	29HD	134	632	134	901
	43LD	81	498	67	646
	76LD	108	811	201	1120

Phosphorus

The total P-stocks increased from 7.2, 8.9, 10.0 to 12.8 g P bush^{-1}, for the 14-, 29-, 43- and 76-year old tea plantations, respectively. The bush frame parts contributed 72–79% of the P storage in the differently aged tea bushes compared to foliage and roots parts that were almost similar at 11–14% and 10–17%, respectively (Table 6). The P content in the frame part increased with age by about two-fold from 5.3 g P in the 14-year old bush to 9.2 g P in the 76-year old bush. When P stocks were converted to kg P ha^{-1} (Table 7), the increase of P content with age was found only within genotypes, e.g. 14- and 29-year old seedling plantations and 43- and 76-year old clonal plantations,. Thus, although P stocks increased with the age of the plantation, comparisons were only valid for similar tea type-density combinations. The total P-stocks for the tea plantations varied between 67.3 and 120.0 kg P ha^{-1}.

Potassium

There was a general increase in K-stocks for the whole tea bush with age, from 66.3 g K to 156.4 g K (Table 6). The bush frame contributed 72–77% of the K stock per bush compared to the storage in foliage and roots of 10–15% and 10–18%, respectively. However, within the clonal HD cultivars, the trend in K stocks per bush (g K bush^{-1}) was reversed and the 29-year old had lower K (66.3 g K) compared to the 14-year old tea bushes (71.3 g K). The lowered K was contributed more by the frame component in the 29-year old tea bushes (Table 6). The increase in total K stocks for the tea plantations with age was consistent only within tea genotypes and ranged between 646 and 1,120 kg K ha^{-1} (Table 7).

Discussion and conclusions

Biomass accumulation and C sequestration

The woody tissue that forms the tea bush frame always had the highest biomass irrespective of age and genotype-density combinations, which has also been reported in literature (Dang, 2005; Magambo and Cannell, 1981; Ng'etich and Stephens, 2001b; Wachira and Ng'etich, 1999). Unlike in forests and tree plantations where tree foliage and fine root biomass decreases with age and maturity (Claus and George, 2005), there were clear differences in the foliage biomass in this study between the two tea types/cultivars. Generally, seedling tea bushes have higher root biomass (Burgess and Sanga, 1994) and a wider spacing, e.g. 1.22 × 1.22 m, implies a better root distribution in the soil. On average there was more root biomass in the seedling tea bushes; however, the root biomass in the 43-year old plantation was much lower than in the 76-year plantation (Table 3). This shows that ageing may also affect the allocation of assimilates to the roots. A lower root biomass is associated with root length density and thus affect the uptake of water and nutrients under drought conditions (Burgess and Sanga, 1994). The low variation noted in C-contents within bush parts of the ageing tea classes (Table 4) had been observed in storage organs of crops of widely different biochemical composition (Vertregt and Penning de Vries, 1987) and in an age sequence of eastern Amazonia forests (Johnson et al., 2001). When a comparison was made with forests and mature plantation trees, the C-stock of tea plantations was lower. In a chronosequence of pine plantations in Turkey, Peichl and Arain (2006) reported C-stocks of standing biomass of 0.27, 37, 54, and 103 t C ha^{-1} for 2-, 15-, 30-, and 65-year old stands. Similarly, Glenday (2006), estimated C-stock for 10-year *Eucalyptus saligna* and 30-year *Cupressus lusitanica* plantations, and an undisturbed indigenous forest at Kakamega in western Kenya at 94, 108, and 356 t C ha^{-1}, respectively. Thus, these standing biomass C levels for tea plantations of between 43 and 72 t C ha^{-1} compare favourably to tree plantations of 30 years and below and not the older plantations or indigenous forests.

Management of the tea bush by periodical pruning and constant removal of the apical buds and breaking-back to maintain the plucking table had been suggested as main reason for the low biomass. Indeed, Magambo and Cannell (1981) attributed the low standing biomass of tea compared to forest trees and C_3 vegetative crops as due to the continuous plucking that limits the amount of young photosynthetically active leaves as well as assimilate supply to other plant organs. Instead of standing biomass, the rate of DM increase per year would be a better indicator for the productivity of tea plantations. The annual rate of DM increase in the clonal cultivars was about 167 g per bush (including roots) and about 194 g per bush in the seedling tea (Figure 1); however, in per unit area, the increase amounts to 1.3–1.4 t ha^{-1} yr^{-1} and 1.8–2.2 t ha^{-1} yr^{-1} for seedling and clonal plantations, respectively. This is within the range reported by Maikhuri et al. (2000) of 1.1 to 3.9 t ha^{-1} yr^{-1} for multipurpose tree species established in degraded and abandoned agricultural land at 1,200 m altitude, respectively. The results show that younger tea plantations at higher plant population densities accumulate more C per unit area per year. So, there is a clear trade off between storage of C-reserves, which may contribute to adaptation of bushes to drought conditions, and the annual productivity under optimal conditions (Chapter 3). Trees are a terrestrial carbon sinks (Houghton et al., 1998). A tea agro-ecosystem, therefore, will sequester carbon both *in situ* (biomass and soil) and *ex situ* (harvested leaf). Thus the biomass in tea plantations though less than in tropical forests imply a sustained carbon sequestration in fragile areas. The contribution of the soil to C sequestration in ageing tea plantations was not assessed in this study, although the small differences reported in Chapter 3 in total organic C of 36, 37, 35, and 33 g kg^{-1}

for the 14-, 29-, 43-, and 76-year old tea plantations, respectively, suggest that the soil carbon stocks of these tea plantations did not vary much. As a consequence of regular pruning, crop residues may have reduced soil erosion and run-off and therefore soil fertility, maintained.

Nutrient accumulation in biomass

With the exception of K, the N and P stocks increased with age of tea bushes irrespective of the genotype-density combination. The lowered K in the 29-yr old clonal tea bushes could not be explained. However, this lack of response to ageing in K-stocks was also observed in secondary forests in Brazil where 10-, 20-, and 40-year old forests were compared and showed a dip in potassium stocks at the 20-year old, especially for the woody component (Johnson et al., 2001). Tea is primarily grown for the production of the young shoots (two leaves and a bud), that also determines made tea yield, rather than for the storage of assimilates in foliage, stems, twigs and roots (Matthews and Stephens, 1998a). The allocation of photosynthates from source to sink is essential to growth and plant yield (Marschner, 1989). Although higher nutrient stocks within the tea plants two leaves and bud are desirable for made tea yield, generally, high stocks in the non-harvestable organs will be important to maintain yield stability under adverse conditions. To our knowledge there are no studies reported on critical N-, P- and K-contents in storage organs for undisturbed growth since it is considered of little economic value. Generally, with increasing amount of C and nutrients reserves, the ratio between mobile and structural material increases as was shown for annual crops (Spiertz, 1977). Therefore, it can be concluded that the amount of reserves is more important than the level of N-, P- or K-contents.

In conclusion, the results herein demonstrate that ageing of tea plantations is associated with increased stocks of carbon and major nutrients (N, P, K) per bush and per unit area; the rate of increase differs between genotypes (seedlings and clonal). Assessments of carbon and nutrient stocks should therefore be carried out per unit area to avoid effects of variation in population density. Older tea bushes with high nutrient reserves may require lower nutrient applications and will depend less on reduced nutrient uptake under adverse weather conditions (Chapter 3). There is a trade-off for this investment in extra reserves in productivity.

CHAPTER 5

Properties and N-dynamics of soils following conversion of forests into intensively managed *Camellia sinensis* L. plantations

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Abstract

Tea was introduced in Kenya in the beginning of the 20th Century although commercial cultivation did not commence until 1924. The total acreage of tea plantations has steadily increased and currently covers some 0.15 million ha, i.e. ~5% of the total area in the world. Usually, highest yields are obtained when plantations are 20–40 years old, but they remain in production till 100 years. Plantations older than 40 years slowly degrade, but the cause of this degradation is unclear. This chapter reports on changes in soil characteristics as a possible feedback of degradation in ageing tea plantations using results of aerobic incubation studies and analyses of soils sampled from a natural forest and a chronosequence of tea plantations (14, 29, 43, and 76 years old). The effects of long-term tea monocropping on soil acidity, extractable aluminum (Al) and manganese (Mn), and their affect on the ratios of the base nutrients (potassium (K), calcium (Ca) and magnesium (Mg)), phosphorus (P) and sulphur (S), were tested. The effect of tea prunings on the rates of N-mineralization and nitrate production in the different soils was also assessed. Measurements were confined to the top 0–20 cm soils, as most tea roots are in the top soil and largest changes were expected here.

The soils were classified as Nitisols with 46–59% clay and 33–38 g kg^{-1} of organic carbon. There were small differences in soil characteristics between the natural forest soil and the tea plantations. Soil pH (H_2O) ranged from 3.5 to 4.7, and was on average lower in tea plantations than the natural forest. Extractable (0.01 M $CaCl_2$) K and Mg were relatively low in tea plantations compared to the forest but there was no trend with age. P, S and micronutrients (Zn, Cu, Co) were similar in soils of the tea plantations and forest. The most evident effect of ageing in the tea plantations was in microbial biomass C and N and total microbial activity (FDA method) that showed an increasing trend along the tea chronosequence. The rate of NH_4^+-N and NO_3^--N production was highest in forest soils and increased with age in tea plantations. Prunings addition caused significant immobilization of N in all tea soils but not in the forest soil. It is concluded that the small differences in soil characteristics are probably not a major contributor to the degradation of ageing tea plantations.

Keywords: Soil characteristics, microbial biomass, tea prunings, incubation, N-mineralization, ageing.

Introduction

In the highlands of Kenya, tea (*Camellia sinensis* L.) plantations are grown on highly weathered acidic soils derived from volcanic origin (Othieno, 1992b). Tea was introduced in Kenya in 1903 but commercial cultivation began in 1924. The total acreage of tea plantations has steadily increased and currently is 0.15 million ha, i.e. ~5% of the total area in the world. The evergreen perennial mono-crop performs best under conditions with sufficient rainfall, well-distributed throughout the year. Under good management practices the tea bush can remain productive up to 100 years, but peak yields in tea plantations usually occur between 20 and 40 years, depending on the genotype, agronomic practices and ecological and biophysical characteristics. The peak yields are followed by a decline in productivity and a degradation of the tea plantations. The causes of the decline in yield and of the degradation of ageing tea plantations are not well-understood.

To enable harvesting of the young shoots, the crop is maintained as a low bush in a continuous vegetative growth by periodic pruning once in three to five years. The prunings are left on the soil surface for recycling of nutrients, soil organic matter build-up and improvement of soil structure. It is known that tea prunings contain large amounts of polyphenols (Forrest and Bendall, 1969), which may impede organic matter decomposition and nitrogen (N) mineralization. Tea growing and the management of tea plantations also contribute to soil acidification and also to increased levels of exchangeable aluminium (Al) in the soils. The plant is also known as an 'Aluminium (Al) accumulator' (Masunaga et al., 1998) and may contain large quantities of Al in mature leaves that are significantly affected by age and genotype (Owuor and Cheruiyot, 1989; Fung et al., 2003; Ruan et al., 2006). Declining productivity in ageing tea plantations has been ascribed to increased stress resulting from a combination of increases in acidity and related elements and changes in the functioning of the microbial community (Han et al., 2007).

In some cases, declining yields have been associated with a decline in soil fertility, related to poor nutrient management practices (Illukpitiya et al., 2004). The tender shoots that contain the largest percentage of nutrients in the plant (Dang, 2005; Chapter 3) are harvested throughout the year, resulting in a relatively high nutrient removal. To sustain productivity, the soil and crop nutrient status have to be maintained. This is done mostly by using inorganic single fertilizers like urea or NPK(S) fertilizers without considering other essential elements. Nitrogen recoveries in the harvested shoots are often low (Wickremasighe, 1981; Malenga and Wilkie, 1994; Chapter 4), suggesting that most of the N applied through large applications of inorganic fertilizers is lost through leaching and erosion (Othieno, 1979b; Bonheure and Wilson, 1992).

To-date, no study has examined the changes in soil characteristics of ageing tea plantations in relation to the productivity of these plantations. Ageing of tea plantations is hypothesized to result in (a) increases in soil acidity and extractable aluminium (Al) and manganese (Mn), (b) imbalances in the supply from the soil of the bases (potassium (K), calcium (Ca), magnesium (Mg)), phosphorus (P), sulphur (S), zinc (Zn) and copper (Cu), and (c) a decline in the decomposition and N mineralization of prunings. A chronosequence of tea plantations with known productivity situated on similar soils and at short distances from each other were selected. The tea plantations ranged in age from 14 to 76 years and were uniformly managed by estates. A neighbouring tropical forest soil was included as the baseline zero-age; all tea plantations were under similar natural forest vegetation prior to tea establishment. As the soils have good soil physical properties and no changes were expected in these properties, the analyses focussed on soil chemical and microbial properties. The study included a soil incubation study where the effects of pruning addition on changes in ammonia and nitrate contents were examined. The measurements were confined to the top 0–20 cm soils, as most tea roots are in the top soil and largest changes were expected therein.

Materials and methods

Study sites

The study area is located in the tea growing region of Kericho District, on the western highlands of Kenya. Preceding tea planting, the area was part of Mau Forest Reserve, an indigenous tropical forest in Kenya's Great Rift Valley. The soils are deep, acidic friable clays and are well drained. These soils were classified as Nitisols and have low CEC and high content of Al and Fe oxides (Sombroek et al., 1980). The field sites were selected on the basis of the ages of the tea plantations and the presence of a neighbouring natural forest site. The tea plantations were aged 14-, 29-, 43-, and 76-years in 2002 and were part of field experiments studying the productivity of ageing tea plantations. Due to their ages, the two youngest plantations had been planted with clonal cultivars (Clone TRFK 6/8), while the two older plantations were seedling teas. The fifth was a natural forest adjacent to the tea plantations. These five sites are located within a radius of four kilometres from the Tea Research Foundation (TRFK) Headquarters at Timbilil Estate, Kericho at an elevation of 2,180 m above sea level, latitude 0°22′ S, and longitude 35°21′ E. The climate of the area can be divided into three main seasons based on rainfall and temperatures. These are a warm-dry season (December–March), a cool-wet season (April–August) and a warm-wet season (September–November). The tea plantations had previously been managed according to recommended practices involving regular pruning and the application of fertilizers (100–300 kg N ha^{-1} yr^{-1} as NPKS, 25:5:5:5). The last pruning of the tea bushes was carried out between August and October 2001. Briefly, the field experiments in each site were laid out in a randomized complete block design consisting of five N-fertilizer rates (0, 50, 100, 200 and 400 kg N ha^{-1}) replicated three times. P and K were uniformly applied at 100 kg P_2O_5 ha^{-1} yr^{-1} and 100 kg K_2O ha^{-1} yr^{-1}, respectively. Other field experimental details and yield measurements are given in Chapter 3.

