Changes in soil properties following conversion of forests into intensively managed *Camellia sinensis* L. plantations along a chronosequence[§]

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ABSTRACT: Tea in Kenya was introduced in the beginning of the 20th Century, although commercial cultivation commenced in 1924. The total acreage of tea plantations has steadily increased and currently covers approx. 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 remain in production till 100 years. Plantations older than 40 years start degrading slowly, but the real cause of this degradation is unclear. This article reports on changes in soil characteristics as a possible feedback of degradation in ageing tea plantations using results of 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 aluminium and manganese, and how they affect the ratios of the base nutrients (K, Ca, Mg), phosphorus and sulphur, were tested. 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 ranged from 3.5 to 4.7, and was lower in tea plantations than in the natural forest. The C:N ratio in the tea soils was found fairly constant and ideal along the chronosequence which helps in increase of microbial biomass C and N and total microbial activity (TMA) in ageing tea plantations. Thus, liming and balanced fertilization of K and Mg is required for sustainable tea plantations.

Keywords: Soil characteristics; *Camellia sinensis* L.; Microbial biomass; Tea prunings; Ageing

Introduction

In the highlands of Kenya, tea (*Camellia sinensis* L.) plantations are grown on highly weathered acidic soils derived from volcanic origin.[1] 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 monocrop does 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,[2] 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 "Aluminium (Al) accumulators"[3] and may contain large quantities of Al in mature leaves that are significantly affected by the ontogeny age of organs and the genotype.[4–6] Declining productivity in ageing tea plantations have been ascribed to increased stress resulting from a combination of increase in acidity and related elements and changes in the functioning of the microbial community.[7]

In some cases, declining yields have been associated with decline in soil fertility, owing to poor nutrient management practices.[8] The tender shoots that contain the largest percentage of nutrients in the plant[9,10] are harvested throughout the year, resulting in a relatively high nutrient removal. To sustain productivity, nutrients have to be added. This is done mostly in the form of inorganic single fertilizers such as urea or NPK(S) fertilizers without considering other essential elements. Nitrogen recov-

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eries in the harvested shoots are often low,[11–13] suggesting that most of the N applied through inorganic fertilizers is lost through leaching and erosion.[14,15]

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 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. The study also included the characterization of prunings normally returned to the soil after every four years when tea bushes are pruned.

Materials and Methods

Study Site

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.[16] 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 4 km (*i.e.* 2.48 miles) from the Tea Research Foundation (TRFK) Headquarters at Timbilil Estate, Kericho, at an elevation of 2180 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 on 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 P2O5 ha^{-1} yr^{-1} and 100 kg K_2O ha^{-1} yr^{-1}, respectively. Other field experimental details are given in Kamau *et al.*[10]

Soil Sampling and Analysis

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 mMicrobial activity (TMA) were sampled at 0–10 cm depth from all the plots (0, 50, 100, 200 and 400 kg N ha^{-1}) due to the cost effectiveness of the extraction method and also 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.[17] Easily extractable nutrients (P, S, K, Ca, Mg, Al, Mn, Fe, Zn, Cu, and Co) were determined following extraction using 0.01 M $CaCl_2$, and ICP.[18] Total extracted nutrients (P, S, K, Ca, Mg, Al, Mn, Fe, Zn, Cu and Co) were determined following digestion with aqua regia (HNO_3 and HCl) and determination of elements with ICP.[19]

Table 1: Some soil characteristics (0–20-cm depth) at the five sites ($n = 3$)

Site	Age of Tea Plantation (yr)				
Parameter	14	29	43	76	Forest Soil
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	–

Note: SD, standard deviation (given in parenthesis); nd, not determined.

Microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN) in field moist soils were extracted using modified fumigation extraction methods.[20] Total microbial activity (TMA) also in field moist samples was determined spectrophotometrically by hydrolysis of fluoresce diacetate (FDA) dissolved in acetone and measured as absorbance at 490 nm.[21]

Pruning Sampling and Analyses

The prunings at 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 the micro-Kjeldahl digestion method. Organic C was determined using the Walkley-Black method.[22] For P, K, Ca and Mg, the milled samples were ashed for 4.5 hrs 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.[23] Extraction was done using 0.05 M hydrochloric acid[22] followed by flame emission for K and atomic absorption spectroscopy (Varian Spectra AA 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.[22] Lignin determination was done *via* the Acid Detergent Fibre method and total polyphenolics analysed using the Folin-Denis method.[24]

Statistical Analyses

A one-way analysis of variance (ANOVA) 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 terms of 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 (see Table 1). Soil organic C ranged from 33 to 37 g kg^{-1} in tea-cultivated soils, while organic carbon of the natural forest was slightly higher, *i.e.* 38 g kg^{-1}. The C:N ratio maintained at an ideal range between 9.4 and 10.9 in the cultivated soils.

Soil Microbial C and N and Total Miscrobial Activity (TMA)

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.

Soil Nutrients

The $CaCl_2$ extractable soil nutrients are shown in Table 3. $CaCl_2$ extractable P was low and uniform at <1 mg

Table 2: Microbial C and N and TMA of 0–10 cm soils at the five sites

Site	Age of Tea Plantation (yr)				
Parameter	14	29	43	76	Forest Soil
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)

Note: SD, standard deviation (given in parenthesis); nd, not determined; *$n = 3$; #$n = 15$.
$Analysis for one-way ANOVA for the tea plantations only.
Values connected horizontally by the same letter are NS at $P < 0.05$.

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, Ca 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 Ca and Mg were positively related to soil pH, while extractable Al and Mn were negatively related to soil pH. Hence the nutrient ratios of extractable K to bases Mg, (Ca+Mg) and extractable Al and Mn to bases (K+Ca+Mg) increased from 1.4, 0.17, <0.01 and 0.07 in the natural forest to 5.8, 0.41, 0.36, 1.40 in the 76-year-old tea plantation, respectively (Table 4).

$CaCl_2$ 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 Ca was related to soil pH and was 0.34, 0.24 and 0.22 g kg^{-1} in the 14-, 43-, and 76-year-old plantations, respectively, and 1.79 and 2.30 g kg^{-1} in the 29-year-old plantation and the natural forest, 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-year-old plantation and the natural forest, respectively. $CaCl_2$ extractable Mn 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. The ratios of extractable aluminium Al and manganese Mn to the base elements (K, Ca, and Mg) were higher for the tea plantations ranging 0.24–0.36 and 0.58–1.40 for Al and Mn, respectively, apart from the 29-year-old tea plantation that was closer

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

	Age of Tea Plantation (yr)				
Analyses	14	29	43	76	Forest Soil
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
Ca (g kg^{-1})	0.34	1.79	0.24	0.22	2.30
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

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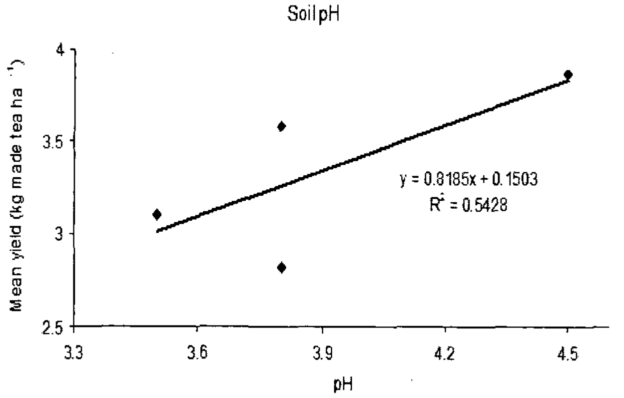

Figure 1. Relationship between tea productivity (t made tea ha^{-1} yr^{-1}) and soil pH.

