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Soil fertility decline in some Major Soil Groupings under permanent cropping in Tanga Region, Tanzania

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Abstract

Soil samples were taken on sisal plantations in Tanga region (Tanzania) in order to investigate changes in soil chemical properties resulting from permanent cropping. Differences in soil fertility decline of eight Major Soil Groupings (FAO–Unesco) were evaluated by comparing (i) data from different soils under permanent cropping, (ii) data from the same soils under bush vegetation and permanent cropping, (iii) soil analytical data for fields which were sampled in the 1950s and 1960s and resampled in the 1980s and 1990s. Differences in soil fertility decline between the Major Soil Groupings were large. Ferralsols and Acrisols under permanent cropping had strongly acid soil reactions and low levels of fertility. The pH of Ferralsols and Acrisols under permanent cropping was 1.2 to 1.4 units lower in both topsoils and subsoils when compared to bush vegetation. Also exchangeable cations and base saturation were significantly lower under permanent cropping. Organic carbon was only significantly lower in the topsoils of the Ferralsols. Exchangeable aluminium was higher under cropping than under bush vegetation in the subsoils of both Major Soil Groupings. The historical data revealed a highly significant decline in both pH and exchangeable cations of the topsoils of the Ferralsols. Cambisols and Luvisols showed resilience despite them being permanently cropped for over 60 years with little or no fertilizer inputs during the past two decades. Phosphorus and potassium had also been reduced to very low levels in these soils. Similar observations were made in Leptosols and Phaeozems. Statistical analysis showed that there were no differences between the 1950s and 1960s and 1980s and 1990s in pH and exchangeable calcium and magnesium of the Cambisol topsoils; only the exchangeable potassium had decreased significantly in the Cambisols. Although the data of some Major Soil

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Groupings were few, all three approaches have shown that soil analytical data at the Major Soil Groupings level can be of use for the assessment of soil fertility decline.

Keywords: soil fertility decline; Major Soil Groupings; resilience; permanent cropping; soil survey data; Tanzania

1. Introduction

Soil resources are exhaustible and infinite (Lal and Stewart, 1992). Nevertheless, humankind neglects these resources and soils are exposed to increasing degrees of chemical, physical and biological stress (Greenland and Szabolcs, 1994). As a result many soils deteriorate and this is a pancontinental phenomena. Nearly 2×10^9 ha in the world are affected by human-induced soil degradation of which around one quarter is located in Africa (Oldeman et al., 1991).

Several types of human-induced soil degradation can be identified including water and wind erosion, structural degradation, salinization, acidification, contamination and nutrient depletion. Erosion is the most visible and complete form of land degradation. Of equal importance to soil productivity is the impact of chemical degradation which includes decline in soil fertility (Logan, 1990). The cause for soil fertility decline is that most agricultural land-use systems result in a net removal of nutrients from the soil either by the harvested product and/or through increased losses as compared with natural ecosystems. Unless the nutrients removed by the harvested product are replaced either naturally, through weathering and bio-geocycling, or through the use of chemical fertilizers, many soils will deteriorate under permanent cropping. Only few soils will be resilient and they have the capacity to recover naturally and rapidly after a cropping period (Greenland and Szabolcs, 1994).

It is only recently that the importance and extent of degradation resulting from soil fertility decline has been recognized, and in one of the first documents on land degradation prepared by the FAO (1971) soil fertility decline was not included. A first global overview of soil degradation was prepared by Oldeman et al. (1991). For Africa, they estimated that about 62 million ha is affected by the loss of nutrients mainly through agricultural activities. Stoorvogel and Smaling (1990) conducted a semi-quantitative study on nutrient depletion at a supra-national scale for Sub-Saharan Africa. They concluded that nutrient mining is common in many parts of the continent and that nutrient depletion in the eastern part of the continent is high. Also at the district and regional level, soil fertility depletion was reported for Sub-Saharan Africa (e.g. Van der Pol, 1992; Smaling et al., 1993).

Few quantitative studies have been conducted on soil fertility decline at lower aggregation scales i.e. the farm or field. For proper assessment of soil fertility decline at this scale, repeated measurements and long-term observations are required as measurements are subject to a large amount of variation both in time and space (Zinck and Farshad, 1995). Another possible explanation for the relatively few studies on soil fertility decline at the farm or field level is that many soil scientists are more at ease at the regional or country level (Latham, 1994).