Soil sampling and analyses

Soil samples were taken from the plantations and forest site in July 2003, using a soil corer. For the determination of total C and total N, and extractable elements three cores (0–20 cm) from unfertilized control plots (minus N) of the field experiments established in December 2001, were mixed to form one sample per plot. Plant residues and roots were removed by hand. The samples were air-dried, sieved (2 mm mesh) and gently ground. The soils were bulked for the determination of P, K, Ca, Mg, Al, Mn, Fe, Zn, Cu, and Co, and for the incubation study. For the determination of microbial biomass C and N, the soils were sampled similarly at 0–10 cm depth from the unfertilized (minus N) plots and stored at 4 °C until analysis. Soils for the determination of total microbial activity (TMA) were sampled at 0–10 cm depth from all the plots (0, 50, 100, 200 and 400 kg N ha^{-1}) and stored at 4 °C until analysis.

Soil pH (H_2O) was determined in field moist soils using the 0–20 cm layer immediately after sampling using a combined glass electrode in 1:1 (w:v) soil : water ratio. Soil textural class was determined on the air dried and 2 mm mesh sieved soils, using the hydrometer method (Gee and Bauder, 1994). Easily extractable nutrients (P, S, K, Ca, Mg, Al, Mn, Fe, Zn, Cu, and Co) were determined following extraction using 0.01 M $CaCl_2$ (1:10 weight/volume ratio) and ICP (Houba et al., 1986). No specific extraction was made for Ca; hence the 'extracted' Ca with 0.01 M $CaCl_2$ can be interpreted in relative terms only. Total nutrients (P, S, K, Ca, Mg, Al, Mn, Fe, Zn, Cu and Co) were determined following digestion with Aqua Regia (HNO_3 and HCl, ratio 1:3) and determination of elements with ICP (Houba et al., 1995).

Microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN) in field moist soils were extracted using modified fumigation extraction methods (ICRAF, 1994). Total microbial activity (TMA) also in field moist samples was determined spectrophotometrically by hydrolysis of fluorescein diacetate (FDA) dissolved in acetone and measured as absorbance at 490 nm (Schnürer and Rosswall, 1982).

Prunings sampling and analyses

The prunings in each site were lopped from 10 tea bushes of the three control treatments and mixed. The samples were oven-dried for 24 hrs at 60 °C, ground and sieved. N was determined using micro-Kjeldahl digestion method. Organic C was determined using Walkley-Black method (IITA, 1979a). For P, K, Ca, and Mg the milled samples were ashed for four and a half hours in a muffle furnace at 450 °C and digested using a mixture of double acid (H_2SO_4 and HCl) and hydrogen peroxide in the ratio 2:3 (Thomas et al., 1967). Extraction was done using 0.05 M HCl (IITA, 1979a) followed by flame emission spectroscopy for K and atomic absorption spectroscopy (Varian SpectraAA 20) for Ca and Mg. P was determined colorimetrically with Spectronic20 at 400 nm after complexing with a mixture of ammonium molybdite and ammonium metavanadate in concentrated nitric acid (IITA, 1979a). Lignin determination was done via Acid Detergent Fibre method and total polyphenolics analysed using the Folin-Denis method (Anderson and Ingram, 1996).

Incubation study

To minimize any effects that may arise from the differing chemical composition, the prunings from the 29-year old tea plantation were used in this incubation study. Portions of 50 g of air-dried and homogenized soil from the 14-, 29-, 43- and 76-year old tea plantations and the forest were weighed into 250 ml plastic bottles and mixed with 0.41 g (equivalent to 200 kg N ha^{-1}) of oven-dried (60 °C for 24 h) and ground prunings from the 29-year old tea plantation, in four replicates. Control treatments (without prunings addition) were included. The water holding capacity of each soil had been pre-determined by the method described by Anderson and Ingram (1996).

Moisture content of the soil samples in the incubation bottles was adjusted to 60% water holding capacity using distilled water. The bottles were loosely closed to allow gaseous exchange and also to maintain the moisture levels. The bottles were incubated at 19–20 °C in a dark room and the moisture content checked and adjusted weekly (water loss always < 4% of initial moisture). At the end of 1, 2, 4, 7, 11, 15 and 19 weeks of incubation, four samples of each treatment and the respective control treatment were withdrawn for mineral-N analysis using 0.5 M K_2SO_4 extracting solution followed by the colorimetric determination by autoanalyser method (Anderson and Ingram, 1996). Means and standard deviations were calculated. Mineral-N was obtained by summation of (NO_3^-+NO_2^--N) and NH_4^+-N at each period of incubation.

Statistical analyses

A one-way analysis of variance was used to compute means and least significant differences (LSD) at each site for TMA analysis. For the other soil properties where composite samples of the unfertilized (minus N) plots were taken, means and standard deviations were calculated.

Results

General soil characteristics

Differences between sites in soil characteristics were relatively small (Table 1). The clay content ranged from 46 to 59%, silt content from 9 to 19%, and sand content from 32 to 35%. All soils were acidic; pH (H_2O) ranged from 3.5 to 4.5 in the tea plantations compared to 4.7 in the forest soil (Table 1). Soil organic C ranged from 33–38 g kg^{-1}, with the lowest values in the 76-year old tea plantation and the highest value in the natural forest site. The calculated C:N ratios ranged from 9.4 to 10.9 and there was no trend along the chronosequence.

Soil microbial C and N and total microbial activity

Microbial biomass C and N increased and microbial biomass C:N decreased along the chronosequence of tea plantations. An alternative interpretation is that microbial biomass C and N and C:N ratio show a close association with genotype where the two younger clonal tea plantations had lower amounts of microbial biomass C and N and a higher C:N ratio than the two older seedling plantations (Table 2). The total microbial activity (TMA) was closely associated with the genotype; the two clonal tea plantations had similar but significantly lower TMA (P<0.05) compared to the older seedling plantations. TMA of the forest soil amounted to 0.87 and was similar to that of the two older (seedling) tea plantations.

Table 1. Texture, pH, total C and N of 0–20 cm soils in the five sites (standard deviation is given in parenthesis, n=3).

Site	Age of tea plantation (yr)				Forest
Parameter	14	29	43	76	
Textural class	Clay	Clay	Clay	Clay	Clay
Clay (%)	59 (0.2)	46 (1.2)	55 (2.1)	58 (1.2)	53 (1.3)
Silt (%)	9 (0.2)	19 (1.2)	12 (2.1)	10 (1.1)	10 (1.2)
Sand (%)	32 (0.4)	35 (0.1)	33 (1.0)	32 (1.1)	37 (1.0)
pH (1:1 soil:H_2O)	3.8 (0.1)	4.5 (0.1)	3.8 (0.2)	3.5 (0.2)	4.7 (0.1)
Total org. C (g kg^{-1})	36 (1.4)	37 (1.2)	35 (1.0)	33 (1.8)	38 (0.9)
Total N (g kg^{-1})	3.3 (0.5)	3.9 (0.4)	3.6 (0.7)	3.3 (0.5)	nd
C:N ratio	10.9	9.4	9.8	10.0	-

nd, not determined.

Table 2. Microbial C (MBC) and N (MBN) and total microbial activity (TMA) of 0–10 cm soils in the five sites.

Parameter	Age of tea plantation (yr)				Forest
	14	29	43	76	
MBC (g kg^{-1})*	0.23 (0.04)	0.28 (0.05)	0.34 (0.04)	0.37 (0.05)	nd
MBN (g kg^{-1}) *	0.05 (0.01)	0.06 (0.01)	0.08 (0.01)	0.09 (0.02)	nd
Microbial C:N ratio	4.6	4.7	4.3	4.1	-
TMA**, ***	0.69 (0.07)a	0.62 (0.13)a	0.86 (0.12)b	0.90 (0.15)b	0.87* (0.06)

*n = 3; **n = 15; *** Analysis for one-way ANOVA for the tea plantations only.

nd, not determined; Values connected horizontally by the same letter are not significantly different at $P<0.05$.

Soil nutrients

The $CaCl_2$ extractable nutrient elements are presented in Table 3. $CaCl_2$ extractable P was low and uniform at < 1 mg kg^{-1} in all soils. $CaCl_2$ extractable S was slightly lower in the younger clonal tea plantations compared to the older seedling plantations and the natural forest. $CaCl_2$ extractable K and Mg were lower in the tea plantations than the natural forest soil, while extractable Al and Mn were much higher in the tea plantations than the forest site. $CaCl_2$ extractable Mg was positively related to soil pH, while extractable Al and Mn were negatively related to soil pH. The lowering of the Ca concentration in the 0.01 M $CaCl_2$ was inversely related to the soil pH; the Ca concentration decreased by 90 to 400 mg kg^{-1} (~2 to 10 mmol kg^{-1}).

$CaCl_2$ extractable K and Mg were low in the tea plantations, and ranged between 0.09 and 0.12 g kg^{-1} and between 0.02 and 0.08 g kg^{-1}, respectively. There was no trend in extractable K and Mg with age but were lower compared to the natural forest of 0.43 and 0.32 g kg^{-1} for K and Mg, respectively. $CaCl_2$ extractable Al was also related to soil pH and was 0.11, 0.12 and 0.12 g kg^{-1} in the 14-, 43-, and 76-year old plantations, respectively, and 0.02 and < 0.01 g kg^{-1} in the 29-years old plantation and the natural forest, respectively. $CaCl_2$ extractable Mn was relatively high; it increased with age of the plantation and ranged from 0.22–0.27 g kg^{-1} in the natural forest and 14- and 29-year old plantations to 0.36–0.46 g kg^{-1} in the 43- and 76-year old plantations. $CaCl_2$ extractable Zn also had no clear trend along the chronosequence of tea plantations and forest, while Cu and Co were very low.

The Aqua Regia digestible nutrient elements are presented in Table 4. Aqua Regia digestible P was low and fairly uniform ranging from 264 to 324 mg kg^{-1} in all sites, including the natural forest soil. Aqua Regia digestible S ranged between 481 to 820 mg kg^{-1} including the natural forest and had no trend pattern. The Aqua Regia

Table 3. Some elements of top 0–20 cm soils in the different sites extracted using 0.01 M $CaCl_2$.

Analyses	Tea plantation age (yr)				Forest
	14	29	43	76	
pH	4.0	4.6	4.1	4.0	4.8
P (mg kg^{-1})	0.7	0.3	0.7	0.8	1.0
S (mg kg^{-1})	21	10	27	44	17
K (g kg^{-1})	0.11	0.12	0.09	0.10	0.43
Na (g kg^{-1})	0.01	0.02	0.01	0.01	0.01
Mg (g kg^{-1})	0.02	0.08	0.02	0.02	0.32
Al (g kg^{-1})	0.11	0.02	0.12	0.12	< 0.01
Mn (g kg^{-1})	0.27	0.20	0.36	0.46	0.22
Fe (g kg^{-1})	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Zn (mg kg^{-1})	1.2	2.0	1.0	3.2	2.8
Cu (mg kg^{-1})	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Co (mg kg^{-1})	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1

Table 4. Some elements of top 0–20 cm soils in the different sites extracted using Aqua Regia.

Analyses	Tea plantation age (yr)				Forest
	14	29	43	76	
P (mg kg^{-1})	264	324	279	303	288
S (mg kg^{-1})	625	481	769	820	774
K (g kg^{-1})	1.51	1.57	1.57	1.68	2.01
Na (g kg^{-1})	0.06	0.21	0.09	0.08	0.09
Ca (g kg^{-1})	0.34	1.79	0.24	0.22	2.30
Mg (g kg^{-1})	0.89	0.98	1.02	1.02	1.32
Al (g kg^{-1})	103	97	98	110	95
Mn (g kg^{-1})	2.9	3.4	4.8	3.8	3.8
Fe (g kg^{-1})	91	73	89	95	84
Zn (mg kg^{-1})	138	179	147	158	168
Cu (mg kg^{-1})	10	12	13	13	11
Co (mg kg^{-1})	15	13	17	18	20

digestible base nutrients (K, Ca, Mg) were much higher in the forest soil compared to the tea soils (for Ca up to a factor of 10). Generally, the Aqua Regia digestible K, Na, Ca, Mg, Zn, Cu and Co had no clear trends along the chronosequence of tea plantations.

Table 5. Some chemical characteristics of tea prunings of the tea plantations.

Age	N	P	K	Ca	Mg	C	C:N ratio	Total polyphenolics	Lignin	Lignin:N ratio
(yr)	($g\ kg^{-1}$)							($g\ kg^{-1}$)		
14	16.6	1.6	9.3	8.1	0.7	478	29	47	297	17.9
29	16.4	1.8	7.5	9.7	1.0	479	29	49	280	17.1
43	18.0	1.4	9.3	8.1	0.5	479	27	34	266	14.8
76	17.6	1.2	6.9	13.1	0.6	479	27	23	244	13.9

There was apparent depletion in both the easily extractable and Aqua Regia digestible K and Mg in the tea plantations compared to the natural forest. Mean differences between the natural forest and the tea plantation soils was 0.32 g kg^{-1} for easily extractable K and 0.18 g kg^{-1} for easily extractable Mg which translates to about 480 kg ha^{-1} for K and 270 kg ha^{-1} for Mg. Similarly, mean differences were seen in the Aqua Regia digestible K, Ca and Mg of 0.43, 1.65 and 0.34 g kg^{-1} for K, Ca and Mg, respectively in the tea plantations and natural forest.