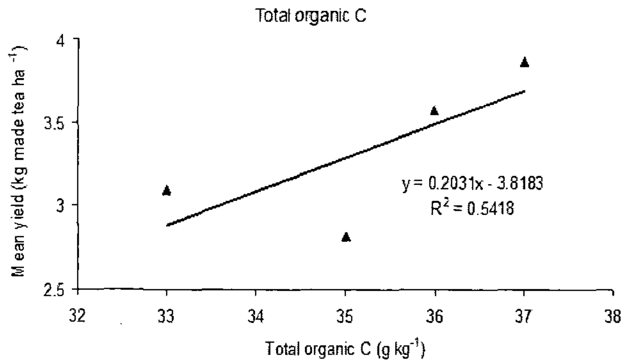

Figure 2. Relationship between tea productivity (t made tea ha^{-1} yr^{-1}) and total organic C (g kg^{-1}).

to the natural forest whose ratios for Al was <0.01 and 0.10 for Mn. $CaCl_2$ extractable Zn also had no clear trend along the chronosequence of tea plantations and forest, while Cu and Co were very low.

Aqua regia digestible P was low and fairly uniform ranging from 264 to 324 mg kg^{-1} in at all sites, including the natural forest soil (Table 5). Aqua regia digestible S ranged between 481 toand 820 mg kg^{-1} including the natural forest and had no trend pattern. Similarly, aqua regia digestible K, Ca, Mg, Zn, Cu and Co had no clear trends along the chronosequence of tea plantations and natural forest as well as the nutrient ratios (Table 4).

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 K and 0.18 g kg^{-1} for 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 and Mg of 0.43 and 0.34 g kg^{-1} for K and Mg, respectively in the tea plantations and natural forest. The large depletion of K is remarkable; while the annual withdrawal *via* harvested crop is about 60 kg ha^{-1} assuming yields of 3,000 kg made tea ha^{-1}.[13]

In summary, $CaCl_2$ extractable Ca, Mg, Al and Mn were related to soil pH, which was higher in the natural forest and the 29-year-old tea plantation than in the 14-, 43-, and 76-year-old tea plantations. $CaCl_2$ extractable P and aqua regia digestible P were low in at all sites, whereas aqua regia digestible K and Mg were lower in the soils of the tea plantations than in the natural forest.

Prunings

The chemical characteristics of the prunings along a chronosequence are presented in Table 6. The elemental composition of the prunings compositions were related to the

Table 4: Effect of tea monocroping on nutrient ratios for easily extractable 0.01 M $CaCl_2$ and aqua regia (conc. HNO_3 + conc. $HClO_3$) complete digestion extractants

Extractant	Vegetation (Age of tea plantation, yr)	K: Mg	K: (Ca + Mg)	Al: (K + Ca + Mg)	Mn: (K + Ca + Mg)
0.01 M $CaCl_2$	Natural forest	1.4	0.17	<0.01	0.07
	Clonal (14-yr)	4.7	0.30	0.24	0.58
	Clonal (29-yr)	1.5	0.06	<0.01	0.10
	Seedling (43-yr)	5.5	0.33	0.34	1.03
	Seedling (76-yr)	5.8	0.41	0.36	1.40
Aqua regia	Natural forest	1.5	0.42	13.9	0.56
	Clonal (14-yr)	1.7	0.34	17.3	0.49
	Clonal (29-yr)	1.6	0.33	15.3	0.54
	Seedling (43-yr)	1.5	0.35	16.0	0.79
	Seedling (76-yr)	1.7	0.37	17.7	0.62

Table 5: Some elements of top 0–20 cm soils at the different sites extracted using aqua regia (conc. HNO_3 + conc. $HClO_3$) complete digestion

	Age of Tea Plantation (yr)				
Analyses	14	29	43	76	Forest Soil
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
Ca (g kg^{-1})	3.55	3.80	3.51	3.52	3.51
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

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[25,26] ranging 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.

