*Expl Agric.* (1996), volume 32, pp. 173–184
*Printed in Great Britain*

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

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(*Accepted 1 August 1995*)

## SUMMARY

Soil fertility decline and fallow effects were studied in Ferralsol-Acrisol catenas of plantations of sisal (*Agave sisalana*) in north-east Tanzania. The fertility of Ferralsols that had been subject to continuous sisal cultivation in the absence of fertilizers was extremely low but that of Ferralsols that had been under 18 years of bush fallow or under secondary forest was slightly better. Acrisols that had been under continuous sisal cultivation were less depleted than the Ferralsols because of greater intrinsic fertility. A comparison of soil analytical data from the 1950s and 1960s with recent data from the same sisal fields showed that the topsoil pH of the Ferralsols had decreased by 1.5 ($r^2 = 0.807$) and that of the Acrisols by 1.2 ($r^2 = 0.494$) under continuous sisal cultivation. Thus there had been a serious decline in soil fertility under sisal cultivation, and this decline was not adequately reversed by fallowing.

## INTRODUCTION

Decline of soil fertility is a major factor affecting productivity in many parts of sub-Saharan Africa. Although several studies have investigated this decline at supra-national and district levels (Stoorvogel *et al.*, 1993; Smaling *et al.*, 1993), few quantitative studies have been reported at the farm or field level. Monitoring of soil fertility trends on smallholders' farms is difficult because of the variability in these farming systems. On plantations, however, large areas are uniformly cropped and managed, and the land-use history is usually known, providing a sound base for soil fertility research.

In Tanzania, there are large sisal plantations on soils derived from limestone adjacent to the Indian Ocean coast. The first sisal plantation was established on such soils in the Tanga region in 1893 (Lock, 1969). Soil fertility decline has not been a serious problem in those soils as nutrients removed by the sisal crop (particularly calcium and magnesium) are replenished by the weathering of the underlying rock (Hartemink and Bridges, 1995). However, most sisal plantations in the Tanga region are found up-country on deep soils which Lock (1969) described as non-laterised red earths, derived from gneiss. The red soils have

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favourable physical properties, but chemically they are poor and they cannot maintain high yields under continuous cropping. From the 1940s to the 1960s large areas of these red soils were planted with sisal and Tanzania became an important fibre producer. Production has decreased steadily over the past two decades (Hartemink and Wienk, 1995) 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, which showed that the decline in sisal yields could have been caused by the depletion of plant nutrients (National Soil Service, 1988; Hartemink, 1991; Braun, 1994).

Hartemink and Van Kekem (1994) analysed nutrient depletion in Ferralsols semi-quantitatively by comparing nutrient removal in a sisal crop with changes in soil composition under unfertilized conditions. They found that the nutrient balances for hybrid sisal with yields of 1.5 t ha$^{-1}$ on Ferralsols showed an annual shortfall of 32 kg nitrogen, 4.5 kg phosphorus, 52 kg potassium, 127 kg calcium and 47 kg magnesium ha$^{-1}$ and that sisal imposed a heavy drain on nutrients even at 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 in which the plantations are only partly planted with sisal. The land close to the sisal processing factory is generally under continuous cultivation while that further away is kept fallow after each 10-year cycle of sisal. Little is known, however, about the quantitative effect of continuous sisal cultivation and bush fallows on the chemical properties of different soil types.

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

## MATERIALS AND METHODS

### *The sisal plantations*

The research was conducted on Bamba, Kwafungo and Kwamdulu Estates in Tanga Region. Bamba Estate (4°55′S, 39°20′E) is in Muheza District and is located at the foot of the Usambara Mountain range. The total plantation area is 1810 ha but less than half the land is planted with sisal. 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 the sisal has become overgrown with trees and bushes. Kwamdulu Estate (5°10′S, 38°50′E) is located near Korogwe town (Korogwe District). The total plantation area covers 4460 ha, of which 2412 ha is cultivated with sisal. Annual fibre yields vary from 1.0 to 1.5 t ha$^{-1}$.

### *Climate and soils*

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

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

The soils on the crest are very deep and have a clayey texture with sesquioxides and kaolinite as the predominant minerals (Nandra, 1977). They are strongly weathered, intensely leached and commonly very acid, with low levels of exchangeable cations and available phosphorus. Nutrient retention capacity (CEC) is low and aluminium saturation in some subsoils reaches over 70%. As a result of the low pH and high exchangeable aluminium content, their capacity for phosphorus fixation is probably high. The soils have a ferralic B horizon ($\mathrm{CEC_{clay}} < 160\ \mathrm{mmol_c\ kg^{-1}}$) and were therefore classified as Rhodic Ferralsols according to the FAO-Unesco classification system (1988). Their physical and chemical properties are given in Table 2.