Prunings

The chemical characteristics of the prunings along a chronosequence are presented in Table 5. The elemental composition of the prunings compositions were related to the genotype and the age of the plantations. The mean N content was slightly lower in the two younger clonal tea plantations compared to the two older seedling plantations, while mean P and Ca contents were slightly higher in the younger plantations. These differences possibly reflect genotypic differences. The lignin and total polyphenolic contents were relatively high (Palm and Sanchez, 1991; Tian et al., 1992) ranging from 244–297 g kg^{-1} and 23–47 g kg^{-1}, respectively. The younger clonal plantations had higher concentrations of both lignin and total polyphenolics compared to the two older tea plantations. The C:N ratios for the clonal tea plantations were higher (29) than for the seedling plantations (27). The lignin:N ratio was also higher in the clonal tea plantations compared to the seedling tea.

Nitrogen mineralization in incubated soils

Changes in the contents of 0.5 M K_2SO_4 extractable ammonium-N (NH_4^+-N) and nitrate-N (NO_3^--N) during the 19 week incubation of soil with and without prunings for the 14, 29, 43, and 76-year old tea plantations and natural forest are shown in Figure 1 and Figure 2, respectively. The ammonification potential of the tea soils was high; the NH_4^+-N content of amended and unamended soil increased by 20–30 and

~30–50 mg kg^{-1}, respectively, during the first two weeks. Initially, ammonification was highest in the natural forest soil followed by the 76-year old tea plantation (Figure 3a). Addition of prunings with a high C to N ratio of 29 (Table 5) gave a much lower rate of ammonification suggesting the immobilization of NH_4^+-N into microbial biomass. The apparent immobilization was highest for the 43-year old tea plantation and lowest (absent) in natural forest soil. The NH_4^+-N content decreased again after the second week of incubation, suggesting that henceforth, nitrification proceeded faster than ammonification. At the end of the incubation period NH_4^+-N contents had decreased to less than 10 mg kg^{-1} for all soil types.

At the start of the incubation, the NO_3^--N content was about 10 mg kg^{-1} in all soils, but 60 mg kg^{-1} in the 76-year old plantation, which suggests high mineralization and nitrifying activity in this soil prior to soil incubation (Figure 3b). Contents of NO_3^--N increased by 10 to 30 mg kg^{-1} in the soils from the tea plantations, and by about 60 mg kg^{-1} in the natural forest soil during the first two weeks of incubation, irrespective of the addition of prunings. During the third and fourth week of incubation, NO_3^--N contents decreased to less than 10 mg kg^{-1} in all soils, suggesting rapid NO_3^--N removal through immobilization and/or denitrification. The subsequent increase in NO_3^--N content to about 50 mg kg^{-1} in all soils between week 4 and 11 coincided with a decrease in NH_4^+-N content (Figure 1). Differences in the changes in NO_3^--N contents in treatments without and with prunings were negligible and there was no clear pattern related to the chronosequence of the tea plantations.

Discussion and conclusions

Changes in soil acidity and $CaCl_2$ extractable Al and Mn

Soil pH decreased with age of the tea plantation, but the trend was weak. The 29-year old tea plantation had a relatively high soil pH (Tables 1 and 3), and also high base cation contents, which may be related to the slope of the site. We speculate that erosion has been slightly higher at this site than in the other sites during geological time, and as a consequence the material in the top soil is less weathered. Other studies have reported increasing soil acidity in tea plantations of increasing age (Song and Liu, 1990; Han et al., 2007). The tea plant itself is known to acidify the soil because of excess cation to anion uptake, which leads to plant roots to excrete H^+ ions (Morita et al., 1998). Application of acidifying $(NH_4)_2SO_4$ based fertilizers may also have contributed to the observed high soil acidity in the older tea plantations (Owino-Gerroh, 1991; Dogo et al., 1994; Ruan et al., 2006). The tea plant is known for its preference for NH_4^+-N, hence the application of ammonium based fertilizers. Common N-fertilizers used in tea growing in Kenya are compound NPKS (25:5:5:5) and urea

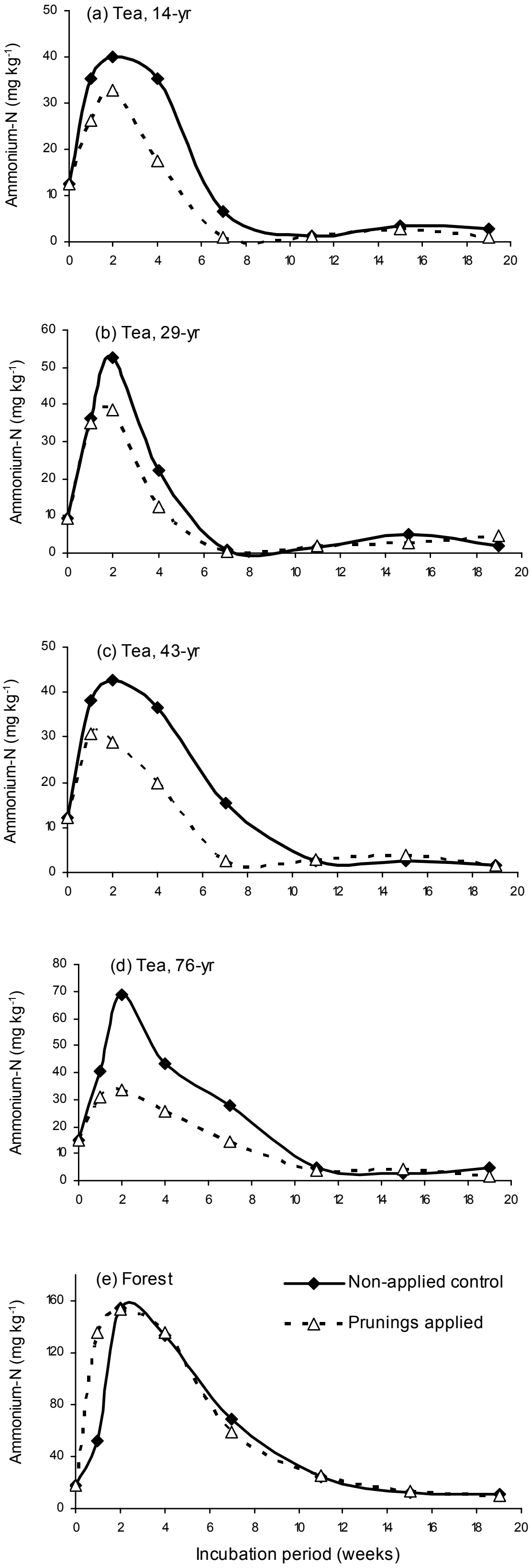

Figure 1. Ammonium-N production dynamics (mg N kg^{-1}) in soils with and without prunings during aerobic incubation.

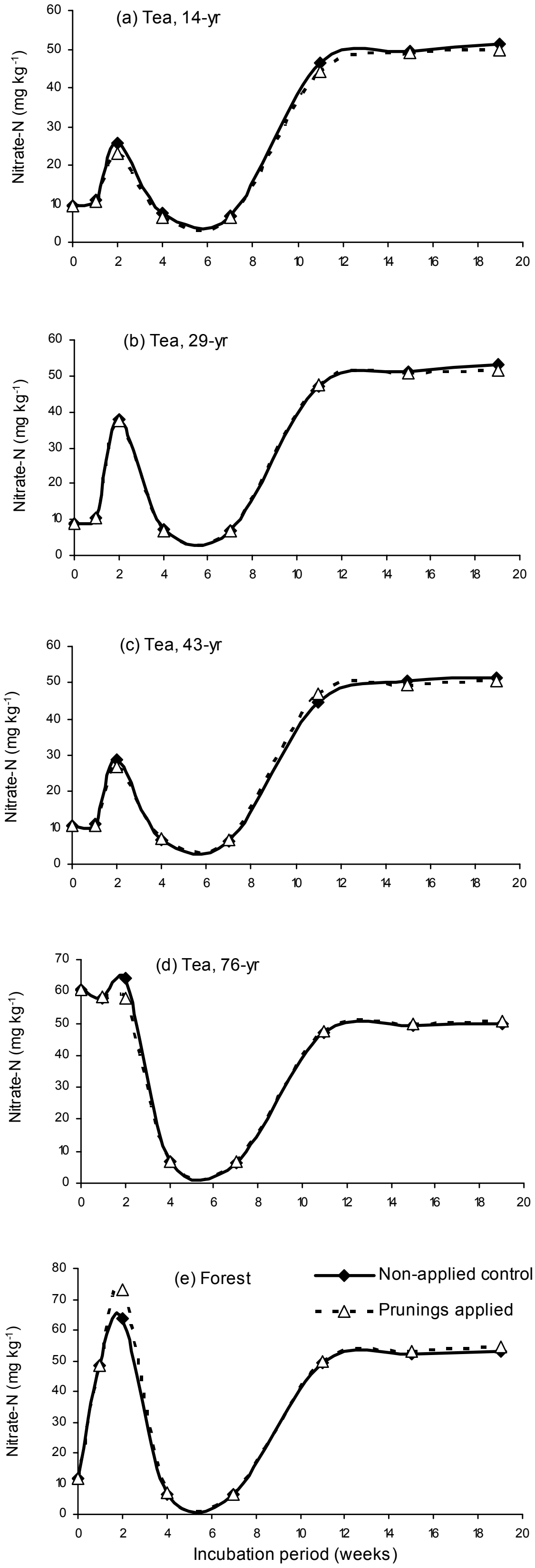

Figure 2. Nitrate-N production dynamics (mg N kg^{-1}) in soils with and without prunings during aerobic incubation.

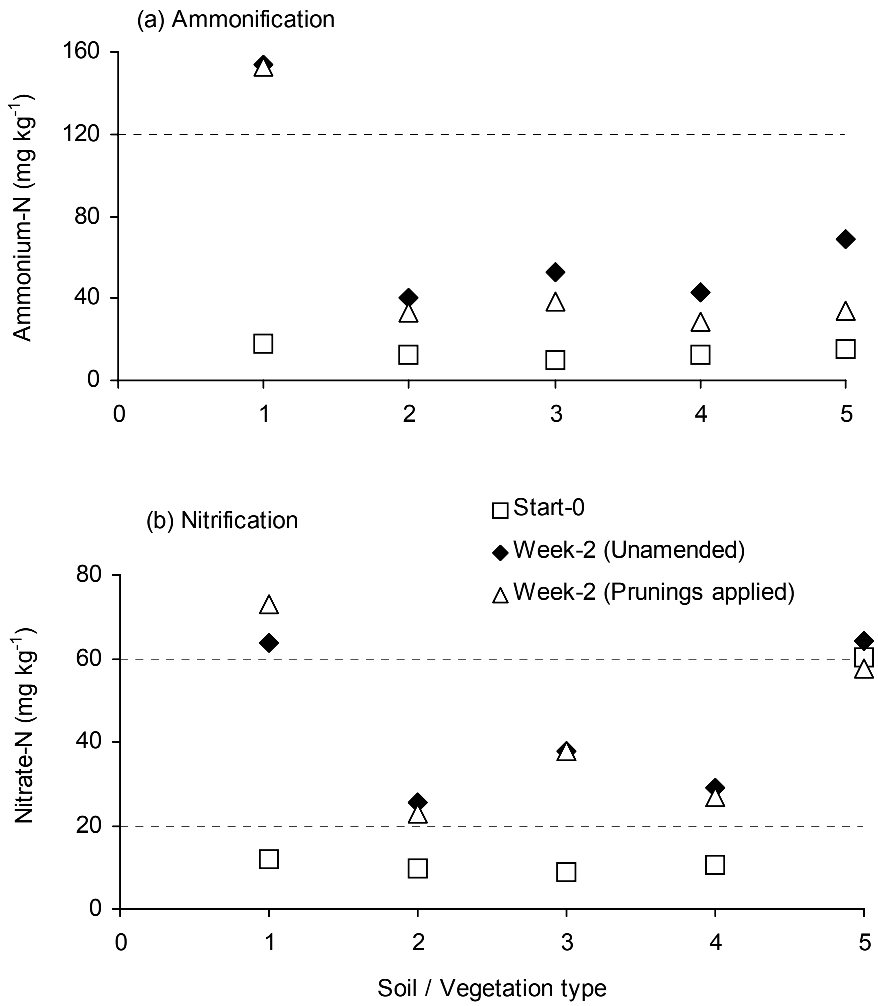

Figure 3. Ammonification (a) and nitrification (b) potential within the first two weeks of incubation for: 1, forest; 2, 14-yr; 3, 29-yr; 4, 43-yr; and 5, 76-yr old tea plantation soils.

fertilizers, which are less acidifying per unit N applied than $(NH_4)_2SO_4$ fertilizer (Tisdale et al., 1985; Bonheure and Willson, 1992). Moreover, mean N-application rates have decreased from a mean of 400 kg N ha^{-1} in the period 1970–1980 (Wanyoko, 1997) to 100–250 kg N ha^{-1} from the 1980s onwards (Othieno, 1988). Soil acidification has also been related to high concentrations of organic acids especially tannins in litterfall and prunings (Eviner and Chapin, 2003). However, most studies have associated increased acidity in older tea plantations with the use of high rates of NH_4^+-based fertilizer in the recent past (Owino-Gerroh and Othieno, 1991).

Soil acidification is usually defined by the decrease in base cations in the soil, which is often accompanied by a decrease in pH and increase in extractable Al (Van

Breemen et al., 1984; Binkley et al., 1989; Owino-Gerroh, 1991). In our studies, the base cations (K, Ca, Mg) in the top soils of the tea plantations were on average much lower than in the natural forest soil, though there was no clear trend with the age of plantations. The older tea plantations were more acidic, had lower Ca and Mg and higher Al and Mn. However, the levels of Al and Mn seem not high enough to cause degradation in tea plantations.