Discussion

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 pH, and also high base cation contents, which may be related to the slope of the site. We speculate that erosion has been slightly higher than in at 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.[7,27] 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.[28] Application of acidifying $(NH_4)_2SO_4$ based fertilizers may also have contributed to the observed high soil acidity in the older tea plantations.[4,29,30] The tea plant is known for its preference for NH_4^+–N, hence the application of ammonium-based fertilizers. Commonly N-fertilizers used in tea growing in Kenya are compound NPKS (25:5:5:5) and urea fertilizers, which are less acidifying per unit N applied than $(NH_4)_2SO_4$ fertilizer.[14,31] Moreover, mean N-application rates have decreased from a mean of 400 kg N ha^{-1} in during the period[32] 1970–1980 to 100–250 kg N ha^{-1} from the 1980s onwards.[33] Soil acidification has also been related to high concentrations of organic acids, especially tannins in litter fall and prunings.[34] 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.[35]

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.[29,36,37] In our studies, the base cations (K, Ca, Mg) in the top soils of the tea plantations were on average 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 and had higher Al and Mn. However, the levels were not high enough to cause degradation in tea plantations.

Changes in Extractable Soil Nutrients

Table 6: Some chemical characteristics of tea prunings for the tea plantations

Age	N	P	K	Ca	Mg	C	C:N	Total poly-phenolics	Lignin	Lignin: N
(yr)				($g\ kg^{-1}$)			ratio	($g\ kg^{-1}$)		ratio
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

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.[38,39] The multi-nutrient extractant 0.01 M $CaCl_2$ provides information about the directly available nutrients; it is a mild one-component extractant.[18] 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 results herein indicate that base cations have been depleted from the soil and have led to changes in the ratios of $CaCl_2$ extractable nutrients. With the exception of the 29-year-old tea plantation, the nutrient ratio of K to Mg tended to increase from 1.4 in the natural forest to 4.7–5.8 in the 14-, 43-, and 76-year-old plantations (Table 4). Similar but increasing trends are seen in the nutrient ratios of K to Ca+Mg, Al to base nutrients (K, Ca, Mg) and Mn to base nutrients (K, Ca, Mg). $CaCl_2$ 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 33 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} and possible leaching.[10] The cause of the Mg depletion suggests that withdrawal *via* harvested crop and leaching are relatively large. Assuming yields of 2,000 to 3,000 kg made tea ha^{-1}, annual mean removal of N, P, and K is 90–120 kg N, 6–9 kg P, and 40–60 kg K ha^{-1} yr^{-1}, respectively.[13] 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 December 2003–November 2004 yield data[10] are presented in Figs. 1 and 2, respectively. Although there is a gentle linear increase of pH and total organic C with the measured productivity, the 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 (as shown in Table 1) of the tea plantations decreased with the age of the plantation, but the difference between the natural forest soil and the 76-year-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.[40] The aboveground standing biomass in tropical forests is large (~200 MgC ha^{-1})[41] but was not measured at forest site. Aboveground standing biomass and root biomass in the tea plantations increased with age of the tea plantation for similar genotypes,[13] 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, suggesting that C input *via* biomass production roughly equals C removal through tea plucking, decomposition of prunings and leaf litter and soil respiration. The C:N ratio in the soil organic matter were also remarkably constant along the chronosequence (Table 1). Pansombat *et al.*[42] reported accumulation of soil organic C and N in long-term tea cultivation trial, but Han *et al.*[7] 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 at high input sites *vs.* low usage of inorganic and organic fertilizers in at 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.*[7] found MBC ranges of 0.10–0.20 g kg^{-1} in tea gardens with different productivities and ages, while Yao *et al.*[43] reported a range of 0.15–0.60 g kg^{-1} in tea plantations aged 4–55 years and 0.40 g kg^{-1} in a highly productive 30-year-old tea garden.[44] 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 total microbial activity values (TMA) values 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.[45] Soil microbial biomass and TMA are therefore useful especially for comparative studies and have been suggested as indicators of soil fertility.[46] However, there were weak correlations between the measured soil properties herein, e.g. soil pH, and productivity (Figs. 1 and 2). It has also been suggested that organic acids released by the tea plant rhizosphere suppresses microbial biomass.[47] 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.