The soils on the slopes are also red and very deep but less weathered and less intensely leached. They have a clear and well structured textural B (argic), particularly when compared with 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 $\mathrm{CEC_{clay}}$ was less than $160\ \mathrm{mmol_c\ kg^{-1}}$, which means the B horizon should be classified as ferralic. The weatherable mineral content of the soils is not known, and as their properties and soil management aspects are markedly different from the soils on the crests (Rhodic Ferralsols), their field classification

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

| | | | | | Soil type (ha) | | | |
|---|---|---|---|---|---|---|---|---|
| | Area (ha) | Sisal (ha) | Rainfall (mm $a^{-1}$) | Altitude (m.a.s.l.) | Ferralsol | Acrisol | Fluvisol/ Gleysol | Other |
| Bamba | 1810 | NA† | 1044 | ~180 | 511 | 1091 | 172 | 36 |
| Kwafungo | 2330 | NA | 1057 | ~250 | 847 | 487 | 246 | 750 |
| Kwamdulu | 4640 | 2412 | 1136 | ~290 | 835 | 2565 | 1060 | 0 |

†NA, not available.

Table 2. *Physical and chemical properties of selected horizons of Rhodic Ferralsols (data modified from National Soil Service, 1988, 1989; and Hartemink, 1991)*

| | Bamba | | | Kwafungo | | | Kwamdulu | | |
|---|---|---|---|---|---|---|---|---|---|
| Sampling 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 ($H_2O$) 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 $kg^{-1}$) | 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 |

†NA, not available.

as Haplic and Ferric Acrisols was preferred in this publication. Properties of selected soil horizons of these soils are given in Table 3.

### *Soil sampling and analysis*

The choice of sample locations on the three sisal plantations was based on evidence provided by soil maps. The soil samples obtained were composites from 10 to 15 randomized spots from mini-pits taken from an area of about 0.5 ha. They were taken from two depths: 0–20 and 30–50 cm. The plantation records at Kwamdulu Estate were examined before sampling and fields from three contrasting land-use systems were identified for the purpose of this study: those that had been under continuous sisal cultivation since the 1930s or 1940s and that had carried four to six cycles of sisal; those that had been under bush fallow for the past 18 years but that had carried two or three cycles of sisal before the bush fallow; and those that had never been under sisal and were covered with a dense secondary forest. In each of these land-use systems, three to five fields on Ferralsols and Acrisols were chosen and composite topsoil samples taken as described. 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 containing soil analysis records from the Sisal Research Station, Mlingano, were consulted. They contained data from sisal fields of nearly every plantation in the Tanga region from the 1950s and 1960s and were extremely well documented. Fields from Bamba, Kwafungo and Kwamdulu Estates which had been sampled in the 1950s and 1960s and in the late 1980s and early 1990s, and which had been under continuous sisal cultivation, were chosen to investigate changes in chemical soil fertility. The soil parameters of pH in $H_2O$ (soil:water 1:2.5) and exchangeable calcium, magnesium and potassium (ammonium acetate ($NH_4OAc$) extraction at pH 7.0) were chosen because the analytical methods of the 1950s and 1960s were identical to the present methods. A linear regression using GENSTAT (version 5) was used to investigate the trend in the pH of the topsoil over the 1950s, 1960s and late 1980s of the Ferralsols ($n = 20$) and Acrisols ($n = 20$) of Kwamdulu Estate. No transformation of data was applied before regression.

## RESULTS

### *Land-use systems*

The Ferralsols that had been under continuous sisal cultivation without fertilization had a pH in $H_2O$ of 4.5 in the topsoil and 4.3 in the subsoil, accompanied by a high aluminium saturation (Table 4).

The pH of soils under bush fallow was similar to that under secondary forest. Only slight differences in the organic carbon content of the Ferralsols were found between the three land-use systems. Levels of available phosphorus were very low in all three land-use systems. The sum of exchangeable cations calcium, magnesium and potassium was low to very low in the topsoil and did not differ much

Table 3. *Physical and chemical properties of selected horizons of Haplic and Ferric Acrisols (data modified from National Soil Service, 1988, 1989; and Hartemink, 1991)*

| | Bamba | | | Kwafungo | | | Kwamdulu | | |
|---|---|---|---|---|---|---|---|---|---|
| Sampling 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 ($H_2O$) 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 |

†NA, not available.

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

| | Sampling depth (cm) | Secondary forest (3 samples) | | Bush fallow (3 samples) | | Continuous sisal (5 samples) | |
|---|---|---|---|---|---|---|---|
| | | | Cv (%) | | Cv (%) | | Cv (%) |
| pH ($H_2O$) 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) 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 C (%) | 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 |

†NA, not available.

between the systems. Exchangeable cations in the subsoils were even lower, but coefficients of variation were high. Aluminium saturation was high in the subsoil under continuous sisal cultivation but lower in the topsoil under bush fallow.