Changes in extractable soil nutrients

Good tests for nutrient availability in soils provide information about (i) what is directly available in the soil solution, and (ii) the quantity that can come into the soil solution to replace what has been withdrawn through plant uptake or leaching losses (Jones, 1967; Van Erp and Van Beusichem, 1998). The multi-nutrient extractant 0.01 M $CaCl_2$ provides information about the directly available nutrients; it is a mild one-component extractant (Houba et al., 1986). In contrast, Aqua Regia provides information about the 'total' capacity of the soil to replace the nutrients in the soil solution that have been withdrawn by uptake and leaching losses. Because of the huge differences between soil characteristics and type of extracting solutions, ranges for critical and optimal values in soils are very wide, depending also on crop type. For $CaCl_2$ extractable nutrients, there are as yet no uniform reference values to be able to judge which content is high or low or critical. The ratio between $CaCl_2$ extractable nutrients and Aqua Regia extractable nutrients was much higher in the forest soil than in the tea plantation soils, especially for K and Mg. On average, the ratio between $CaCl_2$ extractable nutrients and Aqua Regia extractable nutrients was very low for P (~1:300), and relatively high for K, Mg and S (1:4 to 1: 20).

With the exception of the 29-year old tea plantation, the ratio (mol/mol) of $CaCl_2$ extractable K to $CaCl_2$ extractable Mg tended to increase from 0.9 in the natural forest to 3.0–3.5 in the 14-, 43-, 76 years old plantations (Table 6). This indicates a depletion of $CaCl_2$ extractable Mg relative to $CaCl_2$ extractable K. Molar ratios of Aqua Regia extractable K and Mg did not differ much between plantations, but molar ratios of Aqua Regia extractable K and Ca indicate a strong depletion of Ca relative to K with ageing of the tea plantation (Table 6).

$CaCl_2$ extractable P and Aqua Regia extractable P were very low in all tea plantations, suggesting that P input via P fertilizers balances P withdrawal via harvested crop. The large depletion of K reflects that the annual K fertilization of about 40 kg K ha^{-1} for an annual application of 200 kg N ha^{-1} (applied as NPK 25:5:5 fertilizer) does not balance the annual withdrawal via harvested crop of 40–60 kg K ha^{-1} (Chapter 3) and possible leaching. The strong Mg and Ca depletion suggests that withdrawal via harvested crop and leaching are relatively large.

Table 6. Effect of tea monocropping on element ratios (mol/mol) for easily extractable 0.01 M $CaCl_2$ and Aqua Regia.

Extractant	Vegetation	K:Mg	K:Ca	Al:(K+Mg)	Mn:(K+Mg)
0.01 M $CaCl_2$	Natural forest	0.9		0.0	0.2
	Clonal, 14-yr	3.0		1.1	1.3
	Clonal, 29-yr	0.9		0.1	0.6
	Seedling, 43-yr	3.4		1.5	2.3
	Seedling, 76-yr	3.5		1.4	2.7
Aqua Regia	Natural forest	1.0	0.9	33	0.7
	Clonal, 14-yr	1.1	4.6	50	0.7
	Clonal, 29-yr	1.0	0.9	44	0.8
	Seedling, 43-yr	1.0	6.7	44	1.1
	Seedling, 76-yr	1.0	8.0	48	0.8

The relationships between mean annual tea yields (kg made tea ha^{-1}) and soil pH and total soil organic C (g kg^{-1}) in the four tea plantations for the Dec 2003–Nov 2004 yield data (Chapter 3) are presented in Figures 4 and 5, respectively. Although there is an increasing trend relation between pH and measured productivity and between total organic C and measured productivity, the linear regression coefficients show that these soil characteristics are not significant.

Changes in organic C and N mineralization

Soil organic C content of the top soils (Table 1) of the tea plantations decreased with the age of the plantation, but the difference between the natural forest soil and the 76 years old plantation was only 5 g kg^{-1}, i.e. a decrease of about 13% in 76 years. A possible alternative explanation for the slight decrease in soil organic C with age of the tea plantation is that the younger clonal tea plantations have a higher productivity relative to the older seedling tea plantation, and that this higher productivity also translates into slightly higher soil organic C contents though leaf litter return. Most soils in this area have a relatively high soil organic C content because of the relatively high rainfall, moderate temperature and the good, clay soil structure, which favour biomass production and soil organic matter accumulation (Dogo, 1993). The above-ground standing biomass in tropical forests is large (about 200 Mg C ha^{-1}; Glenday, 2006) but was not measured at forest site. Above-ground standing biomass and root biomass in the tea plantations increased with age of the tea plantation for similar genotypes (Chapter 4), whereas soil organic C tends to decrease with plantation age. Overall, the total C stock in the tea plantations are rather constant with plantation age

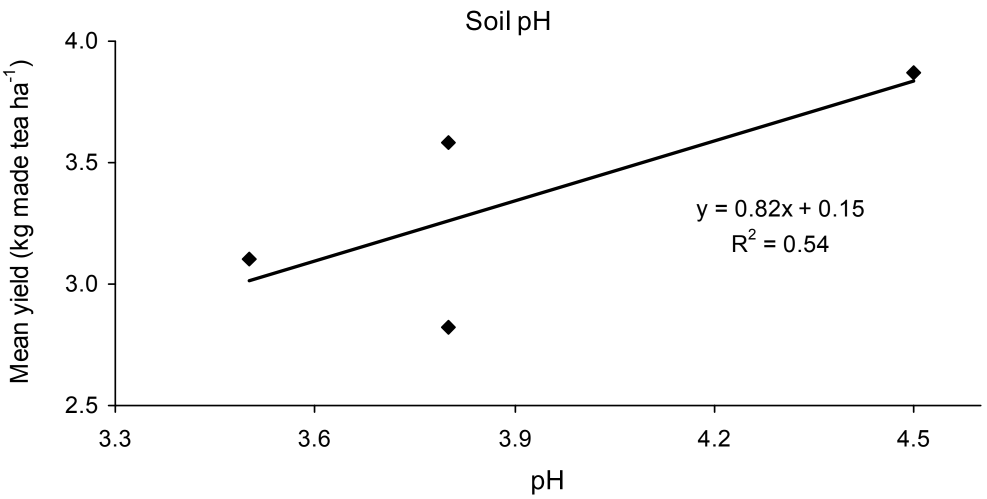

Figure 4. Relationship between tea productivity (t made tea ha^{-1} yr^{-1}) and soil pH.

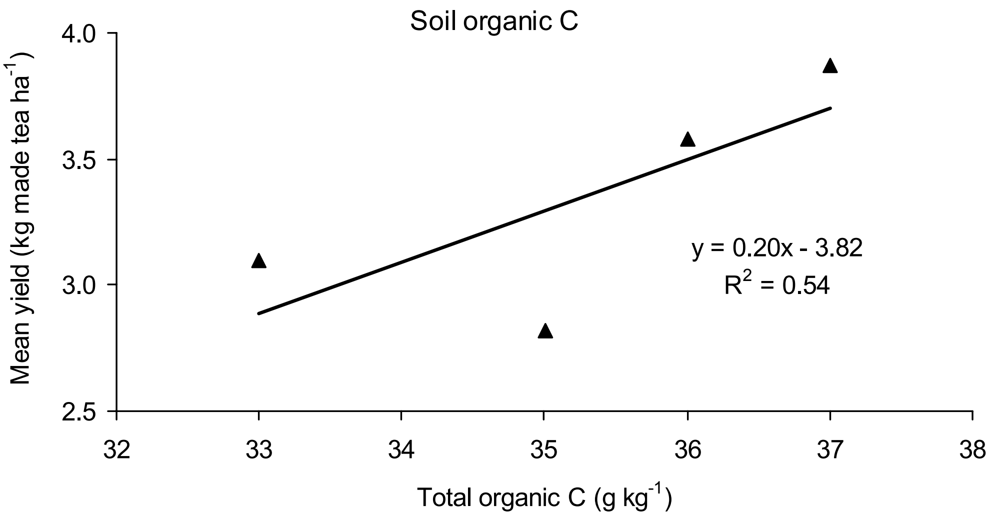

Figure 5. Relationship between tea productivity (t made tea ha^{-1} yr^{-1}) and total organic C (g kg^{-1}).

suggesting that C input via biomass production roughly equals C removal through tea plucking, decomposition of prunings and leaf litter and soil respiration. C:N ratio in the soil organic matter were also remarkably constant along the chronosequence (Table 1). Pansombat et al. (1997) reported accumulation of soil organic C and N in a long-term tea cultivation trial, but Han et al. (2007) could not establish such trends in tea stands of different ages, and suggested an input-driven process existed, i.e. high usage of inorganic and organic fertilizers in high input sites verses low usage of inorganic and organic fertilizers in low input sites.

Microbial biomass C and N marginally increased with age of the tea plantation from 0.23 to 0.37 g kg^{-1} (Table 2). Han et al. (2007) found MBC ranges of 0.10–0.20 g kg^{-1} in tea gardens with different productivities and ages, while Yao et al. (2006) reported a range of 0.15–0.60 g kg^{-1} in tea plantations aged 4 to 55 years and 0.40 g kg^{-1} in a highly productive 30-year old tea garden (Yao et al., 2000). They reported that low MBC values were associated with low productive tea gardens. This is in contrast with the results presented herein, as the younger clonal tea plantations had higher productivity but lower MBC and also lower microbial activity values (TMA) than the older seedling tea plantations. TMA is a measure of organic matter turnover in natural habitats where more than 90% of energy flow passes through microbial decomposers (Heal and MacLean, 1975). Soil microbial biomass and TMA are therefore useful especially for comparative studies and have been suggested as indicators of soil fertility (Sparling, 1997). However, there were weak correlations between the measured soil properties herein, e.g. soil pH, and productivity (Figures 4 and 5). It has also been suggested that organic acids released by the tea plant rhizosphere suppresses microbial biomass (Pandey and Palni, 1996). Hence, the possibility cannot be excluded that the TMA values measured in our study are related to genotypic differences between the older seedling tea and younger clonal tea plantations in organic acid excretion in the rhizosphere.

The results of the incubation study revealed rapid N transformation processes. While some of the changes in 0.5 M K_2SO_4 extractable ammonium-N (NH_4^+-N) and nitrate-N (NO_3^--N) in the soils without and with prunings during the 19-week incubation period are not easy to interpret, in part because of the methodological set-up of the experiment, it is clear that the rates of ammonification, immobilization, nitrification and possibly denitrification were relatively high in all incubated soils. This is in line with the common values for microbial activity and microbial biomass C and N contents, but not so much with the low soil pH and high 0.01 M $CaCl_2$ extractable Al and Mn. Generally, high soil acidity slows down organic matter decomposition and especially nitrification (Hart et al., 1994). However, the changes in 0.5 M K_2SO_4 extractable ammonium-N (NH_4^+-N) and nitrate-N (NO_3^--N) in the soils without and with prunings in our incubation experiment are not related to soil pH and/or 0.01 M $CaCl_2$ extractable Al and Mn. Additions of prunings caused immobilization of NH_4^+-N, but again the rate of immobilization was similar in all soils from tea plantations. These results confirm the findings of Han et al. (2007) that ageing tea plantations apparently have little influence on net N-mineralization.

Visual observations in tea plantations of different ages also reveal no increased accumulation of prunings litter on the soil surface of the older tea plantations. Prunings have high contents of polyphenolics (Table 5) categorized as hydrolysable tannins, condensed tannins and non-tannin polyphenolics (Watermann and Mole, 1994). The polyphenols restrict N-release from their tissues despite having high N content (Palm and Sanchez, 1991; Giller, 2000). However, the protein binding capacity of the tannins is often more important than the total polyphenolic content *per se* (Handayanto et al., 1997). Mutabaruka et al. (2007) compared N-release in soils from maize, sugarcane, *Gliricidia, Peltophorum,* secondary forest and *Imperata* grassland and demonstrated that the high polyphenol rich vegetations like *Peltophorum* were able to develop micro-organisms capable of degrading polyphenol complexes compared to the other low polyphenol vegetations. The high rapid decomposition seen in the tea plantations suggests that the microbial community has been adopted and adjusted to prunings with high polyphenol content. In old tea soils, inhibition of lettuce seed germination and radical growth bioassays has been observed and the presence of allelochemicals that cause allelopathy has been postulated (Owuor, 1996; Anaya et al., 2002). The homogeneity in tea plantation soils may also imply dominance of particular species of microbes resulting from competitive exclusion (Giller et al., 1997). However, this study suggests that the biological soil functioning has not decreased to such extent that it will affect the productivity of the tea plantation, following 76 years of tea cultivation.

Conclusions

This study has shown that the older tea plantations have more acidic soils and have higher contents of $CaCl_2$ extractable Al and Mn, and higher molar ratios of K:Mg, Al:(K+Mg), and Mn:(K+Mg) than younger plantations. Soils of (older) tea plantations were depleted in total Ca and total Mg relative to the natural forest soil. However, these relatively small differences were weakly related to the measured productivity of the tea plantations and are unlikely to cause degradation in tea plantations. The addition of prunings in tea soils lowers net N-mineralization that is not influenced by ageing of the tea stand or soil acidity.

CHAPTER 6

General discussion and conclusions

Components of the study and rationale

The stagnation and decline in productivity of older tea plantations has largely been associated with ageing tea bushes. This study, therefore, aimed at gaining a better understanding of how productivity and resource use of tea agro-ecosystems are influenced by factors associated with ageing. Giller et al. (2006) indicated that scaling up research activities and results about cropping systems in space and time can improve the understanding of resource use dynamics and the targeting of technologies to specific types of farming. In our study, we dealt with different scales to study productivity of tea plantations varying in scale from 0.2 to 4,000 ha and in time from one week to 80 years (Table 1).

First, we assessed whether the yield stagnation and decline in tea plantations was real or just a myth. This was done by reviewing literature on factors affecting growth and productivity of tea plantations and by analysing tea production and area data of the two sectors of the Kenyan tea industry (estate plantations and smallholder farms) for the period 1969–2006. To explore options in the way forward that would assist in decision making of the age-related problems, a simple model was developed to quantitatively evaluate the economic impact of the most promising interventions to enhance productivity under different scenarios. Next we carried out field experiments to get a better understanding of the effects of ageing on above-ground and below-ground biomass and nutrient stocks, and on interactions between nitrogen fertilizer applications and weather (rainfall, temperatures, and radiation) in seasonal and annual productivity of ageing tea plantations. Dry matter and nutrient partitioning and laboratory analyses of leaf tissue and top soils (up to 20 cm depth) were used to supplement the yield data obtained from the field experiments. Finally, we conducted laboratory incubation studies using the top soils (0–20 cm) from the ageing tea plantations and an adjacent natural forest for comparison to assess how N-mineralization and nitrification are influenced by prunings mulch application, which forms an integral part of tea cultivation.