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 6) categorized as hydrolysable tannins, condensed tannins and non-tannin polyphenolics.[48] The polyphenols restrict N-release from their tissues despite having high N content.[25,49] However, the protein-binding capacity of the tannins is often more important than the total polyphenolic content per se.[50] Mutabaruka et al.[51] compared N-release in soils from maize, sugarcane, Gliricidia, Peltophorum, secondary forest and Imperata grassland and demonstrated that the high polyphenol rich vegetations like such as Peltophorum were able to develop microorganisms 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.[52,53] 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

The C:N ratio in the tea soils was fairly constant and ideal along the chronosequence, which helps in increase of microbial biomass C and N and total microbial activity (TMA) in ageing tea plantations and prevents degradation. It is concluded that the older tea plantations have slightly more acidic soils and have higher contents of $CaCl_2$ extractable Al and Mn, and higher ratios of K:Mg, K:(Ca+Mg), Al:(K+Ca+Mg), and Mn:(K+Ca+Mg). However, these relatively small differences in soil properties, which are also weakly related to the measured productivities of the tea plantations, are unlikely to cause degradation in ageing tea plantations. It is further concluded that there is declining trend in soil pH, potassium (K), calcium (Ca), and magnesium (Mg) in ageing tea plantations as compared to forest soils. It is evident that $CaCl_2$ extractable Al and Mn are higher in ageing tea plantations due to decline in soil pH. Thus, liming of tea soils for reclamation of soil acidity and balanced fertilization of K and Mg with N is required for sustainable tea plantations.

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References

1. Othieno CO, 1992, Soils. In: KC Willson and MN Clifford (Eds.), *Tea: Cultivation to Consumption*. Chapman and Hall: London, pp. 137–170.
2. Forrest GI & Bendall DS, 1969, The distribution of polyphenols in the tea plant (*Camellia sinensis* L.). *Biochem J* 113: 741–755.

3. Masunaga T, Kubota D, Hotta M, & Wakatsuki T, 1998, Mineral composition of leaves and bark in aluminium accumulators in tropical rain forest in Indonesia. *Soil Sci Plant Nutr* 44: 347–358.

4. Ruan J, Ma L, & Shi Y, 2006, Aluminium in tea plantations: Mobility in soils and plants, and influence of nitrogen fertilization. *Environ Geochem Health* 28: 519–528.

5. Fung KF, Zhang ZQ, Wong JWC, & Wong, MH, 2003, Aluminium and fluoride concentrations of three tea varieties growing in Lantau Island, Hong Kong. *Environ Geochem Health* 25: 219–232.

6. Owuor PO & Cheruiyot DKA, 1989, Effects of nitrogenous fertilizers on aluminium contents of mature tea leaf and extractable aluminium in the soil. *Plant Soil* 119: 342–345.

7. Han W, Kemmitt SJ, & Brookes PC, 2007, Soil microbial biomass and activity in Chinese tea gardens of varying stand age and productivity. *Soil Biol Biochem* 39: 1468–1478.

8. Illukpitiya P, Shanmugaratnam N, & Kjosavik DJ, 2004, Tea agroecosystems in the Uva Highlands of Sri Lanka: An evaluation of land management activities. *Mountain Res Dev* 24: 52–59.

9. Dang MV, 2005, Soil–plant nutrient balance of tea crops in the northern mountainous region, Vietnam. *Agric Ecosyst Environ* 105: 413–418.

10. Kamau DM, Spiertz JHJ, & Oenema O, 2008a, Productivity and nitrogen use of tea plantations in relation to plant age and genotype–density combinations. *Field Crops Res* 108: 60–70.

11. Wicremasighe KN & Tea Research Institute of Sri Lanka 1981, Fertilizer nitrogen utilization by tea. *Tea Bulletin*, Vol. 1(2).

12. Malenga NEA & Wilkie AS, 1994, Clonal response to high nitrogen rates under rain-fed conditions. *Quarterly Newsletter, Tea Research Foundation (Central Africa)* 115: 6–15.

13. Kamau DM, Spiertz JHJ, Oenema O, 2008b, Carbon and nutrient stocks of tea plantations differing in age, genotype and plant population density. *Plant & Soil* 307: 29–39.

