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SOIL FERTILITY DECLINE AND FALLOW EFFECTS IN FERRALSOLS AND ACRISOLS OF SISAL PLANTATIONS IN TANZANIA

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(Submitted for publication in *Experimental Agriculture*)

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ISRIC
PO Box 353
6700 AJ Wageningen
The Netherlands

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SUMMARY

Soil fertility decline and fallow effects were studied in Ferralsol-Acrisol catenas of sisal plantations in north-east Tanzania. Ferralsols had extremely low fertility levels under continuous sisal cultivation in the absence of fertilizers. Fertility levels of Ferralsols under 18 years of bush fallow or secondary forest were slightly higher. Acrisols under continuous sisal cultivation were less depleted than the Ferralsols because of a higher intrinsic fertility. A comparison of soil analytical data of the 1950s and 1960s with recent data from the same sisal fields, showed that the topsoil pH of Ferralsols had decreased by 1.5 of a unit (r^2=0.807) and of the Acrisols by 1.2 of a unit (r^2=0.494) under continuous sisal cultivation. It was concluded that soil fertility had severely declined under sisal cultivation, and that fallows are insufficient for restoration of soil fertility.

RESUMEN

El decaimiento de fertilidad del suelo y los efectos de barbecho fueron estudiados en Ferralsol-Acrisol *catenas* de plantaciones de sisal (*Agave sisalana* P.) en el nordeste de Tanzania. A consecuencia del cultivo incesante de sisal sin aplicación de fertilizantes, el Ferralsol mostró niveles de fertilidad extremamente bajos. Niveles de fertilidad de Ferralsoles después de 18 años de barbecho matoso de monte secundario eran algo más altos. Acrisoles con cultivo continuo de sisal resultaron menos agotado que los Ferralsoles a causa de su fertilidad intrínseca. Una comparación de datos analíticos de suelos de los años '50 y '60 con datos recientes de los mismos sembrados de sisal, mostró que el pH de la capa superficial del suelo de los Ferralsoles había decrecido 1.5 unidades (r^2 = 0.807) y de los Acrisoles 1.2 unidades (r^2 = 0.494) a consecuencia del incesante cultivo de sisal. Se llegó a la conclusión de que la fertilidad del suelo a consecuencia del cultivo de sisal ha decaído seriamente y que dejar en barbecho es insuficiente para recuperar la fertilidad del suelo.

INTRODUCTION

Soil fertility decline is a major factor affecting the soil productivity in many parts of Sub-Saharan Africa. Although several model studies have been made to investigate soil fertility decline at supra-national and district levels (Stoorvogel *et al.*, 1993; Smaling *et al.*, 1993), few quantitative studies are available at the farm or field level. Monitoring of soil fertility trends at the smallholder's farm is difficult because there is considerable spatial and temporal variability in the farming systems. At a plantation level, however, large areas are uniformly cropped and managed, and the land-use history is usually known which enables a sound base for soil fertility research.

In Tanzania, large sisal plantations can be seen adjacent to the Indian Ocean coast on soils derived from limestone. On such soils in Tanga region, the first sisal plantation was established in 1893 (Lock, 1969). Soil fertility decline has not been a serious problem in those soils as nutrients removed by the sisal crop (particularly Ca and Mg) are replenished by the weathering of the underlying rock (Hartemink and Wienk, submitted). Most sisal plantations in Tanga region are found up-country on deep soils which Lock (1969) described as red earths, non laterised, derived from gneiss. Milne (1947) mentioned that physically the red soils are ideal, but chemically they are poor and cannot maintain high yields under continuous cropping. From the 1940s to 1960s large areas of these red soils were planted with sisal and Tanzania became an important fibre producer. Production decreased steadily in the past two decades (Hartemink and Wienk, submitted) but in the mid 1980s, large rehabilitation programmes were launched. The National Soil Service of Tanzania contributed to those programmes by conducting soil surveys and soil fertility appraisals of several sisal plantations. From their research, evidence was generated that the decline experienced in sisal yields could have been caused by the depletion of plant nutrients (National Soil Service, 1988; Hartemink, 1991; Braun, 1994).