Information at the farm or field level could, however, become available if the archives of soil survey organizations were used. Such archives usually contain soil analytical data of various soil types under different land-use systems and from different periods. Young (1991) suggested that for the assessment of soil fertility decline, samples from different periods from one particular site can be compared. Results can also be obtained when the same soil type but with different land-use history is sampled at one time, for example to compare natural vegetation with arable use. According to Young (1991) the analysis of soil fertility decline using soil survey data could yield important information on where, and to what extent, soil fertility decline is taking place and a position could be reached from which to take action to arrest or reverse it.

The data presented in this paper follow the methods for assessing soil fertility decline as proposed by Young (1991). The basic aim of this study was to detect if there were differences in chemical properties between Major Soil Groupings as a result of permanent cropping in order to assess the degree of soil fertility decline. The assessment is carried out at the Major Soil Groupings level (FAO–Unesco, 1988) only, and no division is made into Units or Phases. Data was obtained from strategic soil sampling schemes developed during soil survey work at large sisal plantations in Tanzania, for which the term *on-plantation* research was introduced (Hartemink, 1995). The soils of the plantations were monocropped with sisal (*Agave sisalana*) for 40 to 60 years and the land-use history was well documented, which provided a suitable base for the sampling schemes.

2. Materials and methods

2.1. The Tanga Region

The research was conducted on sisal plantations located in Tanga Region in north-east Tanzania (Fig. 1). The region covers about 26,900 km^2 and is the main area of sisal production in Tanzania.

Four major physiographic units can be recognized in the region (Agrar- und Hydrotechnik, 1976): (i) mountains, (ii) uplands, (iii) coastal area, and (iv) alluvial plains. The approximate extent of each unit with their lithology and dominant Major Soil Groupings is given in Table 1. In this paper, data are presented from the uplands and coastal area which cover about 76% of the region.

The seasonal pattern of rainfall in Tanga Region is greatly influenced by the Indian Ocean. Throughout the region, rainfall is bi-modal with the main rains falling in April and May (south-east monsoon), and the small or short rains falling between October and December (north-east monsoon). Rainfall at the research sites averages between 1,000 and 1,200 mm yr^{-1}. Potential evaporation (Penman) is about 1,500 to 1,700 mm yr^{-1}, and is exceeded by rainfall in April and May only. There is considerable between year variation in rainfall patterns, and throughout Tanga Region rainfall is highly unpredictable. Mean annual temperature is 26°C with only minor fluctuations. Most of the coastal area has an ustic soil moisture regime with an iso-hyperthermic temperature

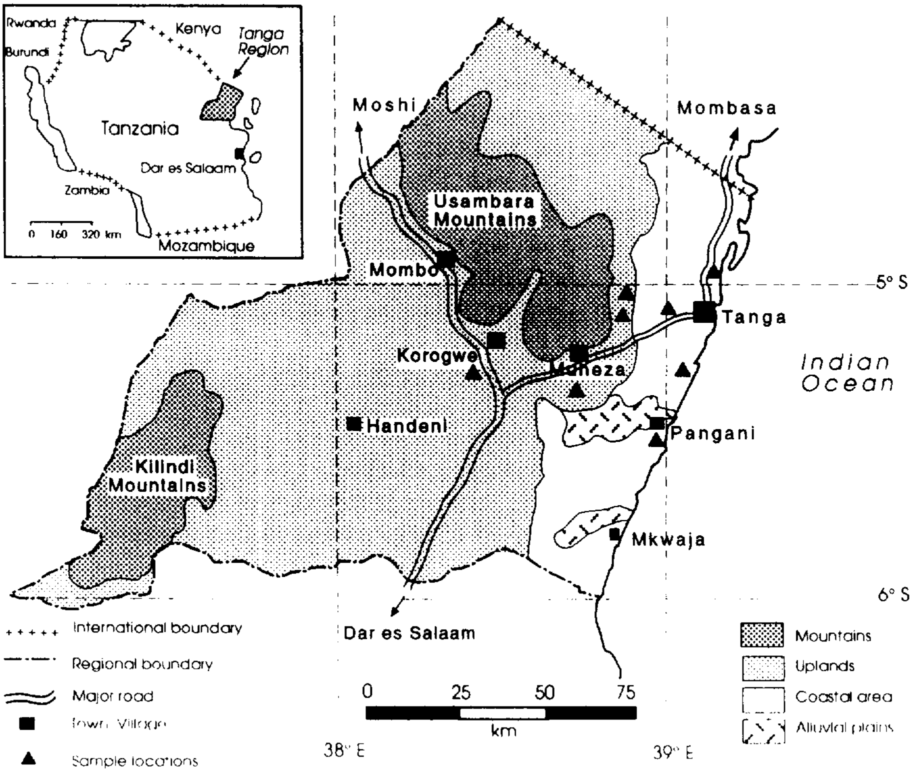

Fig. 1. Sample locations and main physiograpic units in Tanga Region.