14. Bonheure D & Willson KC, 1992, Mineral nutrition and fertilizers. In: KC Willson and MN Clifford (Eds.), *Tea: Cultivation to Consumption*. Chapman and Hall: London, pp. 269–329.

15. Othieno CO, 1979, Assessment of soil erosion in Kenya. *East African Agric For J* 43(Special issue): 122–127.

16. Sombroek WG, Braun HMH, & van der Pouw BJA, 1980, Exploratory soil map and agro-climatic zone map of Kenya, scale 1:1,000,000. Ministry of Agriculture, National Agricultural Laboratories, Kenya Soil Survey, Nairobi, Kenya, pp. 56.

17. Gee GW & Bauder JW, 1994, Particle-size analysis. In: A Klute, Ed., *Methods of Soil Analysis*. Part 1, 3rd edn, *Physical and Mineralogical Methods*, ASA/SSSA: Madison, WI, pp. 377–382.

18. Houba VJG, Novozamsky I, Huybregts AWM, & van der Lee JJ, 1986, Comparison of soil extractions by 0.01 M $CaCl_2$, by EUF and by some conventional extraction procedures. *Plant Soil* 96: 433–437.

19. Houba VJG, van der Lee JJ, Novozamsky I, 1995, *Soil analysis procedures; other procedures (soil and plant analysis, Part 5B)*. Wageningen Agricultural University: The Netherlands.

20. ICRAF, 1994, *Field Moist Soils – Specialty Analysis; Microbial Biomass C and N.* Section 6. In: ICRAF Laboratory Manual, version 1.1, September 1994.

21. Schnurer J & Rosswall T, 1982, Fluorescein diacetate hydrolysis as a measure of total microbial activity in soil and water. *Appl Environ Microbio* 43: 1256–1261.

22. International Institute of Tropical Agriculture (IITA), 1979, *Selected Methods for Soil and Plant Analysis*, Manual Series No. 1. International Institute of Tropical Agriculture: Ibadan, Nigeria.

23. Thomas R, Sheard RW, & Moyer LP, 1967, Comparison of convectional and automated procedures from nitrogen, phosphorus and potassium analysis of plant material using s single digest. *Agron J* 99: 240–243.

24. Anderson JM & Ingram JSI, 1996, *Tropical Soil Biology and Fertility. A Handbook of Methods*. 2nd Ed. CAB International, Wallingford, UK.

25. Palm CA & Sanchez PA, 1991, Nitrogen release from leaves of some tropical legumes as affected by their lignin and polyphenolic contents. *Soil Biol Biochem* 23: 83–88.

26. Tian G, Kang BT, & Brussaard L, 1992, Effects of chemical composition on N, Ca and Mg release during incubation of leaves from selected agroforestry and fallow plant species. *Biogeo Chem* 16: 103–119.

27. Song M & Liu Y, 1990, Effect of biogeochemical cycle in tea garden on soil acidification. *J Tea Sci* 10: 19–26.

28. Morita A, Ohta M, & Yoneyama T, 1998, Uptake, transport and assimilation of ^{15}N-nitrate and ^{15}N-ammonium in tea (*Camellia sinensis* L.) plants.

Soil Sci Plant Nutr 44: 647–654.

29. Owino-Gerroh C, 1991. Acidity in tea soils and related constraints – A review. *Tea* 12: 52–55.

30. Dogo YW, Owuor PO, & Wanyoko JK, 1994, High rates of nitrogen on tea at high altitudes. VII. The effects of rates and frequency of applications on soil chemical properties in Mount Kenya area. *Tea* 15: 17–26.

31. Tisdale SL, Nelson WL, & Beaton JO, 1985, Soil fertility and fertilizers. 4th edn. Macmillan: New York, pp. 485–525.

32. Wanyoko JK, 1997, Advances in fertilizer use in Kenyan tea industry. *Tea* 18: 123–131.

33. Othieno CO, 1988, Summary of observations and recommendations from TRFK. *Tea* 9: 50–65.

34. Eviner VT & Chapin FS, 2003, Functional matrix: A conceptual framework for predicting multiple plant effects on ecosystem processes. *Annu Rev Ecol, Evol Systemat* 34: 455–485.