In a recent paper, Hartemink and Van Kekem (1994) analyzed nutrient depletion in Ferralsols semi-quantitatively by comparing nutrient removal in a sisal crop with changes in soil composition under unfertilized conditions. Nutrient balances for hybrid sisal with yields of 1.5 t ha^{-1} on Ferralsols have shown an annual shortfall of 32 kg N ha^{-1}, 4.5 kg P ha^{-1}, 52 kg K ha^{-1}, 127 kg Ca ha^{-1} and 47 kg Mg ha^{-1} (Hartemink and Van Kekem, 1994). The data showed that sisal imposes a heavy drain on nutrients even with moderate yield levels. Many sisal growers apply no manure or fertilizers to compensate for the removal of nutrients but use a rotational system, which is a form of shifting cultivation. The plantations are therefore only partly planted with sisal. Land close to the sisal processing factory is generally under continuous cultivation while land further away is kept fallow after each cycle of sisal (10 years). Little is known, however, on the quantitative effect of continuous sisal cultivation and bush fallows on the chemical properties of different soil types.

In this paper, soil analytical data of sisal fields which have been under continuous cultivation are compared with data from soils after 18 years of bush fallow, and with land that is under secondary forest. Secondly, soil analytical data of the 1950s and 1960s are compared with recent soil data of the same sisal fields. These comparisons are made for two soil types (Ferralsols and Acrisols), and the data presented are from 3 sisal plantations situated in similar agro-ecological zones.

MATERIALS AND METHODS

Sisal plantations

The research was conducted on Bamba, Kwafungo, Kwamdulu Estate in Tanga Region. Bamba Estate (4°55'S, 39°20'E) in Muheza District, is located at the foot of the Usambara mountain range near Kisangani village and is one of the most recent sisal plantations in Tanga region. Total plantation area is 1810 ha but less than half of the land is planted with sisal; the remaining areas are under bush fallow. Mostly sisal Hybrid 11648 is cultivated, and annual fibre yields are around 1 t ha^{-1}. Kwafungo Estate (5°20'S, 39°10'E) is located near Muheza town (Muheza District) and covers about 2330 ha. Large areas are neglected and as a result sisal has been overgrown by trees and bushes. No yield records are available of Kwafungo Estate. Kwamdulu Estate (5°10'S, 38°50'E) is located near Korogwe town (Korogwe District). The total plantation area covers 4460 ha of which 2400 ha is cultivated with sisal; the remaining areas are fallow (bush or grasslands) or used for small scale farming by plantation workers. Annual fibre yields vary from 1.0 to 1.5 t ha^{-1}.

Climate and soils

The rainfall at the 3 sisal plantations is bi-modally distributed with a yearly mean around 1100 mm (Table 1) but with a considerable variation between years. Rainfall exceeds evaporation in April and May only. The prevailing ustic soil climatic conditions are very suitable for sisal cultivation. The mean annual temperature is around 25°C and the soil temperature is isohyperthermic.

Table 1 Summary of soil and climatic conditions of the 3 sisal plantations.

					soil types (ha)†			
plantation	area (ha)	sisal (ha)	rain (mm $year^{-1}$)	altitude (m a.s.l.)	Ferralsols	Acrisols	Fluvisols/ Gleysols	others
Bamba	1810	na	1044	ca. 180	511	1091	172	36
Kwafungo	2330	na	1057	ca. 250	847	487	246	750
Kwamdulu	4640	2412‡	1136	ca. 290	835	2565	1060	0

† field classifications based on the FAO-Unesco system (1988)
‡ 1992 data
na = not available

The soils are derived from a complex of acid and intermediate gneiss of Precambrian age (National Soil Service, 1988, 1989; Hartemink, 1991). Topography at the sisal plantations is undulating to rolling. The soils constitute a catena with well drained soils on the crests (Ferralsols) and slopes (Acrisols), and imperfectly to poorly drained soils on the footslopes and valleys (Gleysols & Fluvisols). This recurrent topographic sequence of soils was first recognized by Milne (1935).