Table 1
Main physiographic units and soils in Tanga Region

Physiographic unit	Approx. extent (km^2)	Altitude (m a.s.l.)	Lithology	Dominant Major Soil Groupings [a]
Mountains	5,300	700–2,000	mainly Precambrian gneiss	Luvisols, Phaeozems, Lithosols [b], Ferralsols, Cambisols
Uplands	17,000	200–700	acid and intermediate metamorphic rocks	Ferralsols, Luvisols, Nitosols [c], Cambisols, Arenosols, Vertisols
Coastal area	3,500	0–200	Neogene and Quaternarya limestone and sandstones	Cambisols, Vertisols, Arenosols, Luvisols, Ferralsols, Phaeozems, Rendzinas [d]
Alluvial plains	1,100	0–200	unconsolidated material	Fluvisols, Gleysols, Vertisols, Solonchaks

[a] Classification (FAO–Unesco, 1974) according to the 1:500,000 soil map of Agrar- und Hydrotechnik (1976).

[b] Lithosols have been renamed Leptosols in the revised FAO–Unesco legend (1988).

[c] Nitosols have been renamed Nitisols in the revised FAO–Unesco legend (1988).

[d] Rendzinas have been included in the Leptosols in the revised FAO–Unesco legend (1988).

regime but in the western part of the region, soil moisture regimes are aridic (Hartemink, 1989).

2.2. Soils of the research sites

The research took place on eight sisal plantations located in the uplands and coastal area of the region. The main rock types in the undulating to rolling uplands are Precambrian rocks of the Basement Complex and include schist, granulite, quartzite and gneiss of acid and intermediate composition. Intermediate gneiss is a common soil parent material in Tanga Region. This metamorphic rock is composed of a mixture of hornblende, pyroxene and quartzo-feldspatic minerals with a granulitic texture (Hartemink, 1991). Upon weathering these minerals may contribute magnesium, calcium, potassium and iron to the soil.

Soils derived in-situ from gneiss are generally red, very deep (> 4 m), with clayey textures and the predominant soil minerals are sesquioxides and kaolinite (Nandra, 1977). Many of the soils have a ferralic B horizon ($\mathrm{CEC_{clay}} < 160$ $\mathrm{mmol_c\ kg^{-1}}$), and are classified as Ferralsols (FAO–Unesco, 1988). The Ferralsols have typically 35 to 50% clay in the topsoil and 55 to 65% in the subsoil. Silt contents are lower than 15% in the topsoil and less than 10% in the subsoils. The Ferralsols must have formed in a wetter climate as the present rainfall levels are too low for the formation of such highly weathered and leached soils.

Other common soils derived from gneiss are Acrisols, Alisols, Lixisols and Luvisols. These soils have a clear textural B horizon which has a $\mathrm{CEC_{clay}}$ exceeding 160 or 240 $\mathrm{mmol_c\ kg^{-1}}$. It was found that these soils may have lower clay contents in both topsoils and subsoils than the Ferralsols. Silt contents are similar to the Ferralsols.

In large areas of the uplands the soils constitute a recurrent topograpic sequence (catena) which was first recognized by Milne (1935). On the hill crests and slopes, the soils are dusky red and well drained (Ferralsols, Acrisols). On the footslopes, the soils are more yellow, gravelly and moderately well drained (Acrisols, Plinthosols, Gleysols) and in the valleys the soils are imperfectly to poorly drained and have brownish to black colours (Fluvisols). The colour changes usually correspond to various hematite to goethite ratios and coincide also with changes in texture (Hartemink, 1995).

In the coastal area, soils are very heterogeneous and relations between landform and soils are hard to establish. This heterogeneity is caused by the irregular deposition of fluvial sediments from the hinterland and the uneven surface of the underlying coral rock and limestone by which the depth of soil varies over short distances. Differences in soils can mainly be explained by the varying textural composition of the fluvial deposits and the depth to bedrock. Most soils developed in a mixture of weathering products from Neogene limestone and heterogenous Quaternary sediments. They are generally less deep (< 2 m), much younger and less weathered than the soils in the uplands. The soils are classified as Cambisols, Luvisols, Phaeozems, and Leptosols. Some of the soils developed in Quaternary sediments have a very poor fertility and are classified as Arenosols and Ferralsols.

Table 2 summarizes the Major Soil Groupings used in this study with the approximate equivalents in USDA Soil Taxonomy (Soil Survey Staff, 1992).