Synthesis of main findings

The main findings of the study are presented below in an integrated way for productivity, resource use, soil quality and management.

Table 1. Scales in time and space for studying ageing in tea production at plantation, crop and soil level.

Object	Time scale	Units	Topic
Plantation	3–80 years	- Smallholders sector: 0.2–20 ha - Estates sector: 20–4,000 ha	- Productivity (genotype × plant density) - Ageing of tea plantations - Management (pruning, fertilization, weeding, etc) - Economic costs (human resource and external inputs)
Crop	1–52 weeks	- kg per bush, - kg per ha	- Seasonal and annual growth - Yield response to N, rainfall, radiation, temperature - C and NPK stocks
Soil	14–76 years, and a natural forest	- g per kg, or - kg per ha	- Soil physical, chemical and biological quality - N-mineralization and nitrification

Productivity

The factors affecting tea productivity were broadly categorized into four classes as: planting material (genotype traits), abiotic factors, biotic factors, and management practices. A review of factors that limit the productivity of tea plant that have comparatively low yields (often below 4 t ha^{-1} yr^{-1}) is presented in Chapter 2. It is generally accepted that tea plants are capable of producing higher yields if the size of the sink is not limited by the harvesting practice. Alternatively, this can be done by manipulating the partitioning of assimilates through management of the tea bush, i.e. increasing leaf production at the expense of the stems by reducing the proportions of dry matter in the stems by maintaining low plucking tables and use of closer spacings to maintain full canopy cover (Magambo and Cannel, 1981). Maximum yields of up to 11 t ha^{-1} yr^{-1} have been obtained in clonal tea (clone AHP S15/10) plantations (Chapter 2). In this study, yields ranged from 2,000–3,000 kg made tea ha^{-1} yr^{-1} and 2,000–4,000 kg made tea ha^{-1} yr^{-1} in the seedling and clonal tea plantations, respectively (Chapter 3). The wider range in the clonal tea plantations showed the higher variability in response to weather conditions and management.

All tea plantations that were planted by 1966 are 40 years old and approaching the degraded/moribund stage. Plantations older than 40 years now cover 43% and 15% of the estate plantations and smallholder sector, respectively, and this coverage continues to increase rapidly. The plant population density of these old plantations are low (< 8,000 plants per ha). The analysis of the trends in tea production, productivity and area in the estate plantations and smallholder sectors revealed that a higher productivity (yield per unit area) still exists in the estate plantations (2.6 t ha^{-1} in 2006) compared to the smallholder sector (2.2 t ha^{-1} in 2006). Lower mean yields in smallholder tea farms may be a result of the heterogeneity in soil fertility and management of smallholder farms (Tittonell et al., 2007). A yield decline was found in the estate plantations sector during the last decade, while yields still tend to increase in the smallholder sector (Chapter 2). The yield decline suggests that the degradation of the older tea plantations in the estate sector is widening, and/or the newer plantings and replants in ex-tea areas are not yielding as expected.

Using the simple decision-support (DS) model for Managing Ageing Plantations of Tea (MAP-Tea) we identified promising interventions that included good management practices where replanting with high-yielding clonal cultivars is carried out (Chapter 2). For the assumptions made, poor management practices with no replanting resulted in net returns of zero in 52 and 85 years for degradation rates of k=0.06 and 0.02 yr^{-1}, respectively, showing the importance of replanting. A schematic representation for visualization of good and poor management practices is shown in Figure 1. Under good management maximizing the mature/commercial area maintains profitability, while under poor management practices, the degraded/moribund area increases and, therefore, the tea plantation becomes less commercial.

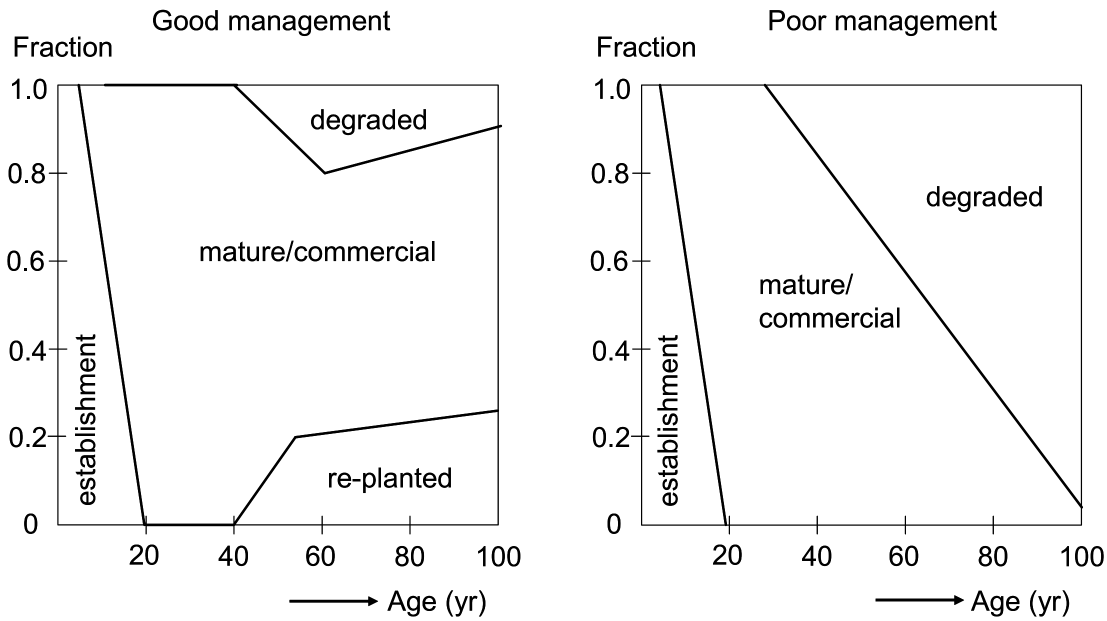

Figure 1. Schematic representation of the effect of good and poor management practices on the fractions of mature/commercial and degraded area in tea plantations.

Resource use

Genotype, nitrogen and weather interactions

Major issues pertaining to yield determining and limiting factors in ageing tea plantations are addressed in Chapters 3 and 4. Clonal tea plantations responded to fertilizer nitrogen (N) with peak yields at levels varying from 100 to 200 kg N ha^{-1} yr^{-1} irrespective of age, while the much older seedling plantations did not respond. Although younger seedling plantations were not part of the tea chronosequence studied, they have been found to respond to N in different regions of Kenya. Owuor et al. (1993) found that a 27-year old seedling tea stand responded to N-fertilizer application at the eastern highlands of Kenya, Nyambene Hills. Similar findings were reported in a long term experiment by Kamau et al. (1999) on seedling plantations that showed annual responses to N from the ages of 26 to 37-years at Kericho, western Kenya. However, responses to N were low or absent during the pruning year. In this study, the 43-year old plantation showed a weak positive response (in 2003/04) to N while the response of the 76-year old plantation was negative. This suggests that the response to N-application fades as the seedling tea plantations age. To maintain profitability, it is important to lower N-rates in synchrony with ageing of the seedling tea plantations. N-use should be restricted to maintain tea quality (Owuor and Odhiambo, 1993) and to enhance shoot growth when leaf damage by pests occurs during stress periods (Sudoi et al., 1996).

Productivity in this study was found to be influenced by seasonal weather conditions in both the clonal and seedling plantations as has been reported in other studies (Othieno et al., 1992; Kamau et al., 2003). An optimum heat-load and even rainfall distribution resulted in high made tea yields. Total solar radiation was not related to yields. The variations in bi-weekly tea yields suggest that clonal bushes were affected more by changes in weather conditions than seedling bushes. Hence, clonal tea bushes responded more strongly to drought stress (Figure 2). Clonal plantations perform well under good and optimum weather conditions, but are likely to be outperformed by seedlings under adverse conditions like drought or nutritional stress.

The carbon (C) and major nutrient (N, P, K) stocks per bush and per unit area of the ageing tea plantations increased with age within genotypes (seedlings and clones). The variation due to age of the dry weight of foliage, frame and roots within genotypes was minimal for C content, but DM weights of these organs increased significantly with age.

Seedling genotypes had significantly higher N-content in most plant organs (two leaves and a bud, twigs, stems, thick woody roots and thin feeder roots), but P-contents were similar. The K-contents in stems, thick woody roots and thin feeder roots in the

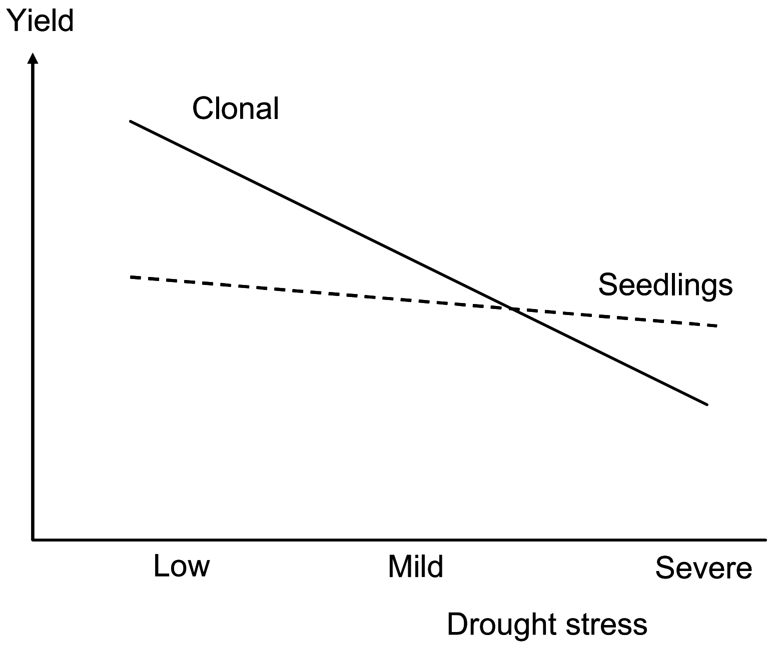

Figure 2. Expected productivity trends as influenced by adverse weather conditions for seedlings and clonal tea plantations based on measurements presented in Chapter 3.

seedlings were higher than in the clonal cultivars. N in tea plants is highly mobile and is translocated from the older leaves to the younger leaves. Hence, the 'two leaves and a bud' may take a longer period to develop N-deficiency symptoms than the older maintenance leaf. Based on the N, P, and K contents in the 'two leaves and a bud' (from control plots that had not received N-fertilizer for two years), the N, P, and K removal in kg per 1,000 kg made tea (Chapter 1) were calculated (Table 2). N-removal in seedlings per 1,000 kg made tea was higher in seedling tea than in clonal tea. However, the clonal plantations show higher yields (Chapter 3) and, therefore, will remove more nutrients. The amounts of N, P, and K removed fall within the range reported in literature (Othieno, 1979a; Bonheure and Willson, 1992; Tandon, 1993). Whereas P removal is similar for both genotypes, N and K showed opposite trends probably due to the antagonism of the uptake of NH_4^+ and K^+ ions by tea plants. Because of the higher mean yield and nutrient removal, clonal tea would require a

Table 2. Removal of N, P and K in harvested tea in kg per 1000 kg made tea.

Genotype	Nitrogen	Phosphorus	Potassium
Seedling	45	2.8	18
Clonal	35	2.8	21

higher fertilizer dose than seedling tea. Most tea-growing countries use the same NPK-based fertilizers for mature tea stands for reasons of cost effectiveness. Remedial applications of specific nutrients should, therefore, be site and dose-specific, e.g. higher K doses for seedling tea than for clonal tea.

Soil quality

Our studies on soil properties addressed the ageing problem in a three-fold manner using the hypotheses that ageing and degradation of tea plantations is related to: (i) increases in soil acidity; (ii) nutrient imbalances arising from acidification and/or unbalanced fertilization practices; and (iii) changes in microbial properties, resulting in lack of microbial functioning of the soil. Based on the results obtained, we concluded (Chapter 5) that soil chemical and microbiological properties were not likely to cause degradation in old tea lands.

The total microbial activity (TMA) and microbial C and N contents tended to increase with the age of the tea plantation, although there was a closer association of these characteristics with tea genotype. Soils in the natural forest and the seedling plantations had higher TMA than soils from the clonal tea plantations. In the incubation study, addition of tea prunings to the tea soils lowered net N-mineralization irrespective of age of tea plantation and soil acidity, compared to forest soil that did not. There was some relationship between measured productivity (using yield data obtained in 2003/04; Chapter 3) and soil pH and total organic C (Chapter 5), but these relationships were statistically non-significant.

Prunings are an important component of tea cultivation and large amounts are returned to the soil. Commonly, decomposition of tea prunings proceeds fast as most organic residues in tropical soils (Yang and Janssen, 2000). Immobilization of any added nutrients during decomposition of prunings seems to occur only during the first year after pruning (Wibowo, 1985). Table 3 presents the amounts of N, P, K, and Mg returned to the soil via prunings, assuming a mean amount of 10.8 t DM ha^{-1} (after Ranganathan, 1973). Generally, larger amounts of N and smaller amounts of P are returned from seedlings compared to those of clonal plantations. Within genotypes, K content decreased while Mg increased with age of plantation. This suggests that more K is required as tea plantations age whereas Mg is not likely to become a problem as long as the prunings are returned. Indeed Mg is rarely applied in tea plantations in Kenya, although Mg deficiency symptoms may occur during dry seasons (Kamau, 2002). However, our data suggests that returning prunings to the soil is essential for the replenishment of the K and Mg withdrawn from the soil via crop uptake. The amounts of $CaCl_2$ extractable and aqua regia digestible K and Mg in the soils of the tea plantations are relatively small (Chapter 5) suggesting indeed little buffering. We

Table 3. Amounts of nutrients returned (kg ha^{-1}) to the soil via prunings in ageing tea plantations.