On the crests, the soils are very deep and have clayey textures with sesquioxides and kaolinite as the predominant minerals (Nandra, 1977). The soils are strongly weathered, intensely leached and commonly very acid with low levels of exchangeable cations and available P. Nutrient retention capacity (CEC) is low and Al saturation in some subsoils reaches values of over 70%. As a result of the low pH and the high exchangeable Al content, the capacity for P fixation is probably high in these soils. Observations in the field supported by laboratory data, show the soils to have a ferralic B horizon (CEC_{clay} < 160 $mmol_c\ kg^{-1}$), and so the soils were classified as Rhodic Ferralsols according to the FAO-Unesco classification system (1988). Physical and chemical properties of Rhodic Ferralsols at Bamba, Kwafungo and Kwamdulu Estate are given in Table 2.

Table 2 Physical and chemical properties of selected horizons of Rhodic Ferralsols.

	Bamba estate†			Kwafungo estate‡			Kwamdulu estate*		
Horizon designation	Ap	Bws1	Bws2	Ap	Bws1	Bws3	Ap	Bw1	Bw2
Depth (cm)	0-20	50-70	90-110	0-10	25-50	50-80	0-20	40-60	110-130
Clay (%)	35	50	51	40	58	62	52	63	66
Silt (%)	6	7	7	16	10	12	8	5	4
Sand (%)	59	43	42	44	32	26	40	32	30
pH (water) 1:2.5	5.0	5.1	5.0	5.2	5.2	5.4	4.6	4.2	5.0
pH (KCl) 1:2.5	3.9	4.0	3.9	4.0	4.2	4.2	4.0	4.2	4.5
Organic C (%)	1.4	0.3	0.3	2.3	0.8	0.5	1.8	0.3	0.1
Total N (%)	0.09	0.02	0.03	0.16	0.08	0.05	na	na	na
Available P (Bray I) (mg/kg)	3	<0.5	<0.5	1	1	1	3	1	1
CEC (NH_4OAc pH 7) ($mmol_c\ kg^{-1}$)	79	67	63	68	98	92	89	51	50
Exchangeable Ca ($mmol_c\ kg^{-1}$)	16	9	1	21	22	15	7	<0.5	<0.5
Exchangeable Mg ($mmol_c\ kg^{-1}$)	5	2	5	7	7	10	5	<0.5	<0.5
Exchangeable K ($mmol_c\ kg^{-1}$)	1	<0.5	<0.5	1	<0.5	<0.5	1	<0.5	<0.5
Base saturation (%)	29	17	10	44	31	28	14	<5	<5
Exchangeable Al ($mmol_c\ kg^{-1}$)	11	10	13	9	2	1	8	5	2
Al Saturation (% ECEC)	29	47	68	23	7	2	37	71	44

† data modified from Hartemink (1991)
‡ data modified from National Soil Service (1989)
* data modified from National Soil Service (1988)
na = not available

On the slopes, the soils are also red and very deep but less weathered and less intensely leached. The soils have a clear textural B (argic) horizon which is well structured, particularly when compared to the weak granular B horizon of the Ferralsols. Soil fertility levels are higher than in the soils on the crests. In the field, these soils have all the characteristics of Haplic and Ferric Acrisols. Laboratory analysis showed, however, that although the B horizon has sufficient clay increase to be argic, the CEC_{clay} was lower than 160 $mmol_c\ kg^{-1}$ which means the B horizon should be classified as ferralic. The weatherable mineral contents of the soils is not known, and as the properties and soil management aspects of theses soils are markedly different from the soils on the crests (Rhodic Ferralsols), their field classifications (Haplic and Ferric Acrisols) were preferred in this publication. Properties of selected soil horizons of these soils are given in Table 3.

Table 3 Physical and chemical properties of selected horizons of Haplic and Ferric Acrisols*.