In the Acrisols the pH was considerably lower after continuous sisal cultivation as compared to 18 years of bush fallow or secondary forest. Topsoil organic carbon contents were similar in the three land-use systems (Table 5). Available phosphorus levels were only slightly higher under bush fallow than after continuous sisal cultivation, although both were very low. Under secondary forest, available phosphorus contents were moderate but variation was high. The levels of exchangeable calcium in the topsoil after bush fallow were higher than after continuous sisal cultivation, but levels of exchangeable magnesium and potassium differed only slightly. Subsoil levels of exchangeable cations did not differ much between the three land-use systems. Levels of aluminium saturation were moderate in the subsoils after continuous sisal cultivation but zero under secondary forest.

### *Historical data*

Continuous sisal cultivation on a Ferralsol at Bamba Estate reduced the pH (Table 6). Levels of exchangeable calcium and magnesium decreased sharply, while potassium was nearly exhausted after 25 years of sisal cultivation. Levels of potassium were, however, moderately high in 1966.

A similar trend was found in the Ferralsols of Kwafungo Estate. Between 1959 and 1989 the pH declined and this was accompanied by a decline in exchangeable calcium. Exchangeable potassium levels were already very low in 1959 and did not alter. At Kwamdulu Estate, the topsoil pH of a Ferralsol under continuous

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

| | Sampling depth (cm) | Secondary forest (5 samples) | | Bush fallow (3 samples) | | Continuous sisal (5 samples) | |
|---|---|---|---|---|---|---|---|
| | | | Cv (%) | | Cv (%) | | Cv (%) |
| pH ($H_2O$) 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) 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 C (%) | 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 |

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

| Soil type | Plantation | Year of sampling | pH ($H_2O$) 1:2.5 | Exchangeable cations ($mmol_c$ $kg^{-1}$) 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.

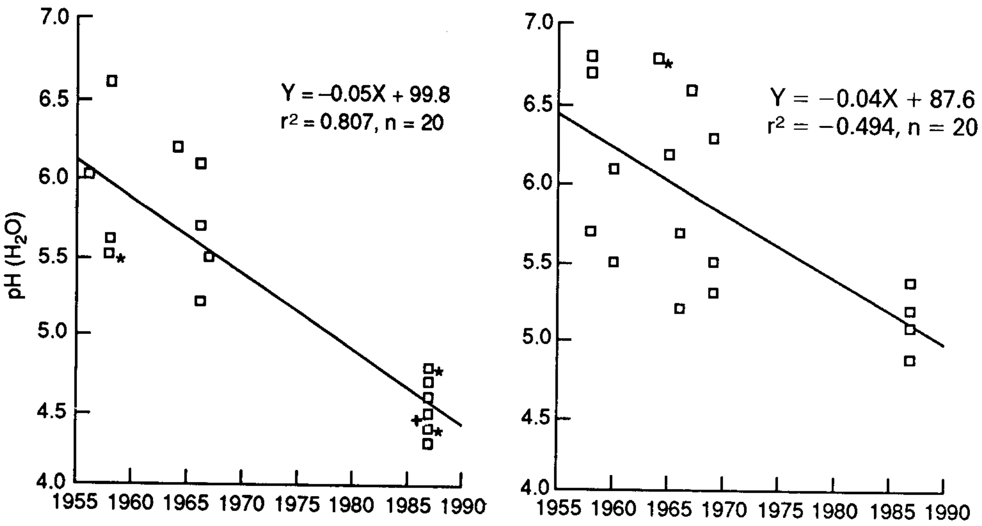

Fig. 1. Change in topsoil pH in (a) Ferralsols and (b) Acrisols under continuous sisal cultivation (* represents 2 points and + represents 3).

sisal cultivation declined from 5.6 to 4.5. There was also a sharp decline in the exchangeable calcium and magnesium levels. Potassium levels were already low in 1958.

Topsoil pH of an Acrisol at Bamba Estate declined by 1 unit between 1966 and 1990. Levels of exchangeable cations also declined sharply in these Acrisols. At Kwamdulu Estate, topsoil pH declined by 1.7 units in the period between 1966 and 1987. Exchangeable calcium declined but levels of exchangeable magnesium and potassium remained unchanged.