35. Owino-Gerroh C & Othieno CO, 1991, Some chemical characteristics of soils under moribund tea: A preliminary assessment. *Tea* 12: 83–88.

36. Van Breemen N, Driscoll CT, & Mulder J, 1984, Acidic deposition and internal proton sources in acidification of soils and waters. *Nature* 307: 599–604.

37. Binkley D, Valentine D, Well C, & Valentine U, 1989, An empirical analysis of the factors contributing to 20-year decrease in soil pH in an old-field plantation of loblolly pine. *Biogeochem* 7: 139–154.

38. Jones JB, 1967, Interpretation of plant analysis for several agronomic crops. In: M Stelly (Ed.), *Soil Testing and Plant Analysis, II: Plant Analysis*. Special publication 2. Soil Sci Soc Am: Madison, Wisconsin, USA, pp. 49–58.

39. Van Erp PJ & Van Beusichem ML, 1998, Soil and plant testing programs as a tool for optimizing fertilizer strategies. *J Crop Prod* 1: 53–80.

40. Dogo YW, 1993, Transformation of organic matter under tea bushes – A review. *Tea* 14: 65–68.

41. Glenday J, 2006, Carbon storage and emissions offset potential in an East African tropical rainforest. *For Ecol Manage* 235: 72–83.

42. Pansombat K, Kanazawa S, & Horiguchi T, 1997, Microbial ecology in tea soils. I. Soil properties and microbial populations. *Soil Sci Plant Nutr* 43: 317–327.

43. Yao H, Liu Y, & Xue D, 2006, Influence of tea cultivation on soil microbial biomass and substrate utilization pattern. *Commun Soil Sci Plant Anal* 37: 641–651.

44. Yao H, He Z, Wilson MJ, & Campbell CD, 2000, Microbial biomass and community structure in a sequence of soils with increasing fertility and changing land use. *Microbiol Ecol* 40: 223–237.

45. Heal OW & MacLean SF, 1975, Comparative productivity in ecosystems – Secondary productivity. In: WH van Dobben and RH Lowe-McConnell (Eds.), *Unifying Concepts in Ecology*. B.V. Publishers: The Hague, pp. 89–108.

46. Sparling GP, 1997, Soil microbial biomass, activity and nutrient cycling as indicators of soil health. In: CE Pankhurst, BM Doube, and VVSR Gupta (Eds.), *Biological Indicators of Soil Health*. CAB International, pp. 97–119.

47. Pandey A & Palni LMS, 1996, The rhizosphere effect of tea on soil microbes in a Himalayan monsoonal location. *Biol Fert Soils* 21: 131–137.

48. Watermann PG & Mole S, 1994, Analysis of phenolic plant metabolites. Blackwell: London, pp. 238.

49. Giller KE, 2000, Translating science into action for agricultural development in the tropics: An example from decomposition studies. *Appl Soil Ecol* 14: 1–3.

50. Handayanto E, Giller KR, & Cadisch G, 1997, Regulating N release from legume tree prunings by mixing residues of different quality. *Soil Biol Biochem* 29: 1417–1426.

51. Mutabaruka R, Hairiah K, & Cadisch G, 2007, Microbial degradation of hydrolysable and condensed tannin polyphenol–protein complexes in soils of different land-use histories. *Soil Biol Biochem* 39: 1479–1492.

52. Anaya AL, Waller GR, Owuor PO, Friendman J, Chou CH, Suzuki T, Arroyo-Estrada F, & Cruz-Oterga R, 2002, The role of caffeine in the production decline due to autotoxicity in coffee and tea plantation. In: MJ Reigosa and N Pedrol (Eds), *Allelopathy: From Molecules to Ecosystems*. Science publishers: Enfield, USA, pp. 71–91.

53. Owuor PO, 1996, Problems of replanting tea or other crops on old tea lands: Possible role of allelochemicals. *Tea* 19: 27–37.