	Bamba estate†			Kwafungo estate‡			Kwamdulu estate§		
Horizon designation	Ap	Bt1	Bt2	Ap	BA	Bt	Ap	BA	Bt1
Depth (cm)	0-20	50-70	90-110	0-20	30-50	50-60	0-20	30-50	90-110
Clay (%)	43	51	48	28	48	50	46	62	62
Silt (%)	7	3	1	14	8	8	11	7	8
Sand (%)	50	46	51	58	44	42	43	31	30
pH (water) 1:2.5	5.9	5.0	4.8	6.4	5.2	5.5	5.5	4.5	4.9
pH (KCl) 1:2.5	4.7	3.9	3.9	5.3	4.2	4.5	4.8	4.1	4.6
Organic C (%)	1.9	0.4	0.3	2.2	1.2	1.1	1.7	0.7	0.4
Total N (%)	0.15	0.04	0.08	0.18	0.10	0.08	na	na	na
Available P (Bray I) (mg kg^{-1})	4	<0.5	<0.5	2	1	1	3	2	1
CEC (NH_4OAc pH 7) (mmol$_c$ kg^{-1})	105	52	37	137	96	107	118	67	65
Exchangeable Ca (mmol$_c$ kg^{-1})	41	9	8	47	17	16	47	11	11
Exchangeable Mg (mmol$_c$ kg^{-1})	17	4	4	22	9	9	22	8	9
Exchangeable K (mmol$_c$ kg^{-1})	3	<0.5	<0.5	5	<0.5	1	1	<0.5	<0.5
Base saturation (%)	59	27	35	54	28	25	60	30	31
Exchangeable Al (mmol$_c$ kg^{-1})	0	0	14	0	4	0	0	3	2
Al Saturation (% ECEC)	0	0	51	0	13	0	0	13	9

† data modified from Hartemink (1991)
‡ data modified from National Soil Service (1989)
§ data modified from National Soil Service (1988)

na = not available
* field classifications

Soil sampling and analysis

The choice of sample locations on the 3 sisal plantations was based on evidence provided by soil maps. The soil samples obtained were composites of 10 to 15 randomized spots from mini-pits of an area of about 0.5 ha. The mini-pits were dug with hoes ('jembes') and the soil was taken from the pit with a small spade. Soil samples were taken from 2 depths: 0-20 and 30-50 cm.

At Kwamdulu Estate prior to soil sampling, the plantation's records were examined and 3 different land-use systems were identified for the purpose of this study. Firstly, fields were selected that had been under continuous sisal cultivation since the 1930s or 1940s and which had carried 4 to 6 cycles of sisal. Secondly, fields were selected that had been under bush fallow for the past 18 years but which had carried 2 or 3 cycles of sisal before the bush fallow. Thirdly, sites were selected that had never been under sisal and were covered with a dense secondary forest. In each of these land-use systems 3 to 5 fields on Ferralsols and Acrisols were chosen and composite topsoil samples were taken as described above. The soil analytical data were averaged and coefficients of variations (cv%) were calculated for each parameter.

Soil analyses were done at the National Soil Service Laboratories in Mlingano (Tanzania) following methods described by Page *et al.* (1982).

Old soil research files were recovered and consulted at the Sisal Research Station Mlingano in the early 1990s. These files contained soil analytical data of sisal fields of nearly every plantation in Tanga region. The data were of the 1950s and 1960s and extremely well documented. Fields of

Bamba, Kwafungo and Kwamdulu Estate were selected which were sampled in the 1950s and 1960s and in the late 1980s and early 1990s, in order to investigate changes in chemical soil fertility. Only fields which had been under continuous sisal cultivation were chosen. The following soil parameters could be used as the analytical methods of the 1950s and 1960s were identical to the present methods: pH H_2O (soil:water 1:2.5) and exchangeable Ca, Mg and K (NH_4OAc extraction at pH 7.0).
In order to investigate the trend in the topsoil pH H_2O between the 1950s, 1960s and late 1980s a linear regression was applied using GENSTAT (ver. 5). This was done for the topsoil pH of Ferralsols (n=20) and Acrisols (n=20) of Kwamdulu Estate. No transformation of data was applied before regression.

RESULTS

Land-use systems

Ferralsols under continuous sisal cultivation without fertilization have a pH H_2O of 4.5 in the topsoil and 4.3 in the subsoil accompanied by a high Al saturation (Table 4, mean of 5 samples).

