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*Soil Use and Management* (1994) 10, 103–107

## Nutrient depletion in Ferralsols under hybrid sisal cultivation in Tanzania

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**Abstract.** Sisal production in Tanzania has declined sharply in the past two decades because of a decrease in the area grown and a decrease in yields. As sisal is cultivated without manuring, depletion of soil fertility is considered one of the main causes of the declining yields. This paper presents a balance of the macronutrients N, P, K, Ca and Mg for sisal grown in a plantation in NE Tanzania on deep, red clay soils (Ferralsols). Annual fibre yields declined from 2.5 t/ha in the 1960s to about 1 t/ha in the 1980s. Hybrid sisal is a demanding crop and in ten years, with a total fibre yield of 11 t/ha, about 260 kg of N, 40 kg of P, 385 kg of K, 890 kg of Ca and 330 kg of Mg are removed in the harvested leaves. A comparison of soils after two and three 10-yr cycles of sisal production showed that in the third cycle the pH decreased by 0.5 units and that exchangeable bases were decreased by fifty per cent or more. The amounts of K, Ca and Mg removed from the soil were similar to those in leaves. However, soil analyses could not detect changes in total N and available P, possibly because of the large amount of total N in the soil and the lack of precision in the N and P analyses. In the Ferralsols, potassium is likely to become deficient first, followed by magnesium and calcium. The soil has little available P, and an increase in soil acidity may decrease it further and also create aluminium and manganese toxicities. In order to maintain sisal production, fertilization with P, K, Ca and Mg is necessary, and to improve yields N must also be applied.

### INTRODUCTION

SISAL is a vegetable fibre extracted from leaves of an agave (*Agave sisalana* Perrine). In Tanzania, sisal was introduced by German settlers in 1893 (Lock, 1969). Most of the sisal is grown on estates of at least 1200 ha (Acland, 1971), which are subdivided into blocks for management purposes. Currently, sisal is planted in double rows, which are clean-weeded in the first years, and are separated by grass/weed strips. Cutting leaves starts in the third year and generally continues for 6–8 years, after which the fields are cleared. The period from planting to clearing is called one cycle, and lasts for 8–15 yr depending on the sisal variety and the agro-ecological conditions.

In Tanzania sisal is grown in three regions that are agro-

ecologically suitable for the crop and two of them have railway connections to the ports of Tanga and Dar es Salaam, (Fig. 1). In the mid-1960s Tanzania was the world market leader in sisal and the industry had an annual production of nearly 230 000 t of fibre. In 1966 and 1967 this was 35% of the total world production (Berger, 1969). Because of changes in the Tanzanian political situation and changes in the world market for sisal resulting from increasing use of synthetic fibres, production has decreased to the present level of about 30 000 t/yr. According to the Food and Agriculture Organization (1977, 1991), world sisal production declined from 670 000 t in 1961–1965 to 378 000 t in 1990.

In the 1960s the sisal hybrid 11648, bred by the Sisal Research Station at Mlingano, was introduced and is by now the most common variety. In lowland areas, on well-drained fertile soils and under good management, the hybrid has an average annual fibre production of 2–3 t/ha, in contrast to normal *Agave sisalana*, which rarely produces > 1.5 t/ha/yr. Average sisal yields in Tanzania declined sharply in the 1970s and 1980s. This was attributed to poor

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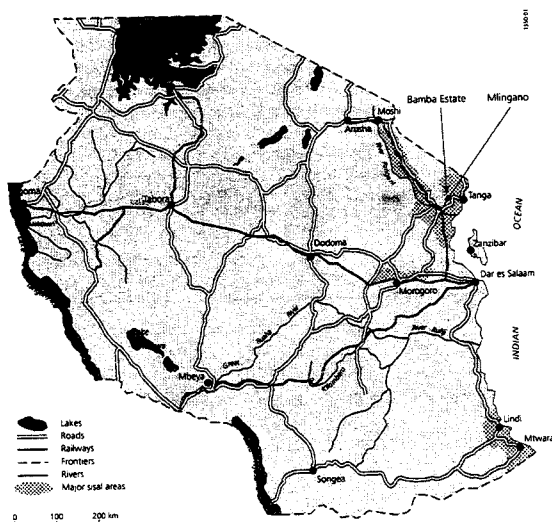


Fig. 1. Major sisal growing areas in Tanzania.

crop husbandry practices, such as mistakenly propagating other varieties than hybrid 11648, poor land management, shortage of labour and nutrient deficiencies; the last was a result of continuous cultivation without manuring. Manuring has never been common in sisal cultivation, possibly because most growers prefer large planted areas with low yields to small, intensively cultivated areas with greater yields. The Tanzanian government has developed a policy to rehabilitate the sisal industry and this prompted our study.

Our work was at Bamba Estate, in N.E. Tanzania (Tanga Region, Muheza District) at the foot of the East Usambara mountain range. In the 1950s virgin forest in the area was cleared to create Bamba Estate, one of the most recent sisal estates in the district. Most blocks of Bamba Estate have carried two cycles of hybrid sisal, each lasting about ten years. Annual fibre yields fluctuated between 1.5 and 2.5 t/ha in the 1970s and declined to less than 1 t/ha in the 1980s.

We focus on the macronutrients (N, P, K, Ca, Mg) removed by hybrid sisal from the deep, red clay soils (Ferralsols). The decline in nutrient content of the soil is compared with nutrients removed in the harvested leaves. This paper contributes to a more quantitative explanation of the causes of the decline in sisal yield under existing management measures, and suggests measures for increasing production without mining the soil.

## PHYSICAL ENVIRONMENT

### Climate

The climate in the study area is suited for sisal cultivation. The mean annual rainfall is 1044 mm with a minimum of 546 and a maximum of 1717 mm in the period from 1971 to 1989. The rainfall pattern is bimodal with peaks in April/May and October/November (Fig. 2). February and August are the driest months with less than 50 mm rain. Mean annual potential evaporation (Penman method) is

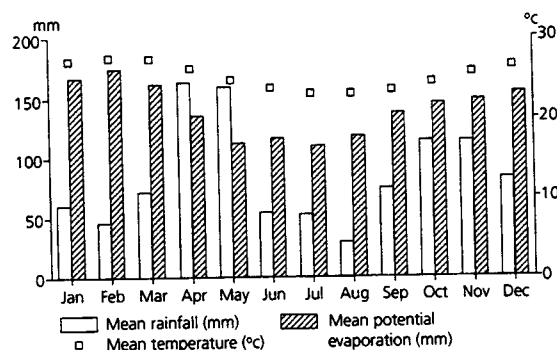


Fig. 2. Climatic data for the study area; rainfall data from Bamba Estate (1971–1989), temperature and potential evapotranspiration data from Mlingano Sisal Research Station (Agrar- und Hydro Technik, 1975).

1695 mm. Mean monthly temperatures range from 23 to 28 °C.

### Landforms and soils

The study area is part of an undulating to rolling plain, with elevations between 140 and 250 m and a local relief of 30–40 m. The soils have been formed in Precambrian gneiss. On the crests and upper slopes very deep, well-drained, dark red, strongly weathered and leached clay soils, classed as Rhodic Ferralsols, are found. They form the highest part of a catena in which Haplic Acrisols and Eutric Fluvisols also occur (Hartemink, 1991).

The Rhodic Ferralsols are over 2 m deep and have dark reddish brown, sandy clay topsoils, 20–30 cm thick, with fine to medium, granular and subangular blocky structures. The subsoils consist of dark red clay with fine subangular blocky structures. Analytical data for a representative profile are presented in Table 1. Soil analysis was done by the National Soil Service at Mlingano following internationally accepted methods (National Soil Service, 1990).

The chemical fertility of these soils is poor: they are strongly acid throughout and have very small amounts of exchangeable bases and small cation exchange capacities (CEC), especially in the subsoil. Available phosphorus is especially small, but the organic carbon content is moderately large.

## SOIL NUTRIENT DEPLETION

### Chemical soil fertility and sisal yields

To illustrate the decline in soil fertility resulting from long-term hybrid sisal cultivation, we compared chemical data for unfertilized sisal fields on which either two or three cycles of sisal had been grown. Four blocks at Bamba Estate, all Rhodic Ferralsols, were sampled. Soil samples (0–20 cm depth) were collected from fifteen points within each block, and combined into one mixed soil sample. The average annual sisal fibre yields were 2.1, 1.7 and 1.4 t/ha in the first, second and third cycles, respectively. Table 2 shows the results of the soil analyses.

Because too few data were available, they were not statistically analysed. However, there are trends between the second and third cropping cycles. The pH decreased by about 0.5 units, exchangeable calcium and magnesium were

Table 1. Analytical data for a Rhodic Ferralsol (after three sisal cycles) at Bamba Estate (Hartemink, 1991)

	Horizon and sample depths (cm)				
	Ah (0-20)	BA (20-30)	Bws 1 (50-70)	Bws 2 (90-110)	Bws 2 (130-150)
Clay (%)	35	46	50	51	53
Silt (%)	6	5	7	7	7
Sand (%)	59	49	43	42	40
pH (water) 1:2.5	5.0	5.2	5.1	5.0	5.0
pH (KCl) 1:2.5	3.9	3.9	4.0	3.9	4.0
Electrical conductivity (1:2.5 soil:solution) (mS/cm)	0.03	0.01	0.01	0.02	0.03
Organic C (%)	1.4	0.7	0.3	0.3	0.2
Total N (%)	0.09	0.06	0.02	0.03	0.05
C:N ratio	16	12	15	10	4
Available P (Bray 1) (mg/kg)	3	1	traces	traces	traces
Cation exchange capacity (ammonium acetate pH 7.0) (mmol <sub>c</sub> /kg)	79	67	67	63	65
Exchangeable Ca (mmol <sub>c</sub> /kg)	16	15	9	1	2
Exchangeable Mg (mmol <sub>c</sub> /kg)	5	4	2	5	8
Exchangeable K (mmol <sub>c</sub> /kg)	0.9	0.3	0.2	0.1	0.3
Exchangeable Na (mmol <sub>c</sub> /kg)	1.1	0.6	0.4	0.1	0.5
Base saturation (%)	29	30	17	10	17
Exchangeable Al (mmol <sub>c</sub> /kg)	11.1	9.2	10.4	13.0	12.1
Exchangeable Al (% of CEC)	14	14	16	21	19

Table 2. Soil chemical data (0-20 cm depth) of Rhodic Ferralsols after two or three cycles of sisal cultivation (Hartemink, 1991)

	Block 1 (2 Cycles)	Block 2 (2 Cycles)	Block 3 (3 Cycles)	Block 4 (3 Cycles)
pH (water) 1:2.5	5.6	5.7	5.0	5.4
pH (KCl) 1:2.5	4.4	4.6	3.9	4.1
Organic C (%)	1.8	1.6	1.5	1.9
Total N (%)	0.12	0.13	0.12	0.16
Available P (Bray 1) (mg/kg)	2	1	3	4
Exchangeable Ca (mmol <sub>c</sub> /kg)	28	36	6	19
Exchangeable Mg (mmol <sub>c</sub> /kg)	13	18	3	6
Exchangeable K (mmol <sub>c</sub> /kg)	4.8	6.8	0.8	1.6
Cation exchange capacity (ammonium acetate, pH 7.0) (mmol <sub>c</sub> /kg)	111	123	64	111
Base saturation (%)	44	52	16	25
Exchangeable Al (mmol <sub>c</sub> /kg)	0	0	11.4	7.2

decreased by fifty per cent or more, and exchangeable potassium decreased even more. The removal of bases from the soil was accompanied by an increase in exchangeable Al. Hardly any change in total N was detected. The amounts of available P were very small in all the samples, and the differences of 1-2 mg/kg can probably be attributed to analytical error.

Lock (1953) was one of the first to report that sisal rapidly depletes soil nutrients. Yields of continuously cultivated land declined from 14.4 t/ha in the first cycle to 11.7 and 5.9 t/ha in the second and third cycles, respectively; in the third cycle the sisal looked unhealthy and suffered from numerous deficiency symptoms. In the 1960s there were many fertilizer experiments, mainly at the Mlingano Sisal Research Station (Tanga Region, Muheza District). The results were summarized by, among others, Lock (1969) and De Geus (1973). However, no link between soil chemical status and the fertilizer recommendations was made, although Rijkebusch & Osborne (1965) were among the first to classify sisal soils according to their fertility status. In the late 1980s, when the sisal rehabilitation programmes started, the National Soil Service (1988a) concluded that

soil fertility depletion, especially of the deep, red clay soils, could have contributed considerably to the decrease in sisal production.

#### Nutrient removal

To estimate the quantity of nutrients removed in the harvested sisal leaves, we need to know the nutrient content of the leaves. However, published data show wide ranges (Lock, 1969; Muller, 1964). Lock (1969) suggested that there are relations between age of the plant, soil fertility and the nutrient content of the leaves. We used the data given by Osborne (1967) for the harvested leaves of the sisal hybrid 11648 (Table 3), because they refer to sisal grown on the deep red soils in the Tanga Region.

Yield data were obtained from the estate's records (Hartemink, 1991). For the third cultivation cycle, yields averaged 11 t/ha. Table 3 gives the estimated amounts of nutrients removed with harvested leaves in this cycle.

Assuming that all the nutrients came from the upper 20 cm of the soil, where most of the sisal roots are concentrated, the nutrients removed from the soil (Table 4) can be calculated from the average difference in soil nutrient con-

**Table 3.** Nutrients (kg) removed with harvested sisal leaves in the third cultivation cycle

Removed	N	P	K	Ca	Mg
per tonne of fibres§	23.5	3.5	35	81	30
per cycle per hectare†	258.5	38.5	385	891	330
per year per hectare‡	37	5.5	55	127	47

§Osborne (1967).

†Total removal per cycle (total 11 t of fibre).

‡Average removal per productive year (seven per cultivation cycle).

**Table 4.** Calculated quantities of nutrients removed from the upper 20 cm of the soil (based on soil analyses) and with the harvested leaves (based on leaf analysis data from Osborne, 1967) by the third cycle of sisal

Nutrient	Difference in soil nutrients content between 2nd and 3rd cycles (mmol <sub>c</sub> /kg)	Loss from topsoil (kg/ha)	Removed with leaves (kg/ha)
Ca	19	988	891
Mg	11	348	330
K	4.6	468	385

tents between the second and third cycles. In the calculation an average bulk density of the topsoil of 1.3 kg/dm<sup>3</sup> was used (Hartemink, unpublished data). The calculated quantities of nutrients removed from the soil were of the same order of magnitude as the amounts in the crops (Table 4).

## DISCUSSION

Large quantities of nutrients, especially of N, Ca, Mg and K, are removed from the soil in harvested sisal leaves. Continuous sisal cultivation without applying fertilizers inevitably leads to soil nutrient depletion and consequently to smaller sisal yields. This is especially true for soils with very small inherent nutrient reserves, such as Ferralsols. The quantities of nutrients remaining in the soil after the third cycle are approximately 650 kg Ca/ha, 145 kg Mg/ha and 120 kg K/ha, which are all less than those removed with the leaves in the third cycle. Therefore sisal yields of the fourth cycle will certainly be less than 11 t/ha, unless fertilizers are applied.

A nutrient balance was made (Table 5) according to Stoorvogel & Smaling (1990); five input and five output factors were considered. At Bamba Estate, the inputs through organic manure, mineral fertilizer and sedimentation were all zero. The only inputs are through atmospheric deposition and biological N fixation which can be calculated using the regression equations given by Stoorvogel &

**Table 5.** Nutrient balance for sisal (kg/ha/yr)

Input/output	N	P	K	Ca	Mg
Atmospheric deposition	4.5	1	3	na	na
Biological fixation	4	0	0	0	0
Product and residue	37	5.5	55	127	47
Leaching	1.5	0	0	0	0
Gaseous losses	2	0	0	0	0
Shortfall	32	4.5	52	127	47

na = not available, probably ≤ 1.

Smaling (1990). The outputs in the leaves are taken from Table 3, and leaching losses and gaseous N losses were also calculated according to Stoorvogel & Smaling (1990). Leaching losses are in fact very small or zero as no fertilizers are applied and the nutrient uptake is large. Losses through erosion were assumed to be zero as grass strips are maintained between the sisal rows; the rows are usually planted along the contours, and erosion has not been observed.