Table 2
Major Soil Groupings (FAO–Unesco, 1988) discussed in this study

Major Soil Groupings	Main diagnostic properties	USDA Soil Taxonomy equivalent[b]
Acrisols	Soils with a base saturation < 50% and low activity clays. The argic B horizon has a CEC_{clay} [a] < 240 $mmol_c\ kg^{-1}$.	Ultisols
Alisols	Soils with base saturation < 50%. The argic B horizon has a CEC_{clay} [a] > 240 $mmol_c\ kg^{-1}$.	Alfisols
Arenosols	Sandy, generally weakly developed soils but without fluvic properties.	Psamments
Cambisols	Weathered but young soils without translocation of soil material, only a Cambic B horizon.	Inceptisols
Ferralsols	Soils with high sesquioxide and kaolinite content. The B horizon has a CEC_{clay} [a] < 160 $mmol_c\ kg^{-1}$.	Oxisols
Leptosols	Weakly developed soils which are less than 30 cm deep.	Lithic subgroups
Luvisols	Soils with base saturation > 50% and CEC_{clay} [a] > 240 $mmol_c\ kg^{-1}$ throughout the profile.	Alfisols
Phaeozems	Soils with a very thick A horizon which is rich in organic matter, and base saturation > 50%.	Mollisols

[a] CEC_{clay} can be estimated by: $(CEC_{soil} - 3.5 \times \%\ \text{organic C}) \cdot (100/\%\ \text{clay})$.
[b] In USDA Soil Taxonomy the CEC_{clay} is not corrected for organic C (Soil Survey Staff, 1992).

2.3. Soil sampling

The selection of soil sampling sites on the plantations was based on detailed soil maps (1 : 20,000 or 1 : 30,000) prepared by the National Soil Service (Mlingano) and the author at the end of the 1980s and early 1990s. Sample sites were selected from records of field history provided by the sisal plantation management.

Three different approaches were followed: Firstly, fields were selected of Ferralsols, Acrisols, Alisols and Cambisols that were permanently cropped since the 1930s or 1940s in order to compare the soil chemical fertility under permanent cropping. The sampled fields had not received fertilizers in the past two decades. Three to five composite topsoil samples of each Major Soil Groupings were selected at three plantations. The analytical data of each Major Soil Grouping were averaged and the range is reported.

Secondly, topsoil samples were taken in permanently cropped fields and in similar soils immediately outside the plantation which had never been cropped to compare the differences in soil chemical fertility as a result of permanent cropping. Sampled sites in each Major Soil Grouping were within a distance of 100 m of each other. The uncultivated land was usually covered with thick woodland (bush vegetation). Such samples were taken in Ferralsols, Acrisols, Arenosols and Cambisols on three plantations.

Thirdly, permanently cropped fields were selected which had been sampled in the 1950s or 1960s and which were resampled in the late 1980s and early 1990s in order to determine a decline in soil fertility. Samples were taken in five different Major Soil Groupings and on three plantations. The sampled soils had been under sisal monocropping since the 1930s and 1940s.

All samples were composites of 10 to 15 randomized mini-pits in an area of about 0.5 ha. Mini-pits were dug with hoes and soil samples were taken with a spade at two depths: 0–20 and 30–50 cm. The samples were taken in the middle of the sisal rows. Sampling methods in the 1950s and 1960s were similar (Hartemink, 1995).

2.4. Soil analysis

Soil analyses were carried out at the National Soil Service Laboratories in Mlingano following standard procedures (Page et al., 1982) described in National Soil Service (1990). The following methods were used: particle size analysis by hydrometer; organic carbon by $K_2Cr_2O_7$ and H_2SO_4 oxidation (Walkley and Black); pH H_2O in 1 : 2.5 suspension of soil and water; pH KCl in a 1 : 2.5 soil and 1 M KCl solution; exchangeable cations Ca, Mg, K, Na and CEC percolation by 1 M NH_4OAc followed by spectrophotometry (K, Na), AAS (Ca, Mg) and titration (CEC); available P by NH_4F and HCl extraction (Bray I) for soils with $pH < 7$, and $NaHCO_3$ extraction (Olsen) for soils with $pH > 7$; exchangeable acidity (H, Al) extraction by 1 M KCl.

In the comparison between the data of the 1950s and 1960s and 1980s and 1990s, the following soil parameters could be used as the analytical methods had not changed: pH H_2O (soil : water 1 : 2.5), organic C (Walkley and Black), and exchangeable calcium, magnesium and potassium (NH_4OAc at pH 7.0).