Table 4 Soil fertility status of Ferralsols under secondary forest, 18 years of bush fallow and continuous sisal cultivation.

		secondary forest		18 years of bush fallow		continuous sisal cultivation	
soil parameter	depth (cm)	(n=3)	cv %	(n=3)	cv %	(n=5)	cv %
pH (water) 1:2.5	0-20	4.9	7	4.8	3	4.5	3
	30-50	4.9	7	4.9	3	4.3	3
pH (KCl 0.01 M) 1:2.5	0-20	4.1	3	4.1	2	3.9	3
	30-50	3.9	0	4.1	1	3.9	3
Organic carbon (%)	0-20	1.7	10	1.5	6	1.8	10
	30-50	0.9	9	0.9	9	0.9	7
Available P (Bray I) (mg kg^{-1})	0-20	2	34	1	110	3	49
	30-50	<0.5	-	1	82	1	67
Exchangeable Ca ($mmol_c$ kg^{-1})	0-20	10	57	12	15	10	37
	30-50	3	57	8	22	3	54
Exchangeable Mg ($mmol_c$ kg^{-1})	0-20	8	25	8	27	7	32
	30-50	3	72	2	73	2	97
Exchangeable K ($mmol_c$ kg^{-1})	0-20	1	71	4	51	2	50
	30-50	<0.5	-	3	71	1	82
Al saturation ECEC (%)	0-20	na	-	4	-	25	39
	30-50	na	-	10	-	60	28

n = number of composite topsoil samples
na = not available

The pH under bush fallow was 4.8 in the topsoil and 4.9 in the subsoil, similar to values found under secondary forest. Only slight differences were found in the organic C contents of the Ferralsols between the 3 land-use systems and C contents ranged from 1.5 to 1.8%. Levels of available P were very low in all 3 land-use systems (< 5 mg kg^{-1}). The sum of exchangeable cations (Ca, Mg and K) was low to very low in the topsoils (< 25 $mmol_c$ kg^{-1}) and did not differ much between the 3 land-use systems. Exchangeable cations in the subsoils were even lower, but coefficients of variation were high (97%). Al saturation was high in the subsoil under continuous sisal cultivation (60% of ECEC), but under bush fallow Al saturation was 21% points lower in the topsoil and 50% points lower in the subsoil.

In Acrisols, the difference in pH H_2O between continuous sisal cultivation and 18 years of bush fallow was 0.9 of a unit (Table 5). The pH under secondary forest was 0.3 of a unit higher than under bush fallow.

In the subsoils of Acrisols under continuous sisal cultivation, the pH was 4.4, under bush fallow the pH was 5.1 and under secondary forest the subsoil pH was 5.5. Topsoil organic C contents were around 1.9% in all 3 land-use systems. Available P levels were only slightly higher under bush fallow than in the topsoils under continuous sisal cultivation although in both soils P levels were very low (< 4 mg kg^{-1}). Under secondary forest, available P contents were medium (8 mg kg^{-1}) but variation was high (cv: 116%). Levels of exchangeable cations were lowest under continuous sisal cultivation and highest under secondary forest. The levels of exchangeable Ca in the topsoils under bush fallow were 8 $mmol_c$ kg^{-1} higher than under continuous sisal cultivation, but levels of exchangeable Mg and K differed only by 2 and 1 $mmol_c$ kg^{-1} resp. Subsoil levels did not differ much between the 3 land-use systems. Moderate levels of Al saturation (17%) were found in the subsoils under continuous sisal cultivation. Al saturation was low (8%) in the subsoils of bush fallows and Al saturation was zero under secondary forest.

Table 5 Soil fertility status of Acrisols under secondary forest, 18 years of bush fallow and continuous sisal cultivation.

		secondary forest		18 years of bush fallow		continuous sisal cultivation	
soil parameter	depth (cm)	(n=5)	cv %	(n=3)	cv %	(n=5)	cv %
pH (water) 1:2.5	0-20	6.2	1	5.9	8	5.0	7
	30-50	5.5	8	5.1	12	4.4	7
pH (KCl 0.01 M) 1:2.5	0-20	5.2	5	4.9	9	4.2	8
	30-50	4.5	8	4.3	12	3.8	8
Organic carbon (%)	0-20	1.9	20	1.9	12	1.8	4
	30-50	0.9	56	1.1	12	1.2	6
Available P (Bray I) (mg kg^{-1})	0-20	8	116	4	17	3	16
	30-50	<0.5	-	1	32	1	17
Exchangeable Ca ($mmol_c$ kg^{-1})	0-20	37	45	31	40	23	25
	30-50	13	46	9	81	16	39
Exchangeable Mg ($mmol_c$ kg^{-1})	0-20	25	11	17	29	15	28
	30-50	13	40	11	43	12	59
Exchangeable K ($mmol_c$ kg^{-1})	0-20	5	38	3	57	2	65
	30-50	4	26	2	102	1	89
Al saturation ECEC (%)	0-20	0	0	1	141	7	155
	30-50	0	0	8	75	17	63