Genotype	Age	Nutrient in kg ha^{-1}			
	(years)	N	P	K	Mg
Clonal	14	179	17	100	7.6
Clonal	29	177	19	81	10.8
Seedling	43	194	15	100	5.4
Seedling	76	190	13	75	6.5

conclude that the differences in soil properties between uniformly managed tea plantations differing in age are relatively small and are also weakly related to productivity, hence are unlikely to cause degradation in ageing tea plantations. The situation in the smallholder tea farms may differ because of the heterogeneity of soil properties that affect productivity and resource use efficiency differently. Generally, the management of such smallholder tea farms is less optimal compared to the estate plantations, suggesting that faster degradation may occur in the smallholder farms than in the estate plantations (Bore, 1996).

Soil carbon (C) sequestration in tea plantations was not assessed in detail in our study. Total soil organic C was only determined in the top 0–20 cm depth where only small differences were found across the chronosequence (Chapter 5). In agroforestry systems, a relatively large sequestration of C has been observed in subsoil layers compared to the topsoil due to the deep rooted tree species (Makumba, 2003). This may suggest that the deeper rooted seedling genotypes may contribute more to C sequestration in the subsoil than clonal plantations. Conversely, more organic C may be found in the top soil of clonal tea plantations compared to those of seedling tea plantations (Chapter 5).

Management options

We recognize that farm managers have to make strategic and tactical management decisions geared to improving profitability of their tea farming business. It is not only important for such decisions to be economically and ecologically sound, but they should also be acceptable by all stakeholders. Crop growth models such as the CUPPA-Tea model (Matthews and Stephens, 1998a, b) may support decision making on how to maximize on tea yields. However, such models do not have an in-built economic component. In Chapter 2, a simple decision support (DS) model, MAP-Tea, clearly showed that ageing tea plantations can only remain economically viable with uprooting and replanting programmes as has been recommended also in some tea-growing regions (Barbora, 1994; Illukpitiya et al., 2004). When replanting is done gradually, net returns can be doubled within a period of 20 years although the net income drops by up to about half during the first few years. However, with proper clonal screening and soil rehabilitation, the period taken to get maximum benefits can be shortened. The sensitivity analysis on degradation rates in the scenario for replanting (Chapter 2) showed that net returns will depend on the site factors, hence the need for proper resource screening prior to carrying out large scale replanting programmes. For the three development phases of the tea bush, i.e. establishment, mature/commercial, and degraded/moribund, the yield gap is illustrated in Figure 3 between the actual yields (low-yielding seedling and high-yielding clonal plantations) and the potential yield. Genetic improvement and improvement of agronomic practices can be used to narrow the yield gap. Differences between seedling tea yield, clonal tea yield and potential yield are indicative for opportunities to increasing yields through improvements in genotypes and management.

Implications

In the past, most research on tea plant-soil interactions has focused more on the short-term studies at field experimental level than on the productivity, resource use and life-time of tea bushes at plantation level. This thesis has shown for the first time that useful information is obtained by scaling up the results of specific plant-soil findings from the bush to plantations level. The implications of our study are categorised as scientific, environmental and societal.

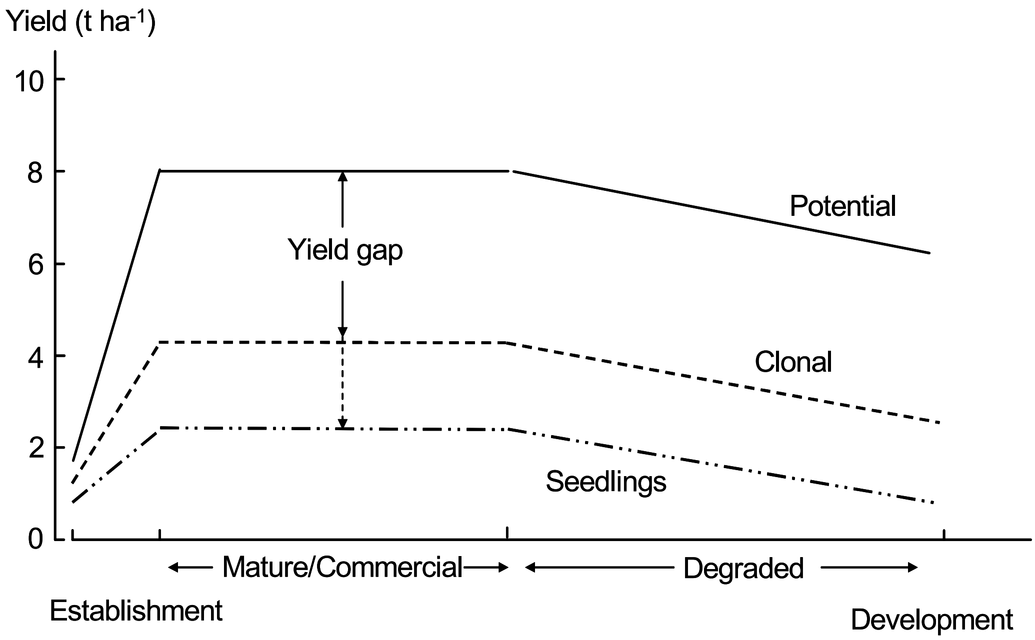

Figure 3. Yield patterns of tea plantations with different genotypes.

Scientific

- Degradation of ageing tea plantations is a result of a complex of interacting factors. Uprooting and replanting degrading tea plantations is costly, but the yield increase associated with modern higher yielding clonal tea genotypes outweighs the yield loss and costs associated with uprooting and replanting in the long-run. Strategic decisions about uprooting and replanting tea plantations require careful considerations at field, farm, estate and tea factory levels. Future research should include the long-term dynamics of productivity and resource use at the plantation level. These studies should be complemented by short-term studies on soil and plant factors at the field and bush level.
- A multiple soil nutrients approach, i.e. C-stocks, macro-nutrients and micro-nutrients provides insight into the differential nutrient depletion of soils under ageing tea plantation, which in the end may lead to useful fertilizer recommendations at plantation level.
- Current breeding strategies aiming targets for yield and quality of clones should be combined with tolerance to adverse weather conditions, as proposed also in the 2005–2010 strategic plan of the Tea Research Foundation of Kenya (TRFK, 2006). The magnitude of expected stress factors (drought, heat, pests, etc.) should be quantitatively monitored and assessed.

Environmental

- Saving on N applications in ageing tea plantations should be considered in the fine-tuning of management practices. It will lead to reduced risks on N-losses.
- Regular surveys of soil quality and productivity indicators in representative tea growing areas can support management practices and can reduce the need for external inputs (fertilizers).
- When uprooting and replanting degrading tea plantations, care should be taken that top soil is not eroded. This requires sequential strip-like replanting approach as recommended in the tea growers handbook (TRFK, 2002).

Societal

- Increasing the tea production per unit of land by reducing the yield gap will raise tea production and the profitability of tea production, depending in part on subsequent market and prices effects.
- The current pressure on land will be eased by improving tea productivity since more land will be available for other uses, i.e. food, fibre and fuelwood.

General conclusion

This thesis has provided a better insight into the ageing of tea bushes in relation to productivity and resource use hitherto not addressed. We have shown that the complexities associated with ageing tea agro-ecosystems in scale and time arise from interactions between genetic improvement of the tea plant and changes in agronomic practices over time. While the old tea plantations based on seedlings genotype and low plant population densities contributed to the declining productivity trend by the estate plantations sector, the clonal cultivars (cultivated at high densities) and improvement in agronomic practices led to increasing yields in the smallholder sector in Kenya. The factors leading to the observed trends were identified and categorized as, genotype traits, agronomic practices, ecological factors, and soil fertility factors. Technological development in agronomic practices like machine pruning, however, implies that some of the factors discussed herein may not affect the productivity trends in ageing of tea plantations in the near future.

This study confirms that the 76-year old seedling bushes are not degraded/moribund as yet. Similarly, the study showed that soils can remain functional for the duration of the tea plantations under good agronomic practices. Further research should focus on identification of tea bush degradation symptoms and criteria to be used as a diagnostic tool for decision making on uprooting and replanting. Research on improvement in productivity of tea plantations should consider Genotype × Environment × Management (G×E×M) relationships in an integrative way. More attention is also needed for multiple abiotic stresses (drought, cold, unbalanced nutrition) under less favourable soil conditions and under weather extremes associated with climate change. On-going research on allelopathic interactions between soil and crop in degraded tea lands aims at understanding factors and mechanisms that limit growth of replanted tea in old tea lands and may offer ways of detoxifying any allelochemicals that may be responsible. Finally, isolation, screening and identification of possible tea-specific soil borne pathogens that could be responsible for the degradation should be explored.

Evidently, degradation of tea plantations may undermine the economic viability of millions of people in Kenya. Understanding the causes, impacts and opportunities is of utmost importance. Dissemination of knowledge on the functioning of the tea ecosystems in participation with all stakeholders (managers, farmers, researchers, extension, policymakers) should, therefore, also get high priority.

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Summary

In Kenya, the tea industry plays a leading role as a foreign exchange earner and a source of livelihood to over three million people representing 10% of the population. It is therefore important to improve the productivity and quality of the produce of tea plantations. The tea plantations if well managed can remain in production for up to 100 years. However, peak yields are obtained at 20–40 years after planting followed by a decline to a level where the plantations may become irredeemably uneconomical.

Commercial tea production in Kenya was started in 1924 by the estate plantations sector and in 1964 by the smallholders sector. In 2006, tea plantations that were 40 years and above comprised of 41% and 10% of the estate plantations and smallholders sectors, respectively. These percentages increase rapidly over time especially in the smallholder sector where the fastest growth occurred between 1969 and 2000. Currently the smallholders sector accounts for 65% of the total tea area and 62% of made tea production; and the productivity gap between the two sectors is narrowing. To gain a better understanding of how productivity and resource use of tea agro-ecosystems in Kenya are influenced by factors associated with ageing in scale and time, studies were carried out using data from the tea industry in Kenya (Chapter 2) and by conducting focused experiments on the plant-soil-environment relations (Chapters 3–5).

The assessment of tea production and area data of the two sectors of the Kenyan tea industry aimed at analyzing whether there existed a stagnation or decline in yields and explore management options for alleviating any decline in productivity. Through a review of factors that limit the growth of the tea bush and ageing of tea plantations, it was shown that the tea crop has comparatively low productivity compared to other C_3 crops due to management practices like pruning to keep the plucking table low and the harvesting of the shoots that forms the main product of ‘two leaves and a bud’. At tea bush level, major factors limiting growth were: temperature, rainfall (including drought stress and hail storms damage), soil fertility, and nitrogen. At tea plantation level, the limiting factors were: pruning practices, genotype choice, planting density, and pests and diseases (biotic) factors. To explore plausible management options for tea productivity improvement, a simple decision-support (DS) model for Managing Ageing Plantations of Tea (MAP-Tea) was developed to identify promising interventions. We showed through scenario analyses that replanting is vital if tea productivity in the ageing tea plantations is to be improved. Estimated net returns would be doubled by replanting with high yielding clonal cultivars within a period of 20 years. However, sensitivity analysis with different degradation rates for the clonal

replants revealed uneconomic returns for degradation rates above 0.2 ha ha^{-1} yr^{-1}. Based on a better understanding of factors that determine degradation of bushes, the right strategic and tactical management decisions can be made.

Major issues pertaining to yield determining and limiting factors in ageing tea plantations are addressed in Chapters 3 and 4. A tea chronosequence was selected consisting of two genotypes (seedlings and clonal) established at different plant population spacing based on technological development. Thus the older seedling plantations had lower plant densities (< 8,000 plants per ha) while the younger clonal cultivars (clone TRFK 6/8) had higher planting densities (> 10,000 plants per ha). Through N-fertilizer field experiments conducted in 2002/03 and 2003/04 in Kericho, it was found that the younger clonal plantations (14- and 29-year old) responded to fertilizer N with peak yields at doses varying from 100 to 200 kg N ha^{-1}, while the older seedling plantations (43- and 76-year old) did not respond to N. Under the contrasting weather patterns, poorly distributed rainfall pattern in 2002/03 and an even distributed rainfall pattern in 2003/04, it was found that clonal outperformed seedling bushes under optimal conditions. The responses to N-application were found to fade as the seedling tea plantations age. Productivity too was found to be influenced by seasonal weather conditions in both the clonal and seedling tea genotypes; an optimum heat-load and an even rainfall distribution resulted in highest yields. The older seedling genotypes were however affected less by adverse weather like drought stress and lower temperatures. We concluded that ageing *per se* does not reduce productivity and the response to N, and that future N-management should be based on the yielding ability of tea bushes. To maintain profitability, it is important to lower N-applications in synchrony with ageing of the seedling tea plantations and/or restrict N-application to maintain tea quality and to compensate for leaf damage by pests during stress periods.

The carbon and major nutrients (N, P, and K) stocks per bush and per unit area of the ageing tea plantations increased with age within genotypes (seedlings and clones). The variation due to age of the dry weight of foliage, frame and roots within genotypes was minimal for carbon content, but DM weights of these organs increased significantly with age. The higher densities (HD) for the clonal plantations and lower densities (LD) for the seedling plantations affected dry weights, C and nutrients stocks at the bush level, but were more clear per unit area. We showed that within cultivars as the tea bushes age, they acquire higher C and nutrients NPK stocks that enables them to depend less on temporary limiting nutrient(s) and moisture conditions, i.e. adverse conditions. There is a trade-off for this investment in extra reserves in productivity. Assessment of carbon and nutrient stocks should therefore be carried out per unit area to avoid effects of variation in population density. Although tea plantations were found

to accumulate less biomass than tropical forests and mature plantation trees, the perennial agro-ecosystems imply a sustained carbon sequestration in fragile areas.