2.5. Statistical analysis

A statistical analysis was carried out for the soil analytical data of the Ferralsols, Acrisols and Cambisols. For other Major Soil Groupings, insufficient reliable data was available for statistical analysis.

Differences in soil chemical properties between bush vegetation and permanent cropping were analyzed by an ANOVA. The data were tested for normality using ANOVA with untransformed data, whereafter the residuals were examined (Lane et al., 1987). The residuals of some soil chemical parameters were not normally distributed and showed a variance that increased with the mean. Log-transformation of data was used to overcome the skewed distribution and non-constant variance of these parameters. For data including small values, 1 was added before log-transformation. After the transformation, data were analyzed by GENSTAT5 (Genstat, 1990). Student's *t*-tests were applied for comparing means of the two sampling depths. Back transformation was used for the skewly distributed data and differences in geometric means between bush vegetation and permanent cropping are presented. For the normally distributed data differences in the arithmetic mean is given.

Statistical analysis was also carried out on the historical soil data after the data had been log-transformed. The number of samples from the 1950s and 1960s were not equal to the 1980s and 1990s samples for both Ferralsols (31 vs. 25) and Cambisols (28 vs.

29). The statistical analysis for groups of unequal sizes follows, however, almost exactly the pattern for groups of equal sizes (Snedecor and Cochran, 1989). The pooled variance for the data of each Major Soil Grouping was calculated from the sum of squared deviations within the population. This was followed by the calculation of the *t*-value taking into consideration the unequal population size. The difference in the geometric means between the two sampling periods is reported.

3. Results

3.1. Permanent cropping

Ferralsols under permanent cropping since the 1930s and 1940s had an extremely acid soil reaction with low levels of exchangeable cations. Aluminium saturation was extremely high in the subsoil (Table 3).

Table 3
Soil analytical data of some Major Soil Groupings under permanent cropping (mean values with range of values in parentheses)

Major Soil Groupings:	Depth (cm)	Ferralsols ($n = 5$)		Acrisols ($n = 5$)		Alisols ($n = 3$)		Cambisols ($n = 3$)	
pH (H_2O) 1:2.5	0–20	4.5	(4.3–4.7)	5.0	(4.3–5.3)	5.9	(5.5–6.6)	7.7	(7.4–7.9)
	30–50	4.3	(4.2–4.5)	4.4	(4.0–4.9)	5.4	(5.1–5.8)	7.5	(6.6–8.1)
Organic C (%)	0–20	1.8	(1.6–2.1)	1.8	(1.7–1.9)	1.7	(0.8–2.8)	2.5	(2.0–3.4)
	30–50	0.9	(0.8–1.0)	1.2	(1.1–1.3)	0.7	(0.5–0.8)	1.1	(0.9–1.5)
Available P [a] (mg kg^{-1})	0–20	3	(< 0.5–4)	3	(2–4)	2	(1–2)	2	(1–4)
	30–50	1	(< 0.5–1)	1	(1–2)	1	(< 0.5–1)	2	(1–3)
CEC (NH_4OAc pH 7) ($mmol_c$ kg^{-1})	0–20	na	–	na	–	136	(108–178)	291	(242–320)
	30–50	na	–	na	–	128	(90–151)	353	(221–386)
Exchangeable Ca ($mmol_c$ kg^{-1})	0–20	10	(4–14)	23	(13–28)	50	(40–67)	213	(140–272)
	30–50	3	(1–6)	16	(6–21)	32	(23–37)	195	(107–282)
Exchangeable Mg ($mmol_c$ kg^{-1})	0–20	7	(3–10)	15	(8–19)	19	(8–37)	33	(20–42)
	30–50	2	(1–7)	12	(2–20)	20	(12–31)	25	(8–44)
Exchangeable K ($mmol_c$ kg^{-1})	0–20	2	(1–3)	2	(< 0.5–3)	4	(2–9)	4	(2–8)
	30–50	1	(< 0.5–1)	1	(< 0.5–2)	1	(1–1)	2	(1–3)
Base saturation (%)	0–20	na	–	na	–	54	(42–64)	86	(58–100)
	30–50	na	–	na	–	44	(27–57)	73	(60–85)
Exchangeable Al ($mmol_c$ kg^{-1})	0–20	6	(5–11)	3	(0–9)	0	–	0	–
	30–50	11	(4–16)	6	(0–9)	0	–	0	–
Al saturation (% ECEC) [b]	0–20	25	(17–39)	7	(0–28)	0	–	0	–
	30–50	60	(33–80)	17	(0–33)	0	–	0	–

na: not available.