n = number of composite topsoil samples

Historical data

Continuous sisal cultivation on a Ferralsol at Bamba Estate decreased the pH in 25 years by 0.5 unit in the topsoil (Table 6). The levels of exchangeable Ca decreased from 19 to 6 mmol$_c$ kg^{-1} and Mg levels decreased by 8 mmol$_c$ kg^{-1} while K was nearly exhausted after 25 years of sisal cultivation. Levels of K were, however, moderately high in 1966 (4 mmol$_c$ kg^{-1}).

A similar trend was found in Ferralsols of Kwafungo Estate. The pH decrease in the topsoil between 1959 and 1989 was 0.9 of a unit to pH 4.8. Levels of exchangeable Ca decreased from 32 to 13 mmol$_c$ kg^{-1} after 30 years of sisal cultivation. Exchangeable K levels were already very low in 1959 (1 mmol$_c$ kg^{-1}) and did not alter. At Kwamdulu Estate, the topsoil pH of a Ferralsol under continuous sisal cultivation decreased from 5.6 to 4.5 between 1958 and 1987. Levels of exchangeable Ca decreased from 15 to 8 mmol$_c$ kg^{-1} and Mg from 17 to 7 mmol$_c$ kg^{-1}. Potassium levels were already low in 1958.

Table 6 Soil fertility status (0-20 cm) of continuously cultivated sisal fields on Ferralsols and Acisoils at different sampling times.

				exchangeable cations (mmol$_c$ kg^{-1})			
soil type	plantation	year of sampling	pH (water) 1:2.5	Ca	Mg	K	modified after:
Ferralsols	Bamba	1966	5.5	19	11	4	†
		1990	5.0	6	3	1	Hartemink, 1991
	Kwafungo	1959	5.7	32	na	1	†
		1989	4.8	13	12	1	National Soil Service, 1989
	Kwamdulu	1958	5.6	15	17	2	†
		1987	4.5	8	7	1	National Soil Service, 1988
Acrisols	Bamba	1966	6.9	75	28	5	†
		1990	5.9	41	17	3	Hartemink, 1991
	Kwamdulu	1966	6.7	49	13	2	†
		1987	5.0	25	13	1	National Soil Service, 1988

† unpublished data of Sisal Research Station Mlingano
na = not available

Topsoil pH of an Acrisol at Bamba Estate decreased from 6.9 to 5.9 between 1966 and 1990. Levels of exchangeable Ca decreased by 34 mmol$_c$ kg^{-1} and Mg levels by 11 mmol$_c$ kg^{-1}. K levels were fairly high in 1966 (5 mmol$_c$ kg^{-1}) but decreased by 2 mmol$_c$ kg^{-1} as a result of continuous sisal cultivation. At Kwamdulu estate, topsoil pH decreased by 1.7 unit to 5.0 in the period between 1966 and 1987. Exchangeable Ca decreased from 49 to 25 mmol$_c$ kg^{-1} while levels of exchangeable Mg and K remained unchanged.

pH trends

The topsoil pH data of the 1950s and 1960s were plotted with the 1987 pH data of Ferralsols at Kwamdulu Estate (Fig. 1).