The soil properties studies using top 0–20 cm soils were set to address the ageing problem in a three-fold manner using the hypothesis that ageing and degradation of tea plantations is related to: (i) increases in soil acidity; (ii) nutrient imbalances arising from acidification and/or unbalanced fertilization practices; (iii) and changes in microbial properties resulting in lack of microbial functioning of the soil. Soils from an adjacent natural forest were used as a control. The study showed that the older tea plantations have slightly more acidic soils and had higher contents of $CaCl_2$ extractable Al and Mn. $CaCl_2$ extractable K and Mg were also low in the tea plantations compared to the natural forest. The addition of prunings in tea soils lowered net N-mineralization (unlike the forest soil) that was not influenced by ageing of the tea stand or by soil acidity. The biological soil functioning was assessed through total microbial activity and soil biomass C and N and differences were more genotype related than age. The natural forest also had similar TMA and soil biomass C and N with the older seedling plantations. Soil pH and total organic carbon were weakly related to the measured productivities of the tea plantations in 2003/04. We concluded that the differences in soil properties which were relatively small and also weakly related to productivity were unlikely to cause degradation in ageing tea plantations.

Summarizing, this study showed that the productivity decline associated with ageing of tea agro-ecosystems arise from the genetic improvement of the tea plant, agronomic practices, and environmental factors. While the old tea plantations based on seedlings genotype and low plant population densities contributed to the declining productivity trend by the estate plantations sector, the clonal cultivars (cultivated at high densities) and improvement in agronomic practices led to increased yields in the smallholder sector of the Kenyan tea industry. The factors and processes leading to the observed trends were identified and categorized as, genotype traits, agronomic practices, ecological factors, and soil fertility factors. Technological development in agronomic practices however implies that other factors may also influence productivity of the current tea plantations. This study confirms that the 76-year old seedling tea bushes are not degraded/moribund as yet. Similarly, the study has shown that the tea soils can remain functional for the duration of the tea plantations under good agronomic practices. Further improvement in productivity of ageing tea plantations should take into account Genotype × Environment × Management (G×E×M) relationships.

Productivity and resource use in ageing tea plantations.
David M. Kamau (2008)

Samenvatting

In Kenia speelt de productie en export van thee een belangrijke rol in het verwerven van buitenlandse valuta en voor de werkgelegenheid van drie miljoen mensen, 10% van de bevolking. Verbetering van productiviteit en kwaliteit van thee zijn derhalve zeer belangrijk. Goed beheerde theeplantages kunnen tot 100 jaar in productie blijven. Topopbrengsten worden echter behaald in plantages van 20–40 jaar oud; na die fase treed er een daling in tot een niveau, waarbij plantages onomkeerbaar niet meer rendabel zijn.

Commerciële productie van thee startte in Kenia in 1924 met plantages en in 1964 door boerenbedrijven. In 2006, waren respectievelijk 41% en 10% van de theevelden bij de plantages en bij de boeren 40 jaar en ouder. Dit aandeel neemt nu snel toe bij de kleine bedrijven, omdat daar de snelste uitbreiding plaatsvond tussen 1969 en 2000. Momenteel omvatten de kleine bedrijven 65% van het areaal en 62% van de productie; het verschil in productiviteit tussen de twee sectoren neemt af. Om een beter inzicht te krijgen hoe de productiviteit en het gebruik van productiemiddelen in thee-ecosystemen in Kenia beïnvloed wordt door factoren, die gerelateerd zijn aan veroudering, werden er deskstudies verricht op basis van data voor de twee theesectoren in Kenia (Hoofdstuk 2); tevens werden er gerichte proeven uitgevoerd naar plant-bodem-milieu interacties (Hoofdstukken 3–5).

Het doel van de evaluatie van gegevens over theeproductie en -arealen in de twee Keniaanse theesectoren was om vast te stellen of er een stagnatie dan wel een daling is in opbrengst en om managementopties te verkennen die een daling in productiviteit kunnen voorkomen. Met een analyse van factoren, die de groei van theestruiken en de veroudering van plantages bepalen, kon worden aangetoond dat het theegewas een relatief lage productiviteit per eenheid van land heeft in vergelijking met andere C_3 gewassen. Dit is een gevolg van teeltmaatregelen, zoals snoeien om de plukhoogte laag te houden en het periodiek oogsten van de jonge spruiten, gevormd door de twee topblaadjes en de knop. Op het niveau van de individuele theestruik zijn de belangrijkste groeibeperkende factoren: temperatuur, neerslag (incl. droogte en beschadiging door hagel), bodemvruchtbaarheid en stikstof. Op het niveau van de theevelden zijn beperkend: snoeiwijze, rassenkeuze, plantdichtheid, en biotische factoren, zoals ziekten en plagen.

Om realistische managementopties voor verbetering van de productiviteit te verkennen, is een eenvoudig beslis(DS)-model *Managing Ageing Plantation of Tea* (MAP-Tea) ontwikkeld als onderzoeksinstrument voor het identificeren van veelbelovende interventies. Met scenarioanalyses konden we aantonen, dat herplanten

noodzakelijk is om de productiviteit van theestruiken te verhogen in verouderde plantages. Op basis van een schatting zouden de netto rendementen binnen 20 jaar verdubbeld kunnen worden als herplant plaatsvindt met hoogopbrengende rassen, die door vegetatieve vermeerdering (‘klonaal’) verkregen zijn. Gevoeligheidsanalyses met verschillende parameterwaarden voor de degradatiesnelheid lieten echter zien, dat de rendementen niet meer positief waren bij degradatiewaarden van meer dan 0,02 kg j^{-1}. Een betere kennis van de factoren, die de degradatie van theestruiken bepalen, zal de basis leggen voor het nemen van de juiste strategische en tactische management-beslissingen.

Belangrijke aspecten betrekking hebbend op de opbrengstbepalende en -limiterende factoren in verouderende theeplantages komen aan de orde in de Hoofdstukken 3 en 4. Een tijdreeks van theeplantages met twee genotypen, voortgekomen uit zaailingen en klonen geplant in verschillende dichtheden op basis van de beste teelttechnologie, werd geselecteerd. De oudere ‘zaailing’-plantages hadden een lage (LD) plantdichtheid (< 8.000 planten per ha), terwijl de jongere ‘kloon’-plantages met het ras TRFK 6/8 een hogere (HD) plantdichtheid (> 10.000 planten per ha) hadden. Uit veldproeven met stikstoftrappen, uitgevoerd in 2002/03 en 2003/04 in Kericho, bleek dat de jongere ‘kloon’-plantages (14 en 29 jaar) een betere N respons gaven; de hoogste opbrengsten werden verkregen bij kunstmest-N giften van 100 tot 200 kg ha^{-1}. De oudere ‘zaailing’-plantages (43 en 76 jaar) gaven geen positieve N respons. De uiteenlopende weersomstandigheden in 2002/03, met een slechte verdeling van de neerslag over het jaar, en in 2003/04 met een optimale verdeling gaven als resultaat, dat ‘kloon’-struiken meer opbrengst gaven dan ‘zaailing’-struiken. De N respons van ‘zaailing’-struiken werd negatief bij de veroudering van de plantage. Gewas-productiviteit van beide genotypen werd ook beïnvloed door de seizoensvariatie in het weer; een optimale temperatuur en een gelijkmatige neerslagverdeling resulteerde in de hoogste opbrengsten. De oudste plantages werden het minst beïnvloed door ongunstige weersomstandigheden, zoals de droogte en lage temperaturen in 2002/03. We concludeerden, dat veroudering *an sich* niet de productiviteit en de N respons verlaagt; derhalve zal het nutriëntenmanagement in de toekomst gebaseerd moeten zijn op de opbrengstpotentie van theegewassen bepaald door de combinatie van genotype en plantdichtheid enerzijds en de leeftijd anderzijds. Om het rendement op peil te houden is het belangrijk de N-giften te verlagen bij de oudere ‘zaailing’-plantages; kunstmeststikstof is dan alleen nodig om op kwaliteit te sturen en om bladschade door insecten in stressperiodes te compenseren.

De voorraden koolstof (C) en macronutriënten (N, P en K) per struik en per eenheid van landoppervlak namen toe met de leeftijd binnen genotypen (zaailing of kloon). De variatie als gevolg van de leeftijd was minimaal voor het koolstofgehalte in blad, takken en wortels; echter, het drooggewicht nam significant toe met de leeftijd. De plantdichtheden in de 'kloon'-plantages (HD) en in de 'zaailing'-plantages (LD) waren van invloed op de drooggewichten, koolstof- en nutriëntenvoorraden van de struiken, maar het meest duidelijk per eenheid landoppervlak. We vonden, dat binnen rassen bij veroudering meer C- en NPK- voorraden aanwezig waren; deze verkleinen de afhankelijkheid van het gewas van water- en nutriëntenbeschikbaarheid tijdens ongunstige omstandigheden. Deze extra investeringen in reserves gaan echter ten koste van de productiviteit onder gunstige omstandigheden. Het bepalen van C- en nutriëntenvoorraden dient te geschieden per eenheid van landoppervlak om het effect van verschillen in plantdichtheid te vereffenen. Ofschoon theeplantages minder biomassa accumuleren dan tropische bossen en bosplantages, dragen deze meerjarige agroecosystemen toch bij aan een continue koolstofvastlegging in kwetsbare gebieden.

Het onderzoek naar bodemparameters in de toplaag van 20 cm werd uitgevoerd om het effect van veroudering op de bodem vanuit drie invalshoeken te bestuderen. De hypotheses voor bodemdegradatie waren: (a) een toename in zuurgraad en in elementen gerelateerd aan verzuring, (b) onevenwichtigheden in de nutriëntenvoorziening als gevolg van pH veranderingen, die leiden tot een verlaagde opname of toxische effecten bij essentiële voedingselementen voor de theeplant en (c) veranderingen in microbiële eigenschappen die leiden tot een gebrekkige biologische activiteit van de bodem. Bodemmonsters van een nabijgelegen natuurlijk bos werden gebruikt als controles. Het onderzoek liet zien, dat in oudere plantages de zuurgraad van de bodem en de gehalten aan in $CaCl_2$ extraheerbaar Al en Mn waren toegenomen. De toevoeging van snoeiafval aan de grond verlaagde de netto N-mineralisatie (niet in de bosgrond); dit effect werd niet beïnvloed door veroudering of door de zuurgraad van de grond. Het biologisch functioneren van de grond, bepaald aan de totale microbiologische activiteit (TMA) en aan de C- en N- biomassa in de bodem, was meer gerelateerd aan het plant genotype dan aan de leeftijd van de plantage. De bosmonsters hadden TMA-waarden en bodem C- en N-biomassa vergelijkbaar met die van de oudere 'zaailing'-plantages. Bodem pH en totaal organisch C waren zwak gecorreleerd met de gemeten gewasproducties van de plantages in het optimale jaar 2003/04. Wij concludeerden, dat de relatief geringe verschillen in bodemeigenschappen met kleine effecten op gewasproductiviteit zeer waarschijnlijk niet de oorzaak zijn van de degradatie van verouderende theeplantages.

Samenvattend; dit onderzoek toonde aan dat de afname in gewasproductiviteit in oudere theeplantages gerelateerd is aan de genotypisch verbetering van het plantmateriaal, de agronomische teeltmaatregelen en aan omgevingsfactoren. In de oude theeplantages droegen de genotypisch minder productieve 'zaailingen' en de lage plantdichtheid bij aan de dalende productiviteitstrend in de plantagesector. De introductie van rassen gebaseerd op geselecteerd kloonmateriaal, geteeld in hogere plantdichtheden, en het gebruik van betere teeltmethoden leidden tot opbrengstverhogingen bij de kleine bedrijven in de Keniaanse theesectoren. De factoren en processen die leidden tot de waargenomen trends werden geïdentificeerd en geclassificeerd als: genetisch-fysiologische interacties, agronomische teeltmaatregelen, ecologische factoren en bodemvruchtbaarheidfactoren. Technologische vooruitgang zal tot gevolg hebben, dat ook andere factoren hebben bijgedragen aan de productiviteitstoename in de huidige theeplantages. Hoewel er genetisch-fysiologische veroudering plaatsvindt, geeft dit onderzoek aan dat niet alle 76-jaar oude 'zaailing'-theestruiken onproductief en stervend zijn. Eveneens, heeft het onderzoek aangetoond dat de grond fysisch-chemisch en biologisch goed kan blijven functioneren gedurende de lange levenscyclus van theeplantages onder een goed bodem- en gewasmanagement. Verdere verbeteringen in productiviteit tijdens de veroudering van theeplantages zullen meer gebaseerd moeten zijn op Genotype × Milieu × Management (G×E×M) relaties.

Productiviteit en groeifactoren bij veroudering van theeplantages.
David M. Kamau (2008)

Muhtasari

Ukuzaji wa majani chai nchini Kenya ni kati ya njia kuu za kuongeza na kuleta mapato ya taifa kwa watu wapatao millioni tatu (10% ya wakenya). Kutokana na umuhimu wa zao la chai kwa pato la taifa na kwa asilimia kumi ya wakenya,kuna umuhimu wa kuzalisha chai bora kwenye mashamba ya chai yaliyopo. Kwa utunzaji mwema, mashamba ya chai yawezakuzalisha kwa kipindi kirefu kufikia miaka 100, tangu ilipopandwa. Hata hivyo kilele cha uzalishaji ni miaka 20 - 40, halafu uzalishaji hupungua hadi kufikia chai kutopatikana.

Upandaji wa chai nchini Kenya uliazishwa mwaka 1924, sekta ya mashamba makubwa (KTGA) na baadaye kwenye sekta ya wakulima wa chai wadogo (KTDA) mwaka 1964. Kufikia mwaka 2006, mashamba ya chai yaliyokuwa yana zaidi ya miaka 40 yakawa asilimia 41% ya KTGA na asilimia 10% ya KTDA. Haya mashamba yanaendelea kuongezeka zaidi katika sektar ya wakulima wadogo ambayo imeongezeka zaidi kuanzia mwaka 1969 hadi 2000. Wakati huu, asilimia 65% ya mashamba yote ya chai nchini Kenya ni ya KTDA na hupataasilimia 62% ya mazao yote; pia mazao kwa hektari yanazidi kukaribia yale yanayopatikana kwa mashamba makubwa (KTGA). Ili kupata ufahamu zaidi jinsi mazao na utumiaji wa rasilimali ya mashamba ya chai yanavyobadilika kwa sababu ya kuzeeka kwa wingi na wakati, utafiti huu ulifanywa haya kwa kutumia takwimu kutoka Bodi ya chai ya Kenya - TBK (Chapter 2) sambamba na majaribio yaliyohusishwa zao la chai-udongo na hali ya hewa (Chapters 3-5).