[a] Soil pH < 7: P-Bray I; soil pH > 7: P-Olsen.

[b] Aluminium saturation of the ECEC is calculated as: (Al/Ca + Mg + K + Na + H + Al) × 100.

Acrisols under permanent cropping had an acid topsoil and also an extremely acid subsoil. Exchangeable aluminium was lower than in the Ferralsols and reached on average 17% (of ECEC) in the subsoils. Organic carbon contents of the Ferralsols and Acrisols were similar. Alisols had higher levels of exchangeable cations but organic carbon was similar to the Ferralsols and Acrisols. Cambisols had a very high base saturation and a slightly alkaline soil reaction despite being cropped with sisal for over 60 years. Organic carbon was highest in the Cambisols when compared to the other Major Soil Groupings.

Common to all these soils under permanent cropping is the very low available phosphorus which is on average below 4 mg kg^{-1} in the topsoil and less than 3 mg kg^{-1} in the subsoil.

3.2. Bush vegetation and permanent cropping

The topsoil pH of a Ferralsol under bush vegetation was one unit higher than in a similar soil under permanent cropping, accompanied by a higher CEC and base saturation (Table 4).

Exchangeable cations were higher under bush than under permanent cropping but absolute levels were, however, low in both Ferralsols under bush vegetation and permanent cropping. Available phosphorus was very low regardless of land-use. Exchangeable aluminium was nil under bush but 10 $mmol_c$ kg^{-1} (42% ECEC) in the subsoils under permanent cropping. Acrisols under bush vegetation had a topsoil pH that was 1.5 units higher than under permanent cropping. Also organic carbon and available phosphorus in the topsoil was higher under bush vegetation than under permanent cropping, but there were little differences in the subsoils. Exchangeable calcium and magnesium levels were also much lower under permanent cropping. Arenosols had very low levels of organic carbon under both bush vegetation and permanent cropping. Topsoil pH in the Arenosol differed by one unit, accompanied by lower exchangeable cations levels. In Cambisols, only the exchangeable magnesium and available phosphorus levels were lower under permanent cropping.

Differences in soil chemical properties between bush vegetation and permanent cropping were statistically analyzed for Ferralsols (10 samples) and Acrisols (6 samples). The pH had significantly decreased in both Major Soil Groupings, and the decrease was largest in the topsoils of the Acrisols (Table 5).

Organic carbon and available phosphorus were significantly lower in the topsoils of the Ferralsols but did not differ between Acrisols under bush vegetation or permanent cropping. Levels of exchangeable cations had decreased significantly in both soils under permanent cropping, except for the exchangeable potassium level in the subsoils of the Acrisols. Likewise, base saturation had decreased significantly and the decrease was largest in the subsoils of the Ferralsols. The CEC did not alter significantly in both Major Soil Groupings. Exchangeable aluminium had increased significantly in the subsoils of the Ferralsols and Acrisols.

3.3. Historical data

A Ferralsol sampled in 1966 had an acid soil reaction with low amounts of exchangeable cations. In 1987 the same field had a strongly acid soil reaction and very

Table 4
Soil analytical data [a] of some Major Soil Groupings under bush vegetation and permanent cropping

	Depth (cm)	Ferralsols		Acrisols		Arenosols		Cambisols	
		bush vegetation	permanent cropping	bush vegetation	permanent cropping	bush vegetation	permanent cropping	bush vegetation	permanent cropping
pH (H_2O) 1:2.5	0–20	6.2	5.2	6.1	4.6	6.3	5.3	7.5	7.4
	30–50	5.7	5.1	5.6	4.7	6.0	5.4	7.5	6.6
Organic C (%)	0–20	2.1	1.7	1.5	1.1	0.7	0.7	1.9	3.4
	30–50	0.9	0.6	0.4	0.3	0.4	0.4	1.3	1.5
Available P [b] (mg kg^{-1})	0–20	3	3	3	< 0.5	3	2	9	4
	30–50	1	1	< 0.5	< 0.5	1	1	4	1
CEC (NH_4OAc pH 7) ($mmol_c$ kg^{-1})	0–20	125	88	157	110	98	60	310	310
	30–50	105	60	127	97	80	53	481	221
Exchangeable Ca ($mmol_c$ kg^{-1})	0–20	68	13	38	11	27	12	161	140
	30–50	23	9	17	11	28	12	97	107
Exchangeable Mg ($mmol_c$ kg^{-1})	0–20	26	5	23	5	14	4	70	36
	30–50	21	3	9	5	16	5	40	23
Exchangeable K ($mmol_c$ kg^{-1})	0–20	5	1	5	3	3	2	3	1
	30–50	4	< 0.5	5	2	3	1	3	1
Base saturation (%)	0–20	80	21	45	24	47	28	76	58
	30–50	54	20	31	27	60	34	29	60
Exchangeable Al ($mmol_c$ kg^{-1})	0–20	0	9	0	na	0	0	0	0
	30–50	0	10	0	na	0	0	0	0
Al saturation (% ECEC) [c]	0–20	0	32	0	–	0	0	0	0
	30–50	0	42	0	–	0	0	0	0

na: not available.