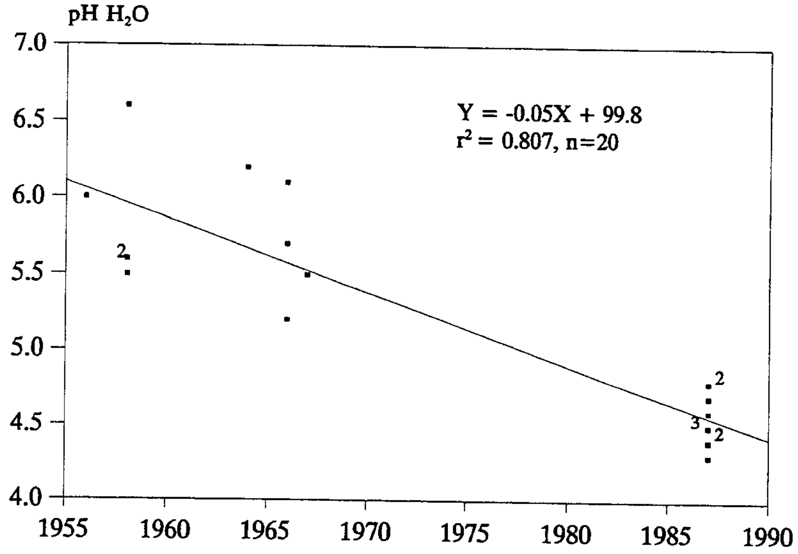

Fig. 1 Trend in pH H_2O of the topsoils (0-20 cm) of Ferralsols under continuous sisal cultivation.

The linear regression reveals a decline in pH of about 0.5 pH unit per 10 years (r^2=0.807, n=20). In other words, the topsoil pH of Ferralsols decreased by 1.5 of a unit between 1957 and 1987. A linear regression was also applied with the pH data of the topsoils of Acrisols (Fig. 2) but correlation was low (r^2=0.494, n=20), because of the wide pH range in the 1950s and 1960s. Nevertheless the data suggest a declining trend of about 0.4 pH unit per 10 years.

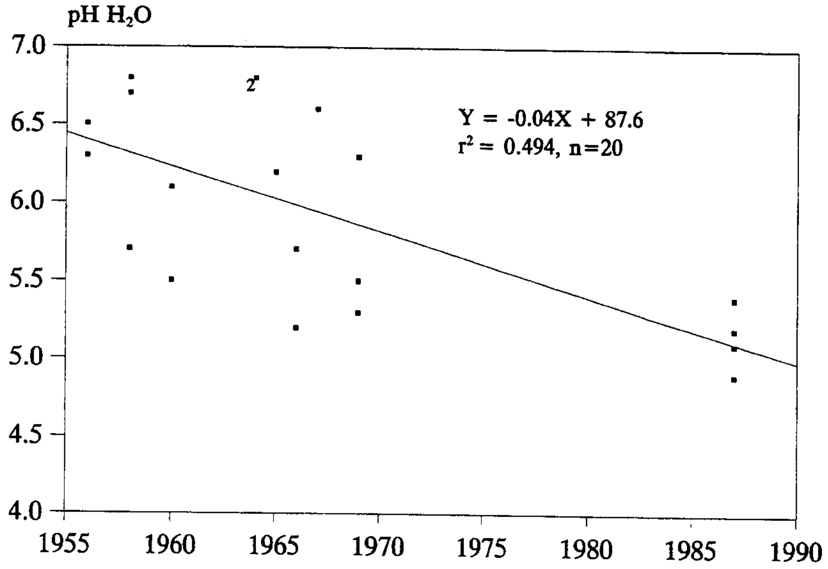

Fig. 2 Trend in pH H_2O of the topsoils (0-20 cm) of Acrisols under continuous sisal cultivation.

DISCUSSION

The chemical soil fertility was lowest under continuous sisal cultivation and highest under secondary forest in both Ferralsols and Acrisols. The fertility decline under continuous sisal cultivation was, however, more severe in the Ferralsols than in the Acrisols. This is explained by the higher initial fertility and possibly the presence of more weatherable minerals in Acrisols. Although the soil data from the 1950s and 1960s were few and taking in account the spatial heterogeneity of the soils, comparing historical soil data with recent data, also revealed a decline in soil fertility with a sharp decrease in soil reaction. Again, the effect of continuous sisal cultivation was more severe in Ferralsols than Acrisols. Haule *et al.* (1989) conducted fertility research with maize on a similar soil catena in Tanga region. The present study confirms their findings that fertility decline in soils of the sloping part of the catena (Acrisols) is much lower when cropped continuously without fertilization, as compared to the soils on the crests (Ferralsols).