Sehemu ya kwanza ya utafiti ilihusu mazao ya mashamba na sehemu ya ardhi kunakokuzwa katika sektar za KTGA na KTDA. Utafiti huo ulikusudia kuona kama kuna upungufu katika mazao ili kutabiria jinsi ya kukabiliana na upungufu wa mazao. Mambo kadhaa huathiri ukuaji bora wa miti ya chai na mashamba. Mambo yanayoathiri ni pamoja na; mmea wa chai unapoanza kuonyesha dalili ya uzee na pia mmea wa chai unapotoa mazao madogo ukilinganishwa na mimea mingine ya aina ya C_3. Hii ni kwa sababu ya kukata mti (pruning) ili wachumaji waweze kuufikia mmea na ili mmea uwe wenye kutoa chai zaidi. Kwa miti ya chai, yale yanaathiri sana ni: joto, mvua, udongo, na maadini kama nitrogen. Kwenye shamba lote, yale yanoadhiri ni ukataji (pruning), aina ya miche, upana wakati wa kupanda, na wadudu na magonjwa. Ili kuongeza matumaini ya utunzi bora ya majani chai, mfano rahisi aina ya model (MAP-Tea) uliundwa na kutumiwa kuongeza ufahamu wa technologia ambayo yaweza kusaidia kuongeza faida kwa mkulima wa chai. Tulionyesha kwamba kubadilisha miche ya aina ya *clones* wakati ile ya kiasili (seedlings) inapozeeka na kung'olewa ndio mtindo bora wa kuongeza faida. Kwa kubadilisha miche hii, faida mara mbili ilionekana kuongezeka kwa muda wa miaka 20. Lakini, tulipofanya 'sensitivity analisis' ambapo miche hiyo ingetoa mazao duni kwa sababu mbali mbali kama udongo, ilionekana kwamba udhaifu kutokana na aina ya miche, udongo, na mmomonyoko wa ardhi zaidi ya 0.2 kwa mwaka ungeletea mkulima hasara. Hii inamaanisha kwamba tukiwa na fahamu bora kinacho sababisha mmomonyoko huu, tunaweza kuwa na njia bora za kutunza mashamba na miche ya majani chai.

Mambo makuu kuhusu mazao nay ale yanayotatiza na kufanya mazao ya majani chai kuwa duni, yamefafanuliwa katika Chapter 3 na 4. Mashamba ya majani chai kati ya miaka 14 , 29, 43 na 76 yalichanguliwa. Mawili ya kwanza (seedlings, miaka 43 na 76) yalipandwa kwa umbali wa miche chini ya 8,000 kwa hekitari, na yale mengine mawili (clone TRFK 6/8, miaka 14 and 29) kupandwa kwa umbali wa miche zaidi ya 10,000 kwa hekitari. Experiment zilifanywa na mbolea ya aina ya nitrogen (N) miaka ya 2002/03 na 2003/04 pale Kericho. Ilionekana kwamba miche aina ya clone iliweza kuongeza mazao kwa kutumia N, likini ile aina ya seedling haikuweza kuongeza mazao. Pia ilionekana kwamba miche aina ya clone iliongeza mazao zaidi mwaka wa pili ambao ulikua na mvua ya kutosha ukilinganishwa na mwaka wa kwanza ambao mvua ilikua duni. Mazao ya miche aina yote mbili ilikaribiana mwaka wa kwanza kuonyesha kwamba miche aina ya seedling haikutatizwa na mvua duni na joto. Ilionekana kwamba uzee wa miche haupunguzi mazao ya majani chai ama jinsi mbolea aina ya N inatumika, mbali na matumizi ya N ni lazima yaangalie mazao ya kila aina ya miche kabla ya kutumiwa. Ili mkulima apate faida, anahitajika kutumia mbolea kulingana na aina na miaka ya miche aliyopanda na kwa aina ya seedlings, mbolea ya N ingefaa kutumika kwa sababu ya kupata ubora wa kiwango cha "matawi mawili na shindano" na kwa kulipishia uharibifu unaotokana na wadudu.

Madini aina ya carbon (C), nitrogen (N), phosphorus (P) na potassium (K) kwa kila mche na kwa eneo la hekta moja la shamba iliongezeka kadiri shamba lilivyozeeka kwa kila aina ya chai (*seedling* na *clone*). Mabadiliko kutokana na umri wa uzito mkavu wa viungo vya miti ya chai (matawi, miti, mizizi) yaliotokana na miaka yalikuwa na kiwango cha chini cha C, lakini uzito mkavu wa viungo hivyo zilithibitika kuongezeka kadiri ya umri ulivyoongezeka. Upandaji wa miche ya chai kwa umbali tofauti (HD kwa clone na LD kwa seedling) ulionekana kusababisha tofauti kati ya madini C, N, P na K kwa miti ya chain a kwa shamba lote la chai. Tulionyesha kwamba miti ya chai inapozeeka, inaongeza C, N, P na K zaidi ambazo inasaidia hii miti wakati wa kiangazi ama wakati madini yana upungufu kwa muda kadiri. Hii nikusema kwamba miti ya chai inapo ongeza madini kwa sababu ya umri, mazao yaweza kupungua. Ni vyema kujumlisha haya madini ya C, N, P na K kwa shamba lote kwa hekta badala ya kwa kila mti wa chai ili kuepuka na upandaji wa umbali tofauti. Tukilinganisha mashamba ya chai na misitu ya kiasili, ama misitu ya aina ya plantations, iliionekana kuwa na mashamba ya chai yako no uzito duni kwenye viungo vyake lakini utunzi wake bora utasaidia kutunza 'C sequestration' kwa maeneo kama haya yanoyopata uharibifu mwingi.

Utafiti wa udongo ulifanywa kwa kutumia sehemu ya juu ya udongo, yaani hadi centi mita 20, na ulifanywa ili kutatua matatizo ya degredesheni na fikira tatu: (i) kwamba inaongeza uchachu (acidification), (ii) inaleta mabadiliko ya vipimo vya madini vinavyokua katika msitu kabla ya kupanda chai (nutrient imbalances), na (iii) inaleta mabadiliko upande wa uhai ndani ya mchanga (microbial functioning). Udongo kutoka msitu ulio karibu ulitumiwa kwa utafiti ili kulinganisha. Tafiti hii ilibaini kuwa udongo wa mashamba ya chai yana uchachu zaidi ya ile ya msitu na pia madini aina ya aluminium (Al) na manganese (Mn). Madini aina ya potassium (K), na magnesium (Mg), yalikuwa chini kwa mashamba ya chai ikilinganishwa na msitu. Matawi ya miti ya chai (prunings) yalisababisha kupungua kwa mineralization ya N ndani ya udongo wa mashamba ya chai lakini sio udongo wa msitu, na umri wa mashamba haukuwa tatizo. Uhai ndani ya udongo uliangaliwa kwa mitizamo miwili: total microbial C na N, na total microbial activity (TMA). Ilibainika kuwa tofauti kubwa zilikuwa upande wa aina ya miche lakini sio umri wa mashamba ya chai. TMA ya msitu ilikaribia ile ya mashamba ya seedling. Mazao ya mashamba ya chai mwakani 2003/04 yalikuwa na uhusiano mdogo na uchachu wa udongo (soil pH) na total organic C. Tulionelea kwamba utafiti wa madini ndani ya udongo na mazao kwenye mashamba ya chai ambayo yalikuwa na uhusiano mdogo hayangeweza kuwa sababu kubwa ya kusababisha degredesheni ya mashamba ya chai.

Kwa ufupi, utafiti huu umeonyesha kuwa kupungua kwa mazao ya mashamba ya chai kunasababishwa na kubadilisha technologia ya miche inayokuzwa, utunzi wa mashamba chai na mambo ya mazingira. Miti ya chai aina ya seedling iliweza kusababisha upungufu wa mazao ndani ya sekta ya mashamba makubwa ya chai Kenya (KTGA) lakini aina ya clones ambazo zimepandwa ndani ya mashamba madogo (KTDA) na kuongezeka kwa utunzaji wa mashamba ya chai imesababisha uongezekaji wa chai katika sectari hii. Sababu zilizotambuliwa na kukusanywa ni kama; aina ya miche (genotype traits); utunzaji wa mashamba (agronomic practices); mambo ya ardhi na hewa (ecological factors); na mambo kuhusu udongo (soil fertility factors). Kubadilika kwa technologia kunamaanisha kuwa sababu hizi huenda zikabadilika katika mashamba ya chai ambayo yamo wakati huu. Utafiti huu unaonyesha kuwa miti ya aina ya *seedlings* ambayo iko katika shamba lenye miaka 76 bado hayajakuwa dhaifu kwenye uzalishaji (degraded). Pia udongo unaweza kuwa na uhai kwa mashamba ya chai kwa muda ambapo chai ipo kama utunzi bora wa chai ungelitumika. Kuongeza mazao ya mashamba ya chai inawezekana kama tutatilia maanani "Aina ya miche x Mahala inakokuzwa x Utunzaji bora"; yani, Genotype × Environment × Management (G×E×M) relationships.

Uzalishaji na matumizi ya rasilimali kwenye mashamba ya chai.
David M. Kamau (2008)

List of publications of the author

Submitted papers in this thesis

Kamau, D.M., Spiertz, J.H.J., Oenema, O., 2007. Productivity and nitrogen use of tea in relation to plant age and genotype-density combinations. Field Crops Research (submitted).

Kamau, D.M., Spiertz, J.H.J., Oenema, O., 2007. Carbon and nutrient stocks of tea plantations differing in age, genotype and plant population density. Plant and Soil (submitted).

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Kamau, D.M., Wanyoko, J.K., Otieno, W., 2007. The use of Brimstone90® in rehabilitation of hutsites for good tea establishment and growth: 3 case studies. Tea, 28 (in press).

Kamau, D.M., Wanyoko, J.K., Owuor, P.O., Ng'etich, W.K., 2006. NPK(S) fertilizer use in commercially cultivated clone BBK 35 in different tea growing regions of Kenya: I. Experimental design and initial soil chemical properties. Tea 27, 41-48.

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PE&RC PhD Education Certificate

With the educational activities listed below the PhD candidate has complied with the educational requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of Literature (5.6 ECTS)
- An overview of long-term monocropping of tea on soil crop ecology (2001)

Writing of Project Proposal (7 ECTS)
- Productivity and nitrogen use in aging tea plantations (2001)

Laboratory Training and Working Visits (4.3 ECTS)
- Soil microbial biomass; World Agroforestry Centre (ICRAF), Nairobi (2002)
- N-mineralization incubations and analysis; Kenya Agricultural Research Institute (KARI), Muguga (2003)

Post-Graduate Courses (2.8 ECTS)
- Competencies for integrated agricultural research; Wageningen Graduate School (WGS) (2007)
- Intellectual property rights seminar, TRFK; Kenya Plant Health Service (KEPHIS) (2005)
- Strategic planning workshop for TRFK management staff; Institute Administration (consultants), Kenya (2005)

Deficiency, Refresh, Brush-up Courses (2.8 ECTS)
- Principles of production ecology; PPS-WUR (2001)
- Systems analysis, simulation and systems management; PPS-WUR (2004)

Competence Strengthening / Skills Courses (1.2 ECTS)
- Use of endnote; WUR (2001)
- Kenyan tea industry stakeholders workshop, TBK/KTGA/KTDA/EAAT); Tea Board of Kenya (TBK) (2005)

Discussion Groups / Local Seminars and Other Meetings (6.6 ECTS)
- Plant-soil relations (SQ) discussion group; WUR (2001)
- Crop and weed ecology (CWE) discussion group; WUR (2004 & 2007)
- TRFK annual technical conference; Kenya (2002-2007)
- Soil fertility and soil conditioners W/shop; Nairobi (2006)

- PE&RC Annual Meetings, Seminars and the PE&RC Weekend (0.6 ECTS)
- PE&RC symposium, theme: food security (2001)
- PE&RC day, theme: collapse: is our civilization able to stand the test of time? (2007)

International Symposia, Workshops and Conferences (6.6 ECTS)
- Soil science of East Africa conference; Eldoret, Kenya (2003)
- Nutrient management in tropical agro-ecosystems; Wageningen (2004)
- Soil science of East Africa conference; Arusha, Tanzania (2004)

Curriculum vitae

David Murathe Kamau was born in Murang'a, Kenya, on September 10, 1963. He enrolled for a Bachelor of Science degree at the University of Nairobi, Kenya in 1984 and majored in Chemistry. After obtaining his BSc degree in 1987, he was employed as an Assistant Research Scientist at the Kenya Forestry Research Institute (KEFRI) – Soil Science Division, Muguga headquarters where he worked for 10 years until June 1997. During this period he obtained a Postgraduate Diploma in Forest Science and a Masters degree in Soil Chemistry and Fertility at the University of Melbourne, Australia, in 1994. His MSc thesis was entitled "P and K sorption characteristics and their relation to seedling growth in a highly weathered kaolinite soil". He joined Tea Research Foundation of Kenya (TRFK) at Kericho in June 1997 as a Soil Chemist where he is involved in conducting research and advisory work on: soil and nutritional requirements of the tea plant, fertilizer use-productivity relations, and developing strategies which make the future of tea production sustainable.

In 2001, he developed and submitted a project proposal to NWO-WOTRO titled 'Evaluation of allelochemicals under chemically degraded old tea lands", which was successfully funded. He registered for a sandwich-PhD programme of the CT de Wit Graduate School of Production Ecology and Resource Conservation (PE&RC) of Wageningen University, The Netherlands, in July 2001. Based on consultations with his supervisors and a detailed literature review, the focus of the research was changed to "Productivity and resource use in ageing tea plantations". Most of the field experimental work was carried out at TRFK, Kericho, between 2002 and 2005. Laboratory analyses were done by TRFK, KARI, ICRAF and the Soil Laboratory of Wageningen University. During the three visits to Wageningen in 2001, 2004 and 2007, he was hosted by the Crop and Weed Ecology Group (CWE) of the Plant Sciences Department.

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