The topsoil pH data of the 1950s and 1960s were plotted with the 1987 data for Ferralsols at Kwamdulu Estate and a linear regression obtained, showing a decline in pH of about 0.05 per year ($r^2$ = 0.807, n = 20). In other words, the topsoil pH of the Ferralsols decreased by 1.5 between 1957 and 1987. A linear regression was also applied to the pH data of the topsoils of the Acrisols but the 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 decline in pH of about 0.04 per year (Fig. 1).

## DISCUSSION

The soil fertility was lowest under continuous sisal cultivation and highest under secondary forest for both Ferralsols and Acrisols. The decline in fertility under continuous sisal cultivation was more severe in the Ferralsols because the Acrisols were more fertile initially and possibly contained more weatherable minerals. Although the data from the 1950s and 1960s were limited, and allowance must be made for the spatial heterogeneity of the soils, comparison of historical soil data with recent data showed a decline in soil fertility combined with a sharp decrease in soil pH. The effect of continuous sisal cultivation was more severe on the Ferralsols, confirming the results of Haule *et al.* (1989).

The most dramatic effect of a bush fallow period was the increase in soil pH, accompanied by a decrease in aluminium saturation, particularly in the Ferralsols where aluminium saturation was 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 aluminium saturation, and a pH below 5.0 limits its growth (Rijkebusch and Osborne, 1965). It is also likely that a reduction in aluminium saturation levels in the subsoil increases the rooting depth of sisal, thus retarding depletion of topsoil nutrients.

The effect of bush fallows on organic carbon content was negligible in both Ferralsols and Acrisols. Very large additions of organic matter are generally required to increase the soil's carbon content and apparently 18 years of bush fallow did not supply enough (B. H. Janssen, personal communication). Furthermore, the organic carbon in the soils is very stable and strongly associated with sesquioxides and kaolinite, and it seems that the land use has little influence on it. This finding contrasts with the report of Nye and Greenland (1960) who found that the largest benefits of fallows were those due to the increase in soil organic matter. Fallowing had no effect on the exchangeable magnesium content in either soil types but exchangeable calcium and potassium increased under bush fallow. But it is disputable whether natural bush fallows are the best option for sustainable soil fertility management under sisal cultivation. Fallow vegetation is initially dominated by grasses which tend to be shallower rooted than woody plants so that there may be considerable leaching of nutrients (Grubb, 1989). In the area studied, leaching may occur in April and May when rainfall exceeds evaporation. Although the restoration of soil fertility under bush fallows is therefore likely to increase after a time once woody plants dominate the fallow vegetation, nutrients may have been lost before this. Our data show that fertility increased after 18 years of bush fallow but the increase was only slight in the Ferralsols, which have few nutrients to recycle. It is likely that the increase in fertility after bush fallow is inadequate for a new 10-year cycle of sisal production. Nye and Greenland (1960) also reported that fallows did not restore fertility when the land was cultivated for prolonged periods.

There are several options for plantation management to cope with the decline in soil fertility and the limited effects of bush fallows. Organic or chemical fertilizers can be applied, but although it has never been shown that fertilization would be economically unsound, sisal is rarely fertilized because of the supposed prohibitive costs of fertilizers and the demand on labour and transport. If chemical fertilizers are to be used, care should be taken in their selection as some nitrogen fertilizers (such as sulphate of ammonia and urea) may further increase soil acidity (Haule *et al.*, 1989). Furthermore the productivity of acid soils cannot be maintained by the use of fertilizers alone as organic inputs are also required (Pieri, 1989).

A second option is to use an improved or managed fallow to speed up the restoration of soil fertility, as suggested for infertile soils in South America (Sanchez and Salinas, 1981) and more recently in sub-Sahara Africa (Balasubramanian and Blaise, 1993). Stephens (1967) reported that fallows with elephant grass (*Pennisetum purpureum*) were much more effective than natural bush fallows in restoring soil fertility in Uganda. But Lock (1969) showed that the growth of sisal was not as good after two years of fertilized fallow with elephant grass and guinea grass (*Panicum maximum*) as on virgin soil. As a cycle of sisal removes large quantities of nutrients (Hartemink and Van Kekem, 1994), fallows may not restore soil fertility adequately if the subsoil is so severely depleted that few nutrients remain to recycle. Similar observations have been reported from West Africa by Juo and Kang (1989).

Our results therefore suggest that rotational sisal cultivation may not be a sustainable system, and that input of nutrients from fertilizers is essential. Natural and improved fallows are of little use for restoring soil fertility once the soils have been depleted of nutrients as in the case of some of the Ferralsols considered here.

*Acknowledgements.* The authors wish to acknowledge the kind cooperation of the director and staff of the Agricultural Research Institute at Mlingano in Tanzania. Useful comments on the draft version of this paper were provided by Drs E. M. Bridges (ISRIC), R. J. Buresh (ICRAF) and E.M.A. Smaling (SC-DLO).

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