The effect of a bush fallow period on the chemical soil fertility differed per parameter and soil type. The most dramatic effect was the increase in soil reaction accompanied by a decrease in Al saturation. This was particular the case in the Ferralsols where levels of Al saturation were 50% points lower in the subsoil under bush fallow than under continuous sisal cultivation. Sisal, being a calcicole plant, is seriously affected by strongly acid soils with high Al saturation, and a pH H_2O below 5.0 must be considered a limitation for sisal growing (Rijkebusch and Osborne, 1965). A positive impact of a fallow period on the consecutive sisal crop may therefore come from the increase in pH and the decrease in Al saturation of the subsoil. Furthermore it is likely that reduction of Al saturation levels in the subsoil increases the rooting depth of sisal which retards depletion of topsoil nutrients.

The effect of bush fallows on organic C contents was negligible in both Ferralsols and Acrisols. Very large additions of organic matter are generally required to increase the C content and apparently this is not supplied in 18 years of bush fallow (B.H. Janssen, pers. comm.). Furthermore the organic C in the soils is very stable and strongly associated with sesquioxides and kaolinite, and it seems that land-use has little influence on its contents. Nye and Greenland (1960) reported, however, that the largest benefits of fallow were due to the increase in soil organic matter.

There were no fallow effects on the exchangeable Mg content in both soil types. Exchangeable Ca and K increased under bush fallow indicating that additions were larger than losses. The main explanation is the absence of nutrient removal from the bush fallow as compared to soils under continuously sisal cultivation while the additions of Ca and K may have been similar under both land use systems.

It is disputable whether natural bush fallows are the best option for sustainable soil fertility management under sisal cultivation. In the beginning, the fallow vegetation is dominated by grasses, and as they tend to be shallower rooted than woody plants, leaching of nutrients may be considerable (Grubb, 1989). The effect of fertility restoration under bush fallows is therefore likely to increase after longer periods i.e. when woody plants dominate the fallow vegetation but in the meantime nutrients may have been lost. Data presented in this paper show that the fertility increased under 18 years of bush fallow. The increase was only slight in the Ferralsols as these soils have few nutrients to recycle. It is likely that the bush fallow effect is insufficient for a new cycle of sisal (10 years). Nye and Greenland (1960) also reported that fallows were incapable in restoring the fertility when the land was cultivated for prolonged periods.

There are a number of options for the plantation management when coping with the decline in soil fertility and the limited effects of bush fallows. Firstly, organic or chemical fertilizers can be applied and although no study has shown that fertilization would be economically unsound, sisal is rarely fertilized because of supposed prohibitive costs of fertilizers and the demand on labour and transport. Care should be taken in the selection of chemical fertilizers as some N fertilizers (e.g. sulphate of ammonia, urea) may further increase the soil acidity (Haule *et al.*, 1989). Pieri (1987) mentioned, however, that the productivity of acid soils cannot be maintained only by the use of fertilizers, organic inputs are required as well.

A second option is to use an improved or managed fallow and this may speed up the restoration of soil fertility as was suggested for the low fertility soils in S. America (Sanchez and Salinas, 1981) and more recently for Sub-Sahara Africa (Balasubramanian and Blaise, 1993). Stephens (1967) reported from Uganda that fallows with elephant grass (*Pennisetum purpureum*) were much more effective than natural bush fallows in restoring soil fertility. But Lock (1969) mentioned that after 2 years of fertilized fallow with elephant grass (*Pennisetum purpureum*) and guinea grass (*Panicum maximum*) the growth of sisal was not as good as that on virgin soil. Since a cycle of sisal removes large quantities of nutrients (Hartemink and Van Kekem, 1994), also improved fallows may be inadequate in restoring the fertility as the subsoil is severely depleted and very little nutrients have remained to recycle. Also Lock (1969) noted that removal of plant nutrients from a soil by sisal cannot be made good through the medium of plants alone i.e. nutrient cycling with bush/grass or improved fallows. Similar observations were made in West Africa by Juo and Kang (1989).

CONCLUSIONS

Continuous sisal cultivation on Ferralsols and Acrisols in Tanzania has severely depleted the chemical soil fertility. The decline is more severe in Ferralsols than in Acrisols as the pH reaches very low levels accompanied by high Al saturations. Long periods of bush fallow assist in soil fertility restoration but the increase in plant nutrients may be insufficient for a new cycle of high yielding sisal. Rotational sisal cultivation might not be a sustainable system, and input of nutrients from fertilizers is essential. Improved or planted fallows are possibly of little use once the soils are depleted like some Ferralsols presented in this paper.

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