[a] One composite topsoil sample from each land-use system per Major Soil Grouping. Sampled sites were within 100 m distance.

[b] Soil pH < 7: P-Bray I; soil pH > 7: P-Olsen.

[c] Aluminium saturation of the ECEC is calculated as: $(Al/Ca + Mg + K + Na + H + Al) \times 100$.

Table 5
Differences in soil chemical properties [a] between bush vegetation and permanent cropping of Ferralsols and Acrisols

Major Soil Groupings:	Ferralsols ($n = 10$)		Acrisols ($n = 6$)	
Depth (cm):	0–20	30–50	0–20	30–50
pH (H_2O) 1:2.5	-1.2^{***}	-1.2^{***}	-1.4^{**}	-1.3^{**}
Organic C (%)	-0.5^{*}	-0.1^{ns}	-0.2^{ns}	-0.1^{ns}
Available P (Bray I) (mg kg^{-1})	-3^{**}	-1^{ns}	-1^{ns}	0
CEC (NH_4OAc pH 7) ($mmol_c$ kg^{-1})	-5^{ns}	$+2^{ns}$	-42^{ns}	-38^{ns}
Exchangeable Ca ($mmol_c$ kg^{-1})	-25^{*}	-13^{**}	-29^{**}	-18^{*}
Exchangeable Mg ($mmol_c$ kg^{-1})	-10^{*}	-10^{*}	-23^{*}	-22^{*}
Exchangeable K ($mmol_c$ kg^{-1})	-2.6^{*}	-2.4^{*}	-3^{*}	-2^{ns}
Base saturation (%)	-40^{**}	-44^{**}	-25^{*}	-21^{*}
Exchangeable Al ($mmol_c$ kg^{-1})	$+2^{ns}$	$+7^{**}$	$+5^{ns}$	$+11^{*}$
Al saturation (% ECEC)	$+3^{ns}$	$+20^{**}$	$+21^{ns}$	$+34^{ns}$

[a] Values reported are calculated as: permanent cropping minus bush vegetation.
***, **, * Significant difference at $p < 0.001$, $p = 0.01$, $p = 0.05$ respectively.
^{ns} No significant difference.

low levels of exchangeable calcium and magnesium (Table 6). Exchangeable potassium was already low in 1966 but in 1987 potassium was nearly depleted.

The topsoil pH of an Acrisol had decreased by one pH unit in 25 years. Levels of exchangeable cations in 1990 were about 60% of their 1966 levels. The pH and exchangeable cations of a Luvisol had changed little between 1960 and 1987. Soil fertility levels in the shallow and stony Leptosol had hardly changed between 1959 and 1987, although exchangeable potassium decreased from 5 to 2 $mmol_c$ kg^{-1}. This was

Table 6
Soil fertility status[a] (0–20 cm) of permanently cropped fields at different sampling times (partly after Hartemink, 1995)

Major Soil Groupings	Year of sampling	pH (H_2O) 1:2.5	organic C (%)	Exchangeable cations ($mmol_c$ kg^{-1})		
				Ca	Mg	K
Ferralsols	1966	5.5	2.5	19	11	4
	1987	5.0	1.5	6	3	1
Acrisols	1966	6.9	1.8	75	28	5
	1990	5.9	1.5	41	17	3
Luvisols	1960	6.5	na	41	9	2
	1987	6.6	0.8	44	12	2
Leptosols	1959	7.0	na	190	18	5
	1987	7.9	0.8	196	62	2
Phaeozems	1959	8.0	na	311	26	9
	1987	7.8	0.8	229	36	1

[a] One composite topsoil sample per sampling time.
na: not available.