The balance calculation shows serious shortfalls of N, P, K, Ca and Mg. The shortfall in N could have been met by a net mineralization of the soil organic matter. The Bamba soils contain an average of 1.7% organic C and have a C:N ratio of 13; a 1% mineralization rate, which is at the low end of what Sanchez (1976) reported for tropical savannas, releases 34 kg N/ha/yr in the top 20 cm of the soil. Such changes in total N content are within the range of analytical error. The net amount of phosphorus removed yearly is small (4.5 kg/ha). The available P in the soil is, however, very small. Moreover, the decrease in pH experienced after several cycles of sisal production will further decrease P availability. This may cause poor establishment of young sisal plants; according to Lock (1969) they need a soil P content of >7 mg/kg for rapid establishment. The soils of the study area have smaller P contents and therefore P fertilization is needed. The amount of exchangeable K in the soil after the third cycle (120 kg/ha) is about 30% of the quantity needed to produce 11 t of fibre in one cycle. Potassium deficiency leads to 'banding disease', which is commonly observed in old sisal fields in East Africa (Lock, 1969). Similarly, Ca and especially Mg are likely to become deficient. Moreover, the amount of exchangeable Al increases with time and becomes toxic. The decrease in pH also increases the mobility of Mn, which may become toxic (Muller, 1964). Ca, Mg and K are mainly supplied by the soil mineral reserves, but Ferralsols have hardly any weatherable minerals and therefore have very limited reserves of Ca, Mg and K.

## MANAGEMENT IMPLICATIONS

Continuous sisal growing cannot be sustained without applying organic or chemical fertilizers. At low yield levels the natural N demand of the crop can be met by deposition, fixation and mineralization. This could be improved by planting leguminous crops in the inter-rows, as suggested by the Tanganyika Sisal Growers' Association (1965). However, to obtain fibre yields more than 2 t/ha, N must be added. The small amounts of soil P also necessitate P fertilization, especially at planting stage, to promote good establishment of the young plants.

As well as applying K, as is generally recommended, maintenance applications of Ca and especially Mg are also necessary on soils with small nutrient reserves. Soil tests to assess its nutrient status are essential before replanting with sisal. The International Fertilizer Industry Association (1992) recommends maintaining the pH of sisal soils between 5.5 and 6.5. Soil pH should not be allowed to decrease below 5.5 to avoid Al and Mn toxicities (Sanchez, 1976). If the pH becomes too low, liming with dolomitic limestone is recommended to supply both Ca and Mg (International Fertilizer Industry Association, 1992).

An ecologically sound way of manuring is to return the

sisal waste from the processing factory to the fields. In this way, most of the nutrients removed in the leaves are returned to the soil (Lock, 1969). In practice, however, this is not easy to achieve because of the demands on labour and transport. A study by the National Soil Service (1988b) showed that long fallow periods (15–20 years) can also assist in restoring soil fertility.

Of the various management options for maintaining or improving the fertility of sisal soils, the most attractive depend on economic factors and pressure on the land.

### ACKNOWLEDGEMENTS

We thank soil scientist Mr H. Van Reuler for his critical and helpful comments on the manuscript.

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*Soil Use and Management* (1994) 10, 107–111

## Nitrogen transformations in a peaty soil improved for pastoral agriculture

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**Abstract.** Microbial transformations and chemical distribution of N were compared in two upland stagnohumic gley soils at the same site. In 1981 one soil was improved for more intensive agriculture by lime and fertilizer applications and reseeded with a grass/clover mixture. The other soil (referred to here as unimproved) was also reseeded in 1981, but no lime was added and the sward has subsequently reverted to rough grazing land. Improvement resulted in greater soil microbial activity. The improved soil showed greater rates of denitrification, net N immobilization and N fixation (acetylene reduction) and contained more microbial biomass N than the unimproved soil. However, no major differences in the distribution of organic N fractions were detected. This indicates that a large amount of the soil N present before improvement did not undergo mineralization and remained unavailable to plants.

### INTRODUCTION

In northern England, stagnohumic gleys and stagnohumic podzols are the predominant soils of hill and upland areas (Jarvis *et al.*, 1984). These soils generally have low pH, are

imperfectly drained, and contain substantial amounts of organic C and N in the upper horizons (Floate, 1977). The soils have limited nutrient availability (Floate, 1970) which, together with the cool and wet climatic conditions, has led to their principal agricultural use being extensive sheep rearing (Jarvis *et al.*, 1984). During the 1970s and 1980s large areas of hill and upland were improved to provide good quality grazing and allow more intensive sheep rearing

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