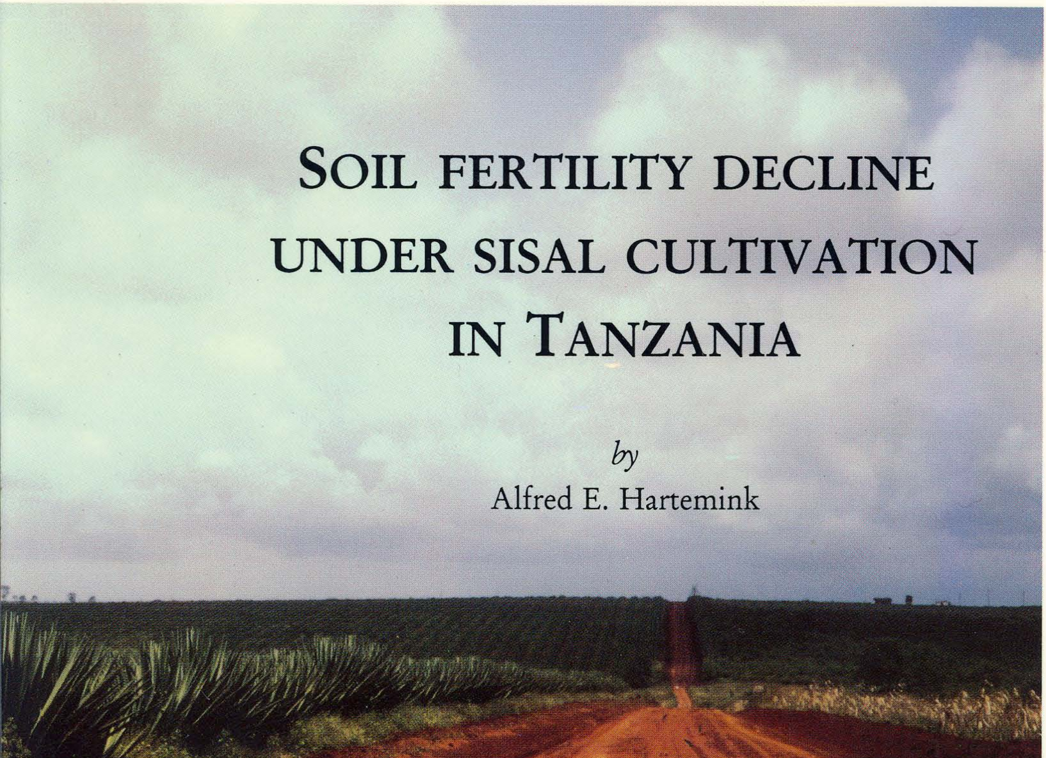

SOIL FERTILITY DECLINE UNDER SISAL CULTIVATION IN TANZANIA

by

Alfred E. Hartemink

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A review of *on-plantation* research
on soil fertility decline
in Tanga Region, Tanzania.

Front cover:
Hybrid 11648 on Ferralsols at Kwamdulu estate in Korogwe district.

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H.J.A. HOFLAND *CS, 16 juni 1995*

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(1) Better unknown than not written at all.

CONTENTS

PREFACE

What tea is to Sri Lanka and coffee is to Brazil, sisal was to Tanzania. An enormous area had been put under sisal in the 1960s, and Tanzania was the world's largest sisal producer. The centre of sisal production was Tanga Region, which had 73 plantations producing over 130,000 tonnes of sisal fibre annually or two-thirds of the national production. The sisal industry was by far the largest employer and a total of 133,400 or one-third of the classified employed population of Tanzania worked in sisal. Those days of the 'white gold' are over for many reasons, and the current national production is around 33,000 tonnes annually.

In order to revive sisal production, large rehabilitation programmes were launched in the mid 1980s following the devaluation of the shilling and a 50% retention allowance on sisal exports. Foreign companies were permitted to buy shares in the nationalized estates, and ambitious replanting programmes were initiated. At that time, an interesting interview with the captains of Tanzania's sisal industry appeared in the *Financial Times* (10th May 1989). They mentioned that nationalization of sisal plantations, marketing problems and low sisal prices were the main causes why the production had decreased and the sisal industry had so dramatically collapsed since the 1960s. None of them mentioned the decline in soil productivity nor any other agronomic factor as a possible cause.

As part of these sisal rehabilitation programmes, soil surveys of several plantations in Tanga Region were conducted, and I became involved in these surveys as a research graduate at the National Soil Service in Mlingano in 1987. During the survey work, the idea emerged that poor agronomic practices and soil fertility decline may have contributed to the decrease in sisal production. Soil sampling programmes were set up to further investigate the soil fertility decline resulting from continuous sisal cultivation. The results of these investigations were published in numerous soil survey and site evaluation reports in the late 1980s and early 1990s, and more recently in some journal articles. However, a regional overview of soils under sisal cultivation and a compilation of data on fertility decline in different soils, was still lacking. This account aims at a first step in that direction, and assesses the decrease of sisal production from a soil scientist's perspective.

In Chapter 1, a concise and general introduction to the study of soil fertility decline is given. This is followed by a discussion on the rise and fall of sisal production in Tanzania in Chapter 2. In the third chapter, the physical environment of Tanga Region is described including details on climate, geology and soils used for sisal cultivation. Chapter 4 analyzes the extent of soil fertility decline under sisal cultivation based on historical soil data, soil samples from different land-use systems, and by calculating nutrient balances. In the last chapter, options for soil fertility management are discussed followed by the Summary and Conclusions.

Throughout this account I have aimed at a quantitative and descriptive treatment of each subject. Little effort was undertaken to integrate advanced statistical techniques or fancy models since the data set was limited and scattered. Moreover, it is felt that the observational approach has still a crucial role to play in soil science, and therefore most data are simply presented as we have found them. Preference has been given to my own field observations and laboratory data wherever possible, which may have resulted in some lack of balance in treatment. Hence, this account is a personal interpretation of soils and soil fertility decline under sisal cultivation based on fairly extensive field experience coupled with data drawn from the literature. The account is, however, not meant to be an exhaustive review of the literature on soil fertility decline but emphasizes the more pressing and contemporary problems of the soils under sisal cultivation in Tanga Region.

There are other omissions which need to be mentioned: little attention is paid to soil physical properties as those data were rarely collected during the soil surveys. In describing the soils of Tanga Region and analyzing the soil fertility decline, the data are presented for Major Soil Groupings of the FAO-Unesco classification system. Only the Major Soil Groupings level is given which is the highest in the system, and no division is made to Units or Phases to avoid a cacophony of soil classification terms. For all presented soil analytical data, a reference is provided in case a full classification is required. The analysis of soil fertility decline is mostly on a concentration base (e.g. $\mathrm{mmol_c\ kg^{-1}}$) instead of a volumetric base ($\mathrm{kg\ ha^{-1}}$) which would have been preferable, but this was not possible as bulk density data were only available from a very few soil profiles. Linking soil fertility decline to sisal yields could only be carried out for a few sites due to the lack of reliable yield data. There are no data presented on soil fertility decline under sisal cultivation from other regions or countries, because they are not available.

Despite these omissions, it is hoped that this account will be of use for those concerned with the rehabilitation of sisal plantations. It is also written as a case of soil fertility decline resulting from agricultural activities, and may exemplify that soil fertility in sub-Saharan Africa is a matter of concern.

Wageningen - Amsterdam
September 1995

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Finally, my greatest indebtedness is to Ariane and Bertrand who have borne patiently the period when this account claimed my attention to their exclusion.

1 INTRODUCTION

Soil resources are exhaustible. Nevertheless, mankind is not careful with these resources and soils are exposed to increasing degrees of stress. As a result, soils deteriorate and this is occurring in all continents. Nearly two billion ha in the world are affected by human-induced soil degradation of which one quarter is located in Africa. A wag once made the observation that albeit many soils in Africa are very old, their problems are only beginning to emerge.

Soils of Africa

Africa is not particularly blessed with extensive areas of naturally fertile soils. Although some land is amongst the most productive in the world, vast areas have soils which are shallow, saline, poorly drained or eroded. About a quarter of the 2,500 million ha of land in Africa, has soils with low-activity clays (Lal, 1990). These soils are classified as Oxisols and Ultisols in Soil Taxonomy, comparable to Ferralsols, Acrisols and Lixisols in the FAO-Unesco system. The soils commonly have a low inherent fertility because of intensive leaching and a high degree of weathering (Sanchez, 1989).

FAO (1986) estimated that 46% of the total land area in Africa has soils with a low cation exchange capacity (CEC), 22% with aluminium toxicity, 14% with high phosphorus fixation, and 22% with low potassium supply. Sanchez & Logan (1992) came up with different figures and estimated that 20% of the land in Africa has low nutrient reserves, 16% suffers from aluminium toxicity and that 13% of the land had soils with low CECs. It is evident that these soils with their low inherent fertility, need to be carefully managed in order to remain productive (Sanchez & Buol, 1975).

Soil degradation

Several types of human-induced soil degradation can be identified like water and wind erosion, compaction, salinization etc. Erosion has been the focus of soil research for a long time since it is the most visible and complete form of land degradation. A recent review of erosion studies in sub-Sahara Africa was prepared by Lal (1995).

Of no less importance on the soil productivity is the impact of chemical degradation which includes nutrient depletion. It is a very gradual process and requires repeated laboratory measurements and long-term observations for proper assessment. For these reasons nutrient depletion was often overlooked and in one of the first documents on land degradation prepared by the FAO (1971), it was not included.

In recent years, a number of studies have shown that nutrient depletion is a serious problem in many of the soils of sub-Sahara Africa. The cause for the depletion 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. Although nitrogen can be replaced wholy or partly through biological fixation, other nutrients must be supplied from the soil reserves through desorption of adsorbed nutrients, mineralization of organic matter, weathering of primary minerals, or dissolution of fixed nutrients. Depletion occurs when the total nutrient reserves are reduced to levels which are inadequate for crop production or when the rate at which nutrients are mobilized is lower than the crop demands (Logan, 1990).

Soil chemical degradation affects about 62 million ha of land in Africa, mainly through the loss of nutrients resulting from agricultural activities (Oldeman, 1994). At a semi-quantitative level, Stoorvogel & Smaling (1990), calculated depletion of nitrogen, phosphorus and potassium at a supra-national scale for sub-Saharan Africa. Based on the difference in nutrient inputs with atmospheric deposition, biological nitrogen fixation, manure and fertilizers, and nutrient outputs with crop removal, leaching, erosion and gaseous losses, a negative balance was found for each of those nutrients in many countries. Using FAO production figures and forecasts, they found that the nutrient balance would be even more negative by the year 2000, notably for nitrogen and potassium. It was concluded that there is gross nutrient mining in sub-Saharan Africa, particularly in the eastern part of the continent.

Following the methodology of the supra-national study, NPK balances were calculated at a lower aggregation level in order to overcome some of the scale-inherent simplifications (Smaling *et al.*, 1993). For Kisii district in Kenya, they found large differences in the nutrient balance between land-use systems, but overall the balance was negative for each of three major plant nutrients (NPK). The losses were particular high under annual crops like maize and pyrethrum. The lowest depletion rates were found under perennials like tea. Similar observations on nutrient depletion were made in Nigeria (Singh & Balasubramanian, 1980), in Northern-Cameroon (Gigou, 1982 cited by Ssali *et al.*, 1985), in two regions in Mali (Van Duivenbooden, 1990; Van Der Pol, 1992; Van Der Pol & Traore, 1993), and in other countries of West Africa (Gigou *et al.*, 1985; Pieri, 1989a). Many of these studies on nutrient depletion have in common that they use aggregated soil data and pedo-transfer functions resulting from regression analyses between two or more soil parameters.

Very few quantitative data are available on soil fertility decline at the farm level, and a number of recent studies have stressed the need to fill this gap (e.g. Janssen *et al.*, 1990;

Smaling, 1993). To establish evidence for soil fertility decline at the farm level, it would be required to monitor the nutrient status of different compartments at regular intervals. Such research is time consuming and difficult because of the soil spatial and temporal variability and the variability in farming systems (Almekinders *et al.*, 1995). The difficulties have been recognized since the early beginning of soil fertility research, and that explains why most soil fertility research takes place at well-fenced stations under conditions which usually differ from the farmers around the station. That is also one of the reasons why soil fertility research in East Africa has had limited impact on food production (Muchena & Kiome, 1995). Much is expected from the *on-farm* research where trials are conducted on farmers' fields (Franzel & Van Houten, 1992; Izak & Swift, 1994). For soil fertility research, these types of studies are beset with experimental design problems (Nelson, 1987).

On-plantation research

The data presented in this account were not collected at a research station, in greenhouses, with on-farm research, nor generated with some kind of model. The data result from strategic soil sampling schemes on large sisal plantations, hence the term *on-plantation* research. The basic aim of the soil sampling was to detect differences in chemical properties as a result of prolonged sisal cultivation. The soils of the sisal plantations were uniformly cropped and managed for decades and the land-use history was well known, which provided a suitable base for such soil sampling schemes. The sampling was conducted as part of detailed soil surveys in Tanga Region (Tanzania) during the late 1980s and early 1990s.

In one of the first soil survey reports of sisal plantations, the National Soil Service (1987b) tentatively concluded that the soil fertility of Ferralsols had gradually declined as a result of continuous sisal cropping. After a number of detailed soil surveys, it was concluded that fertility decline could easily take place under sisal as the crop imposes a heavy drain on nutrients and because the sisal is rarely fertilized (National Soil Service, 1988d). It was also noted that soil fertility decline differs largely between plantations. In the years that followed, increasing evidence of soil fertility decline under sisal cultivation was presented in various reports and some journal articles. This account brings together the available data on soils under sisal cultivation, and compiles and underpins the soil fertility decline perception. It serves the following purposes: (i) to present information on soils under sisal cultivation in Tanga Region, (ii) to compile and expand the data on soil fertility decline (iii) to compare differences in soil fertility decline between, and within, Major Soil Groupings (iii) to discuss options for soil fertility management.

The main sources of information for writing this account were publications of the National Soil Service and the present writer. In these publications, soil sampling procedures and soil analytical methods are described in detail of which a summary follows below: At each plantation, soil samples were collected from soil pits, and as composite topsoil samples containing 10 to 15 subsamples from ca. 0.5 ha. All soil samples were analyzed at the Laboratories of the National Soil Service in Mlingano. The methods for analysis are described in National Soil Service (1990d) and were taken from Page *et al.* (1982)(1).

Some of the consulted publications contained errors varying from miscalculations to wrong soil classification but these could be easily corrected. Throughout this account, the FAO-Unesco Revised Legend (1988) for soil classification is used. A number of profiles from the soil survey reports were re-classified following the revised legend. Diagnostic properties of the Major Soil Groupings discussed, are described in TABLE 1.1 including their approximate equivalent in the USDA Soil Taxonomy system (Soil Survey Staff, 1992). Detailed descriptions of the Major Soil Groupings can be found in FAO-Unesco (1988) and Driessen & Dudal (1991).

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(1) The following soil analytical methods were used: Particle size analysis by pipette method (pit samples) or hydrometer (composite topsoil samples); organic carbon by Walkley & Black; total nitrogen by semi-micro Kjehldalh digestion; pH H_2O in 1:2.5 suspension of soil and water; pH KCl in a 1:2.5 soil and 1 *M* KCl suspension; EC in 1:2.5 suspension of soil and water; exchangeable cations Ca, Mg, K, Na and CEC percolation with 1 *M* NH_4OAc followed by spectophotometer (K, Na), AAS (Ca, Mg) and titration (CEC); available P with Bray I for soils with $pH < 7$ and Olsen for soils with a $pH > 7$; exchangeable acidity (H, Al) extraction by 1 *M* KCl. Results of soil analysis were reproduceable and the outcome of blind duplicate samples was satisfactory.

The following calculations of exchange properties were made:
Base saturation BS% = ((Ca+Mg+K+Na)/CEC)*100
ECEC = Ca+Mg+K+Na+H+Al
Aluminium saturation Al% = (Al/ECEC)*100
Exchangeable sodium ESP% = (Na/CEC)*100

Soil units used in this account are:
% for particle classes (1% = 10 g/kg);
% for organic carbon and total nitrogen (1% = 10 g/kg);
$mmol_c\ kg^{-1}$ for CEC and exchangeable cations ($10\ mmol_c\ kg^{-1} = 1$ me/100g);
$mg\ kg^{-1}$ for available P ($1\ mg\ kg^{-1} = 1$ ppm).

TABLE 1.1 *Major Soil Groupings (FAO-Unesco, 1988) discussed in this study and the approximate equivalent in USDA Soil Taxonomy (Soil Survey Staff, 1992).*

Major Soil Groupings	Short description	USDA-Soil taxonomy equivalent[2]
Acrisols	Soils with a base saturation < 50% and low activity clays. The argic B horizon has a CEC_{clay}[1] < 240 $mmol_c\ kg^{-1}$.	Ultisols
Alisols	Soils with a base saturation < 50% and high activity clays. The argic B horizon has a CEC_{clay}[1] > 240 $mmol_c\ kg^{-1}$	Ultisols
Arenosols	Sandy, generally weakly developed soils, but without fluvic properties.	Psamments
Cambisols	Young soils without translocation of soil material, only a Cambic B horizon.	Inceptisols
Ferralsols	Soils with high sesquioxide content and kaolinite. The B horizon has a CEC_{clay}[1] < 160 $mmol_c\ kg^{-1}$.	Oxisols
Fluvisols	Recently deposited soils of alluvial sediments.	Fluvents
Gleysols	Soils with gleyic properties resulting from poor drainage and anaerobic conditions which dominate the top 50 cm.	Aquic suborders
Leptosols	Weakly developed soils which are less than 30 cm deep.	Lithic subgroups
Lixisols	Soils with a base saturation > 50%. The B horizon has a CEC_{clay}[1] < 240 $mmol_c\ kg^{-1}$.	Alfisols
Luvisols	Soils with a base saturation > 50% and CEC_{clay}[1] > 240 $mmol_c\ kg^{-1}$ throughout the profile.	Alfisols
Phaeozems	Soils with a very thick A horizon which is rich in organic matter, and a base saturation > 50%.	Mollisols
Plinthosols	Soils with > 25% plinthite in the top 50 cm which hardens on exposure to the atmosphere.	Plinthic groups
Vertisols	Dark, predominantly smectite rich clays with shrinking/swelling properties and slickensides.	Vertisols

[1] $CEC_{clay} = (CEC_{soil} - 3.5 * \%\ organic\ C) * (100/\%\ clay)$

[2] In USDA Soil Taxonomy the CEC_{clay} is not corrected for organic carbon.

2 SISAL

Sisal is a vegetable fibre extracted from leaves of an agave (*Agave sisalana* Perrine). It accounts for a large proportion of the world supply of hard fibres which form the raw material for cordage like ropes, cords, and agricultural twines but it is also used for weaving mats and bags. In this chapter the history, cultivation and production of sisal in Tanzania is discussed including a section on the soil requirements of the plant.

2.1 History and Cultivation

Sisal was introduced in Tanzania in 1893 by the German agronomist Dr Richard Hindorf. The first 62 sisal plants, originating from Florida, were planted at Ras Kikogwe near Pangani in Tanga Region (see photograph in the back). These plants were the foundation of the sisal industry in East Africa. Until that time, the German settlers had not found a suitable crop for the coastal plain, but sisal appeared well adapted to the environmental conditions.

In Tanzania, the crop is grown at large plantations of 1,000 to 6,000 ha. Large sisal areas can be found between Tanga and Moshi, between Dar er Salaam and Morogoro, and in the south near Mtwara and Lindi (FIG. 2.1).

In 1934, the Sisal Research Station was founded at Mlingano in the heart of Tanga Region. One of the achievements of this station was the breeding of the long fibre agave hybrid 11648. Presently, most of Tanzania's sisal fields are planted with hybrid 11648 which replaced the lower yielding *Agave sisalana.* The hybrid, however, is more susceptible to diseases than *Agave sisalana.* The fibre from the hybrid is similar to that of *Agave sisalana* and commercially no distinction is made.

The best planting material is obtained from bulbils (small plantlets) which are raised in nurseries for about two years. In general, two to three years after transplanting to the field, the first leaves can be cut, and cutting may continue up to eight years when the plants start flowering (poling) and leaf production ceases. The period from planting to flowering lasts about 10 years and this is termed a *cycle.* The length of a cycle depends on the growth rate of the sisal plants which is influenced by temperature, rainfall and soil fertility. On good soils and with proper management, one cycle of hybrid 11648 may yield 25 t fibre ha^{-1}.

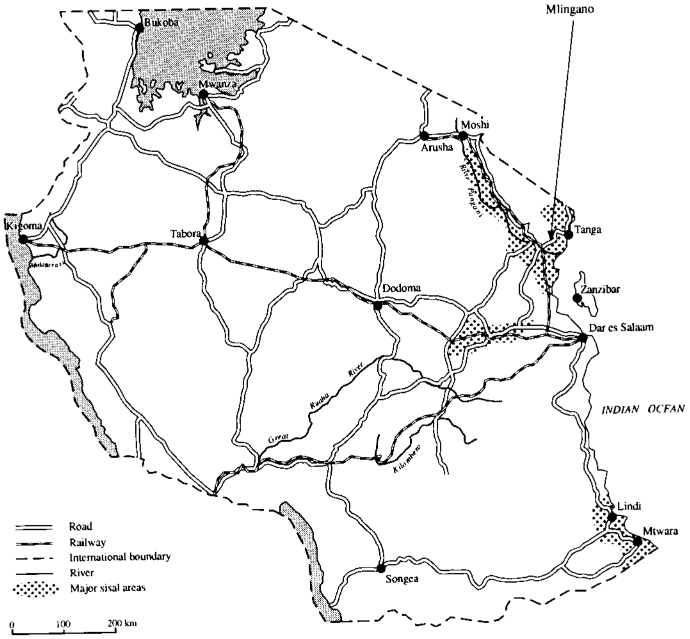


FIG. 2.1 *Main sisal areas in Tanzania.*

After each cycle the land is cleared with heavy machinery and the debris burnt, then the land is harrowed and replanted. Most sisal growers use a rotational system by which the land is left under natural fallow for 10 to 20 years after each cycle of sisal. Despite the heavy drain of nutrients by sisal (Hartemink & Van Kekem, 1994), fertilization and the planting of cover crops have never been widely adopted by sisal growers.

2.2 Sisal Production

The first sisal of Tanzania was exported in 1898, and accounted to 7.5 tonnes in 1900. Exports rose to 1,400 tonnes in 1905 increasing to 20,000 tonnes by 1913. Sisal growing was then firmly established in Tanzania (Lock, 1969). With the construction of railways, sisal was planted up-country and production rapidly increased. Most of Tanzania's sisal was planted in Tanga Region with Muheza and Korogwe District as the main sisal areas.

War in 1914 brought a halt to the expansion and production of sisal-growing in Tanzania. During the British administration that followed, production revived and annual exports rose to nearly 50,000 tonnes in 1930. There was no decline in sisal production during the economic crisis of the 1930s, and annual exports reached 100,000 tonnes by 1938 (FIG. 2.2).

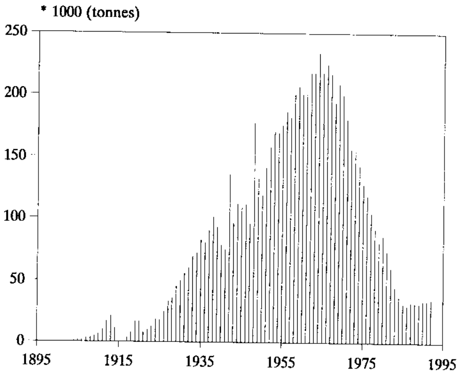


FIG. 2.2 *Total sisal production of Tanzania between 1895 and 1992 (Hartemink & Wienk, 1995).*

After the Japanese invasion of the Philippines and Indonesia in 1941 which were important hard fibre producers, East Africa became the main producer. Sisal production increased steadily in the 1950s, and the highest production was achieved in 1964 with 234,000 tonnes of which 136,000 tonnes were produced in Tanga Region. In those years, Tanzania was the world market leader in hard fibres, and agricultural export earnings were more than 80% of the national income.

However, from 1964 onwards, production declined and in the early 1980s, sisal production was down to 38,000 tonnes. It further decreased to 32,000 tonnes in 1989, which was the same production level as in 1927. The decrease in sisal production is attributed to a number of factors, but the decline in yield and extent of the sisal areas are considered main factors (FIG. 2.3).

Area and yield decline

The area under sisal decreased from 227,000 ha in 1964 to 63,000 ha in 1986 (FAO, 1993). An important cause for this decline were low sisal prices which decreased from 713 USD t^{-1} in 1979 to 519 USD t^{-1} in 1987, and further decreased to around 300 USD t^{-1} in 1992 (International Monetary Fund, 1988; K.P. Legg, pers. comm.). This decrease in prices was the result from competition with synthetic fibres of which the price decreased as a result of low oil prices. The demand for sisal fibre was depressed and sisal binder twine was replaced by twine of polypropylene. Another decrease in sisal prices followed the collapse of the former Soviet Union which was an important sisal importer.

Besides low prices, the area decline also resulted from the nationalization of sisal plantations during the late 1960s and early 1970s (Kimaro *et al.*, 1994; World Bank, 1994). Poor management following the nationalization, resulted in the abandoning of many sisal plantations. The decline in sisal area was further accelerated by the shortage of labour caused by low wages coupled with unpopularity of the work. Mechanization problems resulting from lack of spare parts and investments for tractors, lorries and decorticators further reduced the area under sisal.

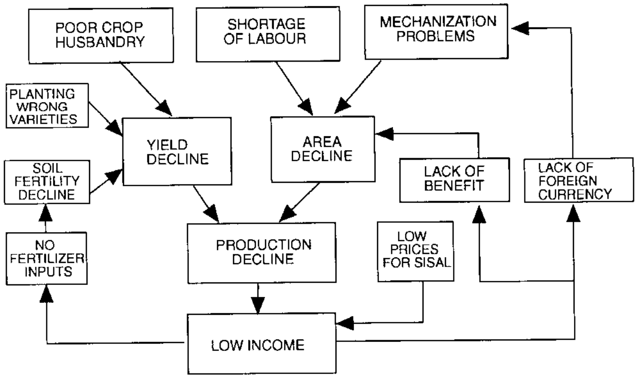


FIG. 2.3 *Simplified relational diagram of factors governing sisal production decline in Tanzania (Hartemink & Wienk, 1995).*

The combination of low sisal prices and inadequate management practices, resulted in an extensification of sisal growing. Crop husbandry standards fell and as a result yield levels dropped. Hartemink & Wienk (1995) have shown that the average yield from 5 sisal plantations in Tanga Region decreased from 1.9 t ha^{-1} yr^{-1} to 1.2 t ha^{-1} yr^{-1} between 1968 and 1988 (FIG. 2.4). Likewise leaf length decreased as may be measured from the percentage fibre grade 3L+1 representing the longest fibres (> 90 cm). The percentage of 3L+1 from a plantation near Korogwe decreased from 90 to 35% of the total sisal production between 1968 to 1988 (FIG. 2.4). Leaf length has a marked effect on fibre yield and although the fibre percentage is not influenced by the leaf length, the weight of a leaf is proportional to the square of its length (Wilson, 1951). This means that long leaves yield relatively more fibre than short leaves. For example, with the fibre percentage being constant, a 3-ft leaf yields 2.25 times more fibre than a 2-ft leaf, or in other words with the same number of leaves harvested, a field with 2-ft leaves would yield 1 t fibre ha^{-1} while a field with 3-ft leaves would yield 2.25 t fibre ha^{-1}.

Lower yields and shorter leaves were also attributed to the unintentional planting of less productive Agave hybrids. In the late 1980s, it was suggested that many fields had not been planted with the hybrid 11648 but with another, less productive hybrid with shorter leaves. This hybrid was nicknamed '*kaptura*' which means shorts in Swahili.

Another important reason for the yield decline is the decrease in soil fertility as most sisal was grown with very little fertilization or manuring. This is further discussed in Chapter 4.

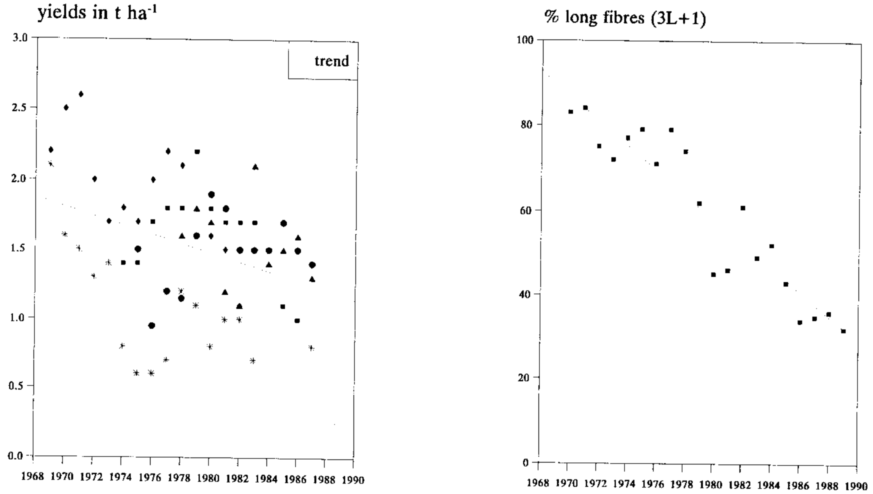


FIG. 2.4 *Yield and leaf length trends of sisal plantations in Tanga region. Yield data from five plantations, leaf length data from one plantation (Hartemink & Wienk, 1995).*

2.3 Soil Requirements

Physical and chemical soil requirements

Like many tropical crops, sisal requires a well structured and porous soil. The soil should be well drained although hybrid 11648 is more susceptible to restricted drainage conditions than *Agave sisalana*. On imperfectly drained soils, the crop grows poorly and leaves are yellow due to poor aeration and nitrogen deficiencies. Moreover, the crop becomes susceptible to bole rot and subsequently sisal weevils.

Although sisal is a drought resistant crop, optimal yields are only obtained if soil moisture is not limiting. Drought stress results in stunted growth, and particularly young sisal with a limited root system is vulnerable to drought. Based on field experience in Tanga Region, the National Soil Service (1988a) considered an effective soil depth of at least 120 cm as being optimal for sisal. Soils shallower than 40 cm are a severe constraint unless they are in zones of subsurface seepage or in areas where rain is amply available. Those areas are few in Tanga Region.

Sisal grows best in slightly acid to mildly alkaline soils, i.e. pH H_2O 6.1 to 7.8 (Rijkebusch & Osborne, 1965). Maintaining a neutral pH has several advantages because sisal is calcicole, and under acid conditions it takes up toxic amounts of manganese and cobalt resulting in 'chlorotic mottle' leaf symptoms (De Geus, 1973). Like tea, sisal is a leaf crop but its nitrogen requirements are only moderate. The soil should contain at least 0.14% total N (TABLE 2.1). Nitrogen deficiency results in retardation of plant growth and in leaf chlorosis. An excess of nitrogen can cause deficiency symptoms for other plant nutrients or result in low fibre contents. Optimum soil organic carbon levels for sisal are high and should be near 2.5% with C/N ratios between 9 and 15. The phosphorus requirement of sisal is modest but values over 10 mg P kg^{-1} (Bray I) are required. The soil should have a CEC of at least 80 $mmol_c$ kg^{-1}. Calcium requirements are high and the soil should contain a minimum of 50 $mmol_c$ Ca kg^{-1} (TABLE 2.1). Potassium is required for the strength of the sisal fibre and deficiencies leads to necrosis at the leafbase, so called 'banding disease'. Minimum amounts of potassium in the topsoil are 2.5 $mmol_c$ K kg^{-1}. Magnesium is an essential constituent of chlorophyll but the requirements for the sisal plant are not exactly known. For high yields, however, at least 17 $mmol_c$ Mg kg^{-1} soil is required (Rijkebusch & Osborne, 1965). Sisal has a medium tolerance to salinity but Lock (1969) mentioned that 1.5% of soluble salts in the surface soils is lethal to sisal.

TABLE 2.1 *Rating of some soil chemical properties for sisal (Rijkebusch & Osborne, 1965).*

	very low	low	moderate	high	very high
Organic C (%)	< 1.4	1.4-1.8	1.9-2.6	2.7-3.5	> 3.5
Total N (%)	< 0.10	0.10-0.13	0.14-0.19	0.20-0.25	> 0.25
Exchangeable Ca ($mmol_c$ kg^{-1})	< 30	30-50	51-90	91-200	> 200

Nutrient removal

Estimation of nutrient removal is usually based on the analysis of nutrient contents in the leaves. These contents are largely influenced by growing conditions (climate, soil) and differs between sisal varieties (Lock, 1969). As a result, large differences in nutrient removal are found (TABLE 2.2). Except for the data of the International Fertilizer Association (1992) which probably refer to sisal in Brazil, most of the data in TABLE 2.2 are probably obtained from experiments at the Sisal Research Station in Mlingano.

TABLE 2.2 *Nutrient removal of sisal (kg ha*$^{-1}$ *per ton fibre).*

Source	Plant	Nutrient				
		N	P	K	Ca	Mg
Boname (1904)†	not specified	28	5	51	77	30
Lommel (1911)†	not specified	50	4	32	159	na
Bellis *et al.* (not dated)†	not specified	35	5	72	100	na
Uexküll (1960)	not specified	47	11	78	na	na
Osborne (1967)	*Agave sisalana*	27	7	69	70	34
Osborne (1967)	hybrid 11648	26	3.5	44	82	31
Berger (1969)	not specified	27-33	5-7	59-69	42-66	30-33
Lock (1969)	not specified	31±9	5±3	79±22	66±25	38±15
IPI‡ (1978)	hybrid 11648	22-25	3-4	30-40	79-83	na
IPI‡ (1978)	*Agave sisalana*	27-33	5-7	59-69	42-66	na
Finck (1982)	not specified	35	6.5	65	na	30
Rehm & Epsig (1991)	not specified	30	5	80	65	40
IFA§ (1992)	not specified	20	23	33	54	20
range of values:	all data	20-50	2-23	30-101	41-159	20-53
	Agave sisalana	27-33	5-7	59-69	42-70	34
	hybrid 11648	22-26	3-4	30-44	79-83	na

na not available

† quoted by Osborne (1967) and Berger (1969)

‡ International Potash Institute

§ International Fertilizer Association

All available data show that sisal removes large amounts of calcium, magnesium and potassium per ton fibre. The data of Osborne (1967) and the International Potash Institute (1978) imply that hybrid 11648 uses more calcium than *Agave sisalana* but potassium consumption seems to be lower. The table shows the modest removal of phosphorus by sisal.

3 PHYSICAL ENVIRONMENT

Tanga Region is located in the northeast of Tanzania, bordering Kenya in the north and the Indian Ocean in the east. The extent of the region is about 26,900 km^2 and several agro-climatic zones can be distinguished. Sisal is grown along the shores of the Indian Ocean, and near the Usambara mountains up to about 600 m above sea level. In this chapter the climate, physiography, geology and soils of the sisal environments in Tanga Region are described.

3.1 Climate

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 (southeast monsoon), and the small or short rains falling between October and December (northeast monsoon). Annual rainfall is about 1,300 mm directly along the coast, reducing to 1,100 mm near Korogwe and decreasing to less than 400 mm further inland. The Usambara mountains receive the highest rainfall (up to 2,000 mm yr^{-1}). Rainfall in Tanga Region is highly variable, and both the onset of the rainy seasons and the amount of monthly and annual rain differs between years. In FIG. 3.1 rainfall and temperatures diagrams are given of four representative meteorological stations in the region.

Tanga airport (35 m a.s.l.) is located near the coast and has an average annual rainfall of 1,321 mm but it ranges from 807 to 2,016 mm (18 years of records). April and May have on average 265 mm each, and in these months precipitation exceeds the potential evapotranspiration. Total annual evapotranspiration is about 1,512 mm (Penman). Temperatures along the coast are high throughout the year and average 26.3°C.

At Mlingano (205 m a.s.l.) which is located about 50 km from the coast, temperatures are slightly lower. Total annual rainfall is 1,115 mm with extremes of 616 mm and 1,736 mm (21 years of records). Rainfall exceeds potential evapotranspiration in April and May only, and total annual evapotranspiration is about 1,695 mm (Penman).

Mombo airport (410 m a.s.l.) located at the foot of the West Usambara mountains, receives on average 611 mm per annum, ranging from 312 to 1,543 mm (17 years of records). A pronounced dry season occurs from June to October in which rainfall is lower than 50 mm per month. Temperature is on average 25.1°C, and diurnal as well as monthly variation is larger than at the coast. The higher elevation and lower temperatures, result in lower potential evapotranspiration than at Mlingano, and the mean annual is 1,490 mm (Penman).

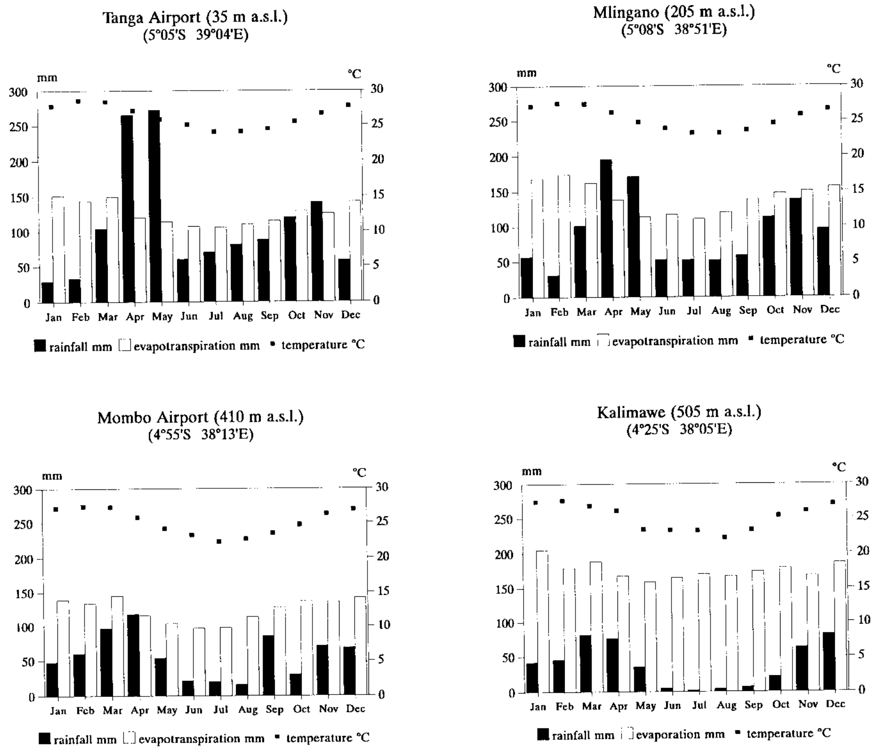


FIG. 3.1 *Rainfall and temperature diagrams for Tanga Region (data: AHT, 1976b; FAO, 1984).*

Further north-west at Kalimawe station near the Pare mountains, mean annual rainfall is 461 mm. There is a long dry season from June to October with less than 10 mm rain per month. Evaporation exceeds rainfall in each month and total annual evaporation is about 2,100 mm (Open Pan).

Most of the coastal area has an ustic soil moisture regime with an iso-hyperthermic temperature regime but up-country soil moisture regimes are aridic (Soil Taxonomy terminology). In the mountains, the soil moisture regime is udic and temperature regimes are hyperthermic or thermic at the higher elevations. As sisal requires about 1,200 mm of rain annually (Acland, 1971), rainfall along the coast is optimal. Weed growth is also more prolific at the coast because of the favourable soil fertility levels, whereas up-country it is generally drier and soil fertility levels are lower, both of which limit weed growth.

3.2 Physiography and Geology

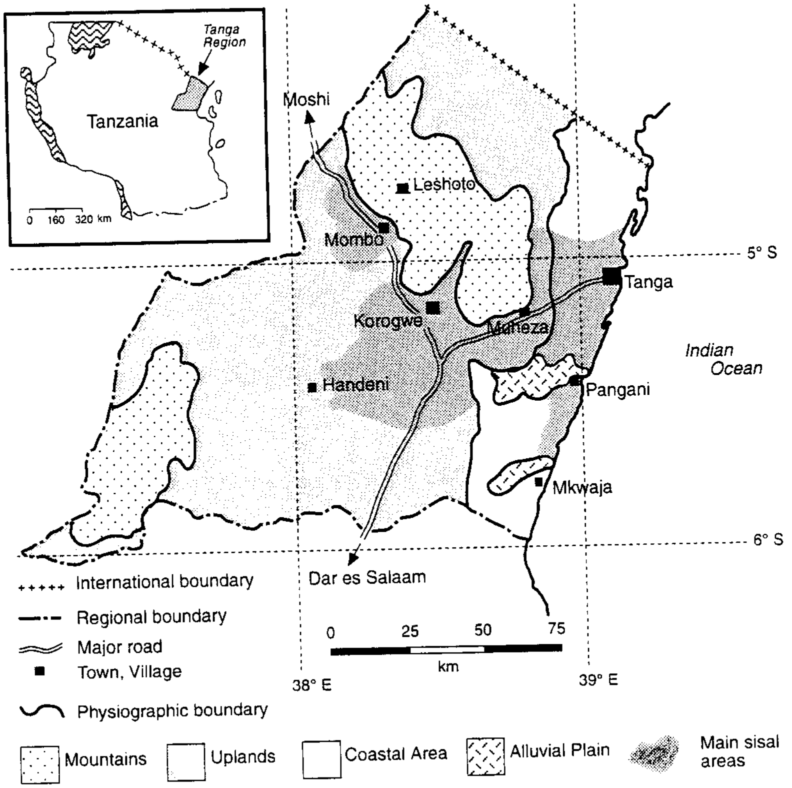
Tanga Region can be divided into four main physiographic units (Agrar- und Hydrotechnik, 1976a): (i) The *Mountains*, (ii) the *Uplands*, (iii) the *Coastal Area*, and (iv) *Alluvial Plains*. In FIG. 3.2 the physiographic units are shown including the approximate areas where sisal is cultivated in Tanga Region.

The *Mountains* comprise the East and West Usambaras in the north, and Kilindi mountains in the south-west of the region; they are not considered because no sisal is cultivated there.

The *Uplands* occupy two-third of the region and cover the central, western and southern parts. The topography of the Uplands is undulating to rolling and altitude is below 700 m a.s.l. The main rock types in the Uplands are Precambrian rocks of the Basement Complex. These rocks include schist, granulite, quartzite and gneiss of acid and intermediate composition. In the northern and central part of the Uplands, intermediate metamorphic rocks are dominant but in the southern part near Handeni, acid metamorphic rocks prevail. Gneiss is the main parent material for the soils of many sisal plantations in Tanga Region. This metamorphic rock has a mixture of hornblende, pyroxene and quartzo-feldspatic minerals with a granulitic texture (Hartemink, 1991a). Upon weathering these minerals may contribute magnesium, calcium, potassium and iron to the soil. Major crops in the Uplands are maize, cassava, cotton and sisal.

The *Coastal Area* (14% of Tanga Region) is about 20 to 40 km wide with altitudes below 150 m a.s.l. Adjacent to the coast, Jurassic limestone is the predominant rock which was covered in the late Jurassic by weathering products from the hinterland (National Soil Service, 1998c). These weathering products included clay and sandy materials from Basement Complex rocks (Halligan, 1958). In some areas along the coast, the Jurassic limestone is covered by coral limestone of Neogene age (Tertiary period). Additional sediments of varying composition were deposited during the Quaternary period. The major constituent of the coral limestone is calcium with minor amounts of magnesium and iron. Major crops in the Coastal Area are coconut, cashew, maize, cassava and sisal

Only small areas of the *Alluvial Plains* of the Mkomazi and Pangani rivers are planted with sisal, and these plains are not extensively dealt with in this account.



Physiographic Unit	Approx. Extent (km^2)	Altitude (m a.s.l.)	Lithology	Major Soil Groupings†
Mountains	5,300	700-2,000	mainly Precambrian gneiss	Luvisols, Phaeozems, Lithosols§, Ferralsols, Cambisols
Uplands‡	17,000	200- 700	acid and intermediate metamorphic rocks	Ferralsols, Luvisols, Nitosols, Cambisols, Arenosols, Vertisols
Coastal Area‡	3,500	0- 200	neogene and quaternary limestone and sandstones	Cambisols, Vertisols, Arenosols, Luvisols, Ferralsols, Phaeozems, Rendzinas§
Alluvial Plains	1,100	0- 200	unconsolidated material	Fluvisols, Gleysols, Vertisols, Solonchaks

† FAO-Unesco Legend (1974).

‡ used for sisal cultivation

§ In the revised legend (FAO-Unesco, 1988) Lithosols have been renamed Leptosols, and Rendzinas have been included in Leptosols.

FIG. 3.2 *Main physiographic units and sisal areas in Tanga Region.*

3.3 Soils

Soils of Tanga Region

Exploratory and reconnaissance soil maps of Tanzania and Tanga Region include: FAO-Unesco, 1:5M (1976); Samki, 1:2M (1977); De Pauw, 1:2M (1984); and Agrar- und Hydrotechnik, 1:0.5M (1976a). The reconnaissance soil map of Agrar- und Hydrotechnik is used here to give a broad overview of the Major Soil Groupings occurring in Tanga Region(1): Imperfectly drained soils like Vertisols (230 km^2), occur directly adjacent to the coast, particularly in the area around Pangani and south of Tanga town. Locally these soils are referred to as 'Mbugas' or black cotton soils. North and west of Tanga town, there is a range of soils including Arenosols, Ferralsols and Luvisols (1,300 km^2). South of Pangani, Cambisols, Luvisols, Phaeozems and Rendzinas(2) are the dominant soils and they cover about 1,600 km^2.

In the Uplands north of the Usambara mountains where intermediate metamorphic rocks are common, Ferralsols and Luvisols are the Major Soil Groupings and they cover about 2,400 km^2. These soils also occur extensively in the central Uplands roughly in the triangle delimited by Muheza, Mombo and Handeni where their extent is approximately 4,200 km^2. In the southern and western parts of the Uplands, where acid metamorphic rocks are common soil parent materials, Luvisols, Nitosols, Arenosols and Cambisols are found (6,800 km^2). Ferralsols are less common on acid gneiss because ferralitization, the main process in their formation, generally proceeds slower on acid rock as there are less weatherable minerals and more quartz (Driessen & Dudal, 1991).

Sisal is grown only in the central Uplands and Coastal Area (FIG. 3.2). Soils of the sisal plantations in the Uplands of Tanga Region are discussed below following the FAO-Unesco revised legend (1988).

Soils of sisal plantations in the Uplands

Many soils in the Uplands are derived from Precambrian rocks and they are usually red and highly weathered. Various detailed soil surveys have shown that Ferralsols and Acrisols are common Major Soil Groupings. Although also occurring, Luvisols are not as widely spread as was reported by Agrar- und Hydrotechnik (1976a). Analytical data of a representative Ferralsol, Acrisol and Alisol(3) in the Uplands are given in TABLE 3.1.

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(1) Major Soil Groupings on this map are of the FAO-Unesco legend of 1974.

(2) In the revised FAO-Unesco legend (1988) Rendzinas are included within the Leptosols

(3) These soils were previsouly included in the Acrisols.

TABLE 3.1 *Physical and chemical properties of a representative Ferralsol, Acrisol and Alisol in the Uplands of Tanga Region.*

Major Soil Grouping:	Ferralsol†			Acrisol‡			Alisol§		
Parent material:	intermediate gneiss			acid quartzitic gneiss			intermediate gneiss		
Horizon designation:	Ap	Bw1	Bw2	Ap	Bt1	Bt2	Ap	Bt1	Bt2'
Sampling depth (cm):	0-20	40-60	110-130	0-20	60-80	90-110	0-10	35-65	65-105
Clay (%)	52	63	66	31	51	60	38	56	50
Silt (%)	8	5	4	10	8	6	16	10	8
Sand (%)	40	32	30	59	41	34	46	34	42
pH (H_2O) 1:2.5	4.6	4.2	5.0	5.9	6.2	5.7	5.7	5.8	5.8
pH (1 *M* KCl) 1:2.5	4.0	4.2	4.5	4.9	4.0	4.0	4.7	4.6	4.6
Organic C (%)	1.8	0.3	0.1	2.1	0.4	0.4	2.8	0.8	0.6
Total N (%)	0.15	na	na	0.16	0.04	0.06	0.23	0.08	0.06
Available P (Bray I) (mg kg^{-1})	3	1	1	3	< 0.5	< 0.5	2	< 0.5	< 0.5
CEC (NH_4OAc pH 7) (mmol$_c$ kg^{-1})	89	51	50	127	86	91	178	142	130
Exchangeable Ca (mmol$_c$ kg^{-1})	7	< 0.5	< 0.5	51	5	6	67	35	21
Exchangeable Mg (mmol$_c$ kg^{-1})	5	< 0.5	< 0.5	21	7	5	37	31	24
Exchangeable K (mmol$_c$ kg^{-1})	1	< 0.5	< 0.5	7	4	9	9	1	1
Exchangeable Na (mmol$_c$ kg^{-1})	< 0.5	< 0.5	< 0.5	4	2	4	1	2	2
Base saturation (%)	14	< 5	< 5	65	21	26	64	49	37
Exchangeable Al (mmol$_c$ kg^{-1})	8	5	2	0	12	0	0	0	0
Al Saturation (% ECEC)	40	> 80	> 60	0	44	0	0	0	0

† data modified from National Soil Service (1988b)
‡ data modified from Hartemink (1991c)
§ data modified from National Soil Service (1990b)
na not available

The well drained Ferralsol is a typical example of a very acid, infertile soil with low activity clays indicating an advanced stage of weathering. The soil is located on a convex hill-crest (330 m a.s.l.) being the high remnant of a dissected peneplain. The site receives a mean annual rainfall of about 1,140 mm. The soil is very deep and has high termite activity throughout the profile. Levels of exchangeable cations (calcium, magnesium, potassium) are extremely low in the subsoil and aluminium is the major cation on the exchange sites. An Acrisol developed *in situ* from acid quartzitic gneiss was described on a hill crest at 200 m a.s.l., with about 1,260 mm of rain per year. The soil is very deep and below 130 cm depth weathered gneiss fragments appear. The soil is well drained and has a clear clay increase caused by illuviation. Soil chemical fertility levels are higher than in the Ferralsols, but aluminium saturation is high in the 60-80 cm soil horizon. Alisols are less common in the Uplands but they are among the better soils found on Precambrian Basement rock. The soil in TABLE 3.1 was described on a 11% slope at 260 m a.s.l. with an average yearly rainfall of 1,275 mm. The soil is very deep but a stoneline, probably caused by bioturbation, is found below 65 cm depth. The soil has a fair amount of exchangeable cations and the $\mathrm{CEC_{clay}}$ in the subsoil exceeds 240 $\mathrm{mmol_c\ kg^{-1}}$. Like most of the soils derived from Precambrian rock, the Alisol has very low levels of available phosphorus.

In the Uplands, many soils from gneiss parent materials constitute a recurrent topographic sequence (*catena*) which was firstly recognized by Milne (1935). Although the soils were formed in similar rock types, differences in soils from crest to valley floor were brought about by drainage conditions, erosion, leaching and lateral movement of chemical constituents. On the hill crests and upperslopes, the soils are dusky red and well drained. On the footslopes, the soils are more yellow and in the valleys the soils have brownish to black colours. The colour changes usually correspond to various hematite to goethite ratios and coincide also with changes in texture. In the lower part of the catena, where drainage is slow, iron concentrations in the soil solution are lower. This favours the crystallization of goethite rather than the precipitation of ferrihydrite (Van Wambeke, 1992). Such typical relation between landform and soils in the Uplands of Tanga Region is schematically presented in FIG. 3.3. Analytical data of the Acrisol and Fluvisol in this figure are given in TABLE 3.1 and TABLE 3.2 respectively.

The soils on the hill crest are very deep and have clayey textures with sesquioxides and kaolinite as predominant minerals (Nandra, 1977). They are strongly weathered and intensely leached. These soils must have formed in a wetter climate as the present rainfall (1,000 to 1,300 mm $\mathrm{yr^{-1}}$) is too low for the formation of such leached soils. The soils are very acid with low levels of exchangeable cations and available phosphorus. The soils have a ferralic B horizon ($\mathrm{CEC_{clay}} < 160\ \mathrm{mmol_c\ kg^{-1}}$), and they are classified as Ferralsols.

On the upper- and midslopes, the soils are also red and very deep but less weathered and less intensely leached. The soils commonly have a clear argic B 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 Acrisols. Laboratory analysis frequently shows that although the B horizon has sufficient clay increase to be argic, the CEC_{clay} is lower than 160 $mmol_c\ kg^{-1}$ which means the B horizon should be classified as ferralic. As the properties and soil management aspects of these soils are markedly different from the soils on the crests (Ferralsols), their field classification (Luvisols, Acrisols) is commonly used in many publications.

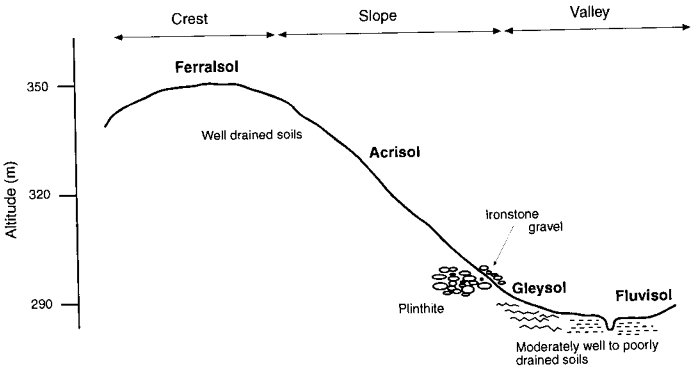

FIG. 3.3 *Common soil catena in the Uplands of Tanga Region (National Soil Service, 1988b).*

At the lower footslope bordering the valley bottom, ironstone gravel occurs at the soil surface as a result of erosion of the surface soil. The extent of these soils is usually very small, and they are classified as Plinthosols. The gravel is locally used for road building (see photograph in the back).

Towards the valley, drainage is imperfect and the soils have gleyic and stagnic properties (Gleysols). In the flat valley bottoms, Fluvisols are common. Although the lower members of the catena may have a fair chemical fertility derived from lateral enrichment of nutrients and the lack of nutrient removal by crops, their physical properties are unfavourable for crop production.

TABLE 3.2 presents data of three Major Soil Groupings on which sisal is also grown in the Uplands of Tanga Region.

TABLE 3.2 *Physical and chemical properties of a representative Cambisol, Vertisol and Fluvisol in the Uplands of Tanga Region.*

Major Soil Grouping:	Cambisol†			Vertisol†			Fluvisol§		
Parent material:	colluvial gneiss			unconsolidated material			unconsolidated material		
Horizon designation:	Ap	2C	4C	Ap	2C	3C	C1	2Ahg	2C2g
Sampling depth (cm):	0-15	65-80	100-120	0-15	30-50	90-110	0-15	30-50	70-90
Clay (%)	16	18	12	32	49	60	51	28	28
Silt (%)	18	13	13	59	31	16	14	19	33
Sand (%)	66	69	75	9	20	24	35	53	39
pH (H_2O) 1:2.5	6.3	7.4	7.5	6.8	8.4	8.6	5.1	4.7	4.7
pH (1 *M* KCl) 1:2.5	4.6	5.6	5.9	6.0	7.2	7.7	4.3	4.1	3.9
EC (mS cm^{-1}) 1:2.5	0.03	0.05	0.04	0.63	0.37	3.26	0.41	2.00	2.60
Organic C (%)	1.1	0.3	0.2	4.7	1.5	0.7	2.5	0.7	0.4
Total N (%)	0.08	0.03	0.03	0.52	0.11	0.04	0.18	0.06	0.04
Available P (mg kg^{-1})‡	44	14	18	66	6	6	1	1	< 0.5
CEC (NH_4OAc pH 7) ($mmol_c$ kg^{-1})	115	123	94	526	380	223	181	159	222
Exchangeable Ca ($mmol_c$ kg^{-1})	53	74	66	343	564	526	61	53	91
Exchangeable Mg ($mmol_c$ kg^{-1})	21	41	24	100	103	111	38	63	75
Exchangeable K ($mmol_c$ kg^{-1})	4	4	3	12	4	3	5	7	1
Exchangeable Na ($mmol_c$ kg^{-1})	< 0.5	3	2	4	13	106	8	21	39
Base saturation (%)	68	99	100	87	100	100	62	91	93

† data modified from Hartemink (1990a)

‡ pH H_2O < 7.0: Bray I; pH H_2O > 7.0: Olsen

§ data modified from Hartemink (1991a)

na not available

The Cambisol is located at the footslope of the West Usambara mountains at an altitude of 400 m a.s.l. with an average yearly rainfall of 763 mm. The profile is located on a 6% slope. The soil is very deep, well drained and consists of a large number of layers within 180 cm depth. Textures are generally coarse and sandy loam is most common. The topsoil is slightly acid and subsoils are slightly alkaline. Organic carbon contents are low. Levels of exchangeable cations are high in the subsoil, and the very high level of available phosphorus is remarkable. A Vertisol was described in the alluvial plain of the Mkomazi river at the foot of the West Usambara mountains (375 m a.s.l.) where yearly rainfall is about 700 mm. The soil is very deep, cracks when dry and has slickensides in the clay subsoil. Topsoil texture is silty clay. Levels of organic carbon, available phosphorus and exchangeable cations are all very high in the topsoil. In the deep subsoil, the exchangeable sodium percentage (ESP) is 48%, which is harmful for many plants. The Fluvisol was described at a lower slope near a broad and flat valley bottom at an altitude of 150 m a.s.l. Mean annual rainfall at this site is 1,044 mm. The soil was somewhat poorly drained and was cultivated with *Agave sisalana*. The chemical fertility of the topsoil is favourable with a fair amount of organic carbon, but available phosphorus is extremely low.

Another typical relation between landform and soils in the Uplands occurs at the foot of the Usambara mountains where many sisal plantations are situated. Although rainfall may be too low for high yielding sisal cultivation, sub-surface water coming from the mountains significantly contributes to the water requirements of the sisal crop.

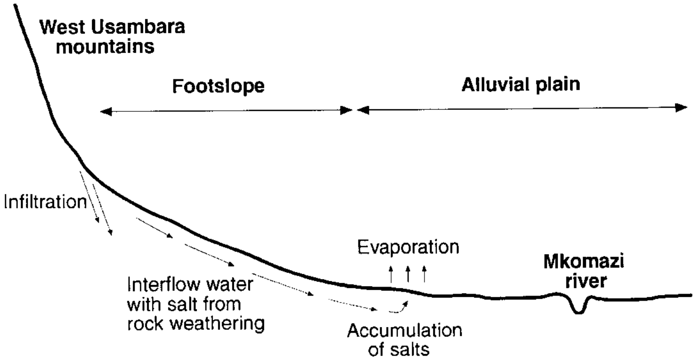

FIG. 3.4 *Cross-section at the footslopes of the West Usambaras in Tanga Region (Hartemink, 1990a).*

At the footslope of the escarpment, soils are derived from colluvial deposits and stratified (FIG. 3.4). The soils are well drained, compacted and hard when dry. They are classified as Cambisols (analytical data given in TABLE 3.2). Runoff water from the mountains infiltrates readily in these coarsely textured soils and moves down as a subsurface flow of groundwater (interflow). As the weathering of the gneiss rock in the upper catchment areas releases small amounts of salts, the interflow water is slightly saline. At the lower end towards the alluvial plain, interflow water accumulates and comes close to the surface. Here evaporation is much higher than rainfall resulting in a net upward movement of water and salts by capillary action. As a result, salts accumulate and saline and saline/alkaline soils are formed. The salt content of some of the soils is sufficiently high that it is mined locally in large pits.

Interflow salinity is aggravated by changes in land-use in the upper-catchment areas. Under natural conditions of a dense forest, interflow is limited because tree roots intercept much of the percolation water. Deforestation and erosion increase interflow and this may lead to a worsening of interflow salinity at the footslopes of the Usambara mountains. Lock (1969) observed that salty patches steadily spread into adjoining sisal fields at the foot of the Usambaras. Remedial measures lie in drainage and leaching of the salts coupled with liberal dressings of gypsum.

Soils of sisal plantations in the Coastal Area

In the Coastal Area, soils are very heterogeneous and relations between landform and soils are hard to establish. The heterogeneity is caused by the irregular deposition of fluvial sediments from the hinterland, and the uneven surface and consistence of the coral by which the depth of soil and weathering 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. Throughout the Coastal Area, chemically very poor soils developed in these deposits can be found next to soils with high levels of exchangeable cations developed from limestone. TABLE 3.3 presents properties of soils described and sampled on sisal plantations in the Coastal Area.

The first example is an Arenosol which has a low silt and clay content. The soil was described at about 1 km from the coastal shore on a plain with 1% slope (20 m a.s.l.). Annual rainfall is on average 1,241 mm and the soil parent material is a sandy deposit covering coral limestone. The soil is very deep, somewhat excessively drained and weakly structured. Water holding capacity of the soil is low because of the sandy texture and the low organic carbon content. The soil has a neutral reaction, and very low levels of exchangeable cations. In its present state, both physical and chemical properties of this soil are unfavourable for crop cultivation. A Lixisol developed *in situ* from sandstone has been described at a sisal plantation north of Tanga with an average annual rainfall of 1,339 mm. The soil is located on a plain with a 1% slope and at an altitude of 20 m a.s.l. The soil is very deep, well drained and has a very low organic carbon content. The cation exchange capacity is low and so are the levels of exchangeable cations. Another example of a common soil in the Coastal Area is the Cambisol, with rotten limestone rock within 150 cm soil depth. The soil is located on a lower slope at 80 m a.s.l., with an average yearly rainfall of 1,295 mm. The subsoil is strongly structured with some gleyic properties. The soil has a neutral to slightly alkaline reaction, a high cation exchange capacity and high levels of exchangeable calcium and magnesium. Levels of exchangeable potassium and available phosphorus are very low. Nutrient imbalances i.e. unfavourable calcium-potassium ratios, as well as the strongly structured subsoil, adversely affect sisal growth.

TABLE 3.3 *Physical and chemical properties of a representative Arenosol, Lixisol and Cambisol in the Coastal Area of Tanga Region.*

Major Soil Grouping:	Arenosol†			Lixisol‡			Cambisol§		
Parent material:	sandy deposits over coral limestone			sandstone			Neogene limestone		
Horizon designation:	Ap	Bw1	BC	Ah1	Bt1	Bt2	Ap	AC1	2C1
Sampling depth (cm):	0-20	45-60	85-120	0-15	50-70	80-200	0-15	40-60	130-150
Clay (%)	8	7	23	7	21	30	27	34	29
Silt (%)	5	7	3	4	3	1	18	16	28
Sand (%)	87	86	74	89	76	69	55	50	43
pH (H_2O) 1:2.5	6.4	6.2	5.5	6.3	5.8	5.7	7.1	7.9	8.8
pH (1 *M* KCl) 1:2.5	5.5	5.0	4.4	4.9	4.0	4.2	6.0	6.6	7.4
EC (mS cm^{-1})	0.05	0.03	0.03	0.05	0.02	0.02	1.20	1.40	0.40
Organic C (%)	0.5	0.1	0.1	0.7	0.2	0.2	2.0	0.6	0.2
Total N (%)	na	na	na	na	na	na	na	na	na
Available P (mg kg^{-1})††	3	2	3	2	3	4	2	1	1
CEC (NH_4OAc pH 7) ($mmol_c$ kg^{-1})	48	34	69	36	37	56	264	246	247
Exchangeable Ca ($mmol_c$ kg^{-1})	16	6	14	14	15	21	211	200	343
Exchangeable Mg ($mmol_c$ kg^{-1})	15	5	13	8	7	10	17	26	46
Exchangeable K ($mmol_c$ kg^{-1})	2	2	2	5	2	2	1	1	< 0.5
Exchangeable Na ($mmol_c$ kg^{-1})	1	2	1	1	1	1	1	5	15
Base saturation (%)	71	44	43	77	65	60	87	94	100

† data modified from National Soil Service (1987a)
‡ data modified from National Soil Service (1987b)
†† pH $H_2O < 7.0$: Bray I; pH $H_2O > 7.0$: Olsen
§ data modified from National Soil Service (1988a)
na not available

4 SOIL FERTILITY DECLINE

In Tanga Region, planting of sisal expanded rapidly in the 1940s to 1960s mostly on virgin land. For such land the need for fertilizers or manure was not compelling. Growers relied heavily on the soil's nutrient reserves and the decline in yields taking place in the oldest fields initially escaped notice. In 1969, however, Lock observed that nutrient depletion became perceptible in the shape of reduced annual fibre outputs and higher operation costs. Today, more than 25 years after these observations, the decline in fertility has proceeded in many soils under sisal, and this chapter shows approximately how much it has continued.

4.1 Historical Soil Data

Methodology

In the 1950s and 1960s, the Sisal Research Station at Mlingano collected and filed soil information of many sisal plantations. John Osborne, researcher in the 1950s and 1960s at Mlingano, informed us about the existence of these files in 1990, but they could not be found. Fortunately, they were recovered in 1992 by workers of the National Soil Service. The files contained soil analytical data of composite topsoil samples, their exact field location and date of sampling and analysis. The soil samples were taken from 10 to 15 locations in about one acre with a soil auger, and then thoroughly mixed (Osborne, pers. comm.). Soil analysis took place at the Sisal Research Station in Mlingano.

Using the old files and the recent data of the soil survey reports, fields were selected which had been sampled in the 1950s and 1960s, and again in the late 1980s and early 1990s in order to investigate changes in chemical soil fertility in the period 1950 to 1990. Only those fields were chosen which had been continuously under sisal, and which were located in one mapping unit i.e. uniform soils from one Major Soil Grouping. For comparison of the soil analytical data, the following soil parameters could be used as the methods of analysis of the 1950s and 1960s were identical to the present methods: pH H_2O (soil:water 1:2.5), organic carbon (Walkley Black) and exchangeable calcium, magnesium and potassium (1 M NH_4OAc extraction at pH 7.0). Organic carbon data were available from only a few estates for the 1950 and 1960 samplings.

Overview of Major Soil Groupings

With continuous sisal cultivation on a Ferralsol at Bamba estate the topsoil pH decreased in 25 years from 5.5 to 5.0 (TABLE 4.1). The levels of exchangeable calcium decreased from 19 to 6 mmol$_c$ kg^{-1} and magnesium levels decreased by 8 mmol$_c$ kg^{-1}, whereas potassium was nearly exhausted after 25 years of sisal cultivation.

TABLE 4.1 *Soil fertility (0-20 cm) of continuously cultivated sisal fields at different sampling times.*

				Exchangeable cations (mmol$_c$ kg^{-1})			
Major soil grouping	Plantation	Year of sampling	pH (H_2O) 1:2.5	Ca	Mg	K	Source:
Ferralsol	Bamba	1966	5.5	19	11	4	†
		1990	5.0	6	3	1	Hartemink, 1991a
	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, 1988b
Acrisol	Bamba	1966	6.9	75	28	5	†
		1990	5.9	41	17	3	Hartemink, 1991a
	Kwamdulu	1966	6.7	49	13	2	†
		1987	5.0	25	13	1	National Soil Service, 1988b
Luvisol	Mwera	1960	6.5	41	9	2	†
		1987	6.6	44	12	2	National Soil Service, 1988a
Phaeozem	Mwera	1959	8.0	311	26	9	†
		1987	7.8	229	36	1	National Soil Service, 1988a
Leptosol	Mwera	1959	7.0	190	18	5	†
		1987	7.9	196	62	2	National Soil Service, 1988a

† unpublished data of Sisal Research Station Mlingano
na not available

A similar trend was found in the Ferralsols of Kwafungo estate, where the topsoil pH decreased from 5.7 to 4.8 between 1959 and 1989. Levels of exchangeable calcium had decreased sharply after 30 years of continuous sisal cultivation, but exchangeable potassium levels were already very low in 1959 and did not alter. At Kwamdulu estate, the topsoil pH of a Ferralsol decreased from 5.6 to 4.5 between 1958 and 1987. Levels of exchangeable calcium decreased to 8 mmol$_c$ kg^{-1} and magnesium to 7 mmol$_c$ kg^{-1}. Potassium levels were already low in 1958. Topsoil pH of an Acrisol at Bamba estate decreased from 6.9 to 5.9 between 1966 and 1990. Levels of exchangeable calcium decreased by 34 mmol$_c$ kg^{-1} and magnesium levels by 11 mmol$_c$ kg^{-1}. Potassium levels were 5 mmol$_c$ kg^{-1} in 1966 but had decreased to 3 mmol$_c$ kg^{-1} in 1990. At Kwamdulu estate, topsoil pH of an Acrisol decreased from 6.7 to 5.0, and exchangeable calcium decreased from 49 to 25 mmol$_c$ kg^{-1}. Levels of exchangeable magnesium and potassium remained about the same.

Although the data from the 1950s and 1960s were few, and taking into account the natural heterogeneity of the soils, a comparison of historical soil data with recent data, revealed a decline in soil fertility of both Ferralsols and Acrisols. The decline was more severe in Ferralsols than in Acrisols as was also observed under continuous maize cultivation at Mlingano (Haule *et al.*, 1989). The difference between the two Major Soil Groupings is explained by the higher initial fertility and possibly the presence of more weatherable minerals in the Acrisols.

Soil fertility changes were also investigated in a Luvisol, Phaeozem and Leptosol developed in clayey sediments over coral limestone (TABLE 4.1). The Luvisol showed no decrease in exchangeable calcium and magnesium between 1960 and 1987. Levels of exchangeable potassium were low in both 1960 and in 1987. The topsoil pH of this Luvisol was slightly acid in 1960 and did not alter despite the soil was continuously cultivated with sisal. There was no clear change in exchangeable calcium and magnesium in the Phaeozem and Leptosol between 1959 and 1987. Levels of exchangeable potassium decreased, however, from 9 to 1 mmol$_c$ K kg^{-1} in the Phaeozem and from 5 to 2 mmol$_c$ K kg^{-1} in the Leptosol.

Coastal Area and Uplands

Soil analytical data from two plantations in the Coastal Area, was compared with data from three plantations in the Uplands. Soils in the Coastal Area were Cambisols with minor inclusions of Phaeozems and Luvisols, developed in clayey sediments overlying limestone rock. Soils in the Uplands were Ferralsols, mainly derived from intermediate gneiss.

Between the 1960s and late 1980s, the topsoil pH of Ferralsols declined by 1.2 of a unit and in the Cambisols by 0.4 of a unit (TABLE 4.2). More important, however, is the relative decrease. The pH in the Ferralsols reached 4.9 whereas the topsoil pH of the Cambisols remained near neutral after nearly 30 years of continuous sisal cultivation. The organic carbon contents in the Ferralsols decreased from 2.0 to 1.7%. Exchangeable calcium in the Ferralsols decreased from 39 to 14 mmol$_c$ kg^{-1}, but in the Cambisols levels decreased from 116 to 89 mmol$_c$ kg^{-1}, which is still a favourable calcium level for sisal. The weathering of the limestone, which is found within two meters depth, and the transport of calcium by capillary rise (yearly potential evaporation exceeds rainfall) may have resulted in topsoil calcium levels remaining high. Magnesium levels were higher in the Ferralsols than in the Cambisols in the 1950s and 1960s, but the decrease in magnesium content was larger in the Ferralsols than in the Cambisols. Base saturation decreased in both Major Soil Groupings and reached low levels in the Ferralsols.

TABLE 4.2 *Soil fertility status (0-20 cm) of sisal fields on Ferralsols and Cambisols at different sampling times (median with range of values in parentheses) (Hartemink & Bridges, 1995).*

Parent material:	Intermediate gneiss (Uplands)				Limestone covered by sediments (Coastal Area)			
Major Soil Grouping:	Ferralsols				Cambisols			