Table 7

Changes in soil chemical properties[a] (0–20 cm) of Ferralsols and Cambisols between the 1950s and 1960s and the 1980s and 1990s

	Ferralsols ($n = 56$)	Cambisols[b] ($n = 57$)
pH (H_2O) 1:2.5	-1.1^{***}	-0.3^{ns}
Exchangeable Ca (mmol$_c$ kg^{-1})	-28^{***}	-62^{ns}
Exchangeable Mg (mmol$_c$ kg^{-1})	-8^{***}	-1^{ns}
Exchangeable K (mmol$_c$ kg^{-1})	-1.2^{*}	-2.3^{*}

[a] Values reported are the difference in the geometric means between the 1980s–1990s and the 1950s–1960s values.

[b] With minor inclusions from Luvisols.

***, * significant difference at $p < 0.001$, $p = 0.05$ respectively.

$^{\mathrm{ns}}$ no significant difference.

also found in a Phaeozem where pH and exchangeable calcium and magnesium showed no clear trend but exchangeable potassium declined from 9 to 1 mmol$_c$ kg^{-1}.

A statistical analysis of samples from the 1950s and 1960s and the 1980s and 1990s in permanently cropped fields revealed a significant decline in pH and levels of exchangeable cations in Ferralsols (Table 7).

The decline in pH and cations was about the same as was found in the statistical analysis between bush vegetation and permanent cropping (Table 5). In Cambisols, only exchangeable potassium levels declined significantly.

4. Discussion

Soil fertility had seriously declined in Ferralsols and Acrisols as indicated by samples from permanently cropped fields compared to samples under bush vegetation and, from the soil analytical data of the 1950s and 1960s. It confirms other observations on soil fertility decline in these soil types (Kimaro et al., 1994; Hartemink et al., 1996). The decline in fertility is caused by the removal of cations due to permanent cropping and lack of fertilization, resulting in a negative nutrient balance which has to be offset by the soil nutrient pool. Since these soils have only very few weatherable minerals remaining they are easily depleted and nutrient inputs are required. It is difficult to cover all nutrient requirements using organic manures, and for sustainable production farmers have to aim at integrated nutrient management which implies that both organic and inorganic nutrient inputs should be used, rather than one versus the other (Sanchez, 1994).

The increasing acidity of the Ferralsols and Acrisols under permanent cropping has a number of direct and indirect effects which are unfavourable for crop production. The uptake of calcium, magnesium and potassium is suppressed in the presence of high proton concentrations which is particularly problematic in soils with very low CECs (Kamprath, 1984). As acidity increases, aluminium is released from soil particles into the soil solution where it has effects similar to high proton concentrations. Also manganese becomes soluble and may be found at toxic levels. Furthermore high levels of acidity in the subsoil affect the rooting depth which limits deep nutrient and water uptake (Ritchey et al., 1980).

Organic carbon decreased significantly in the topsoils of the Ferralsols with 0.5% points, and such decline generally results from permanent cropping (Nye and Greenland, 1960). This decrease has important consequences for crop production because organic matter supplies most of the nitrogen taken up by unfertilized crops (Sanchez, 1976). For a field in Tanga Region permanently cropped with sisal since 1957 it was calculated that due to dwindling organic matter contents, 115 kg N ha^{-1} was released with organic matter mineralization in 1966 and only 63 kg N ha^{-1} in 1990 (Hartemink, 1995). In the Ferralsols and Acrisols examined, most of the phosphorus is in the organic form and becomes available with mineralization (Stewart and Sharpley, 1987). The combination of increasing acidity resulting in phosphorus immobilization with the decrease in soil organic matter may severely reduce the phosphorus availability and affect the soil's productivity. Organic carbon is important for the retention of cations in highly weathered soils like these Ferralsols (ca. 2,500 to 3,500 $mmol_c$ kg^{-1} C). There were, however, no significant changes found in the CECs of the topsoils and subsoils of the Ferralsols and Acrisols.

Soil fertility has hardly changed in Cambisols, Leptosols, Luvisols and Phaeozems as a result of permanent cropping. These soils are able to resist the process of decline as nutrients removed by the crop are replenished by weathering of the underlying limestone rock and the subsequent capillary rise of cations (National Soil Service, 1988). This replenishment has maintained high calcium and magnesium levels and the pH has remained near neutral. Levels of exchangeable potassium, however, have decreased in these soils. Apparently potassium is not replenished by the weathering of primary minerals or the underlying limestone rock.

5. Conclusions

Large differences were found in soil fertility decline between the Major Soil Groupings. Although for some Major Soil Groupings the data were few and allowance must be made for spatial and temporal heterogeneity, Ferralsols, Acrisols and Arenosols showed a striking decline in soil fertility under permanent cropping whereas Cambisols, Luvisols, Phaeozems and Leptosols showed resilience. The study has shown that soil analytical data at the Major Soil Groupings level can be used for a general assessment of soil fertility decline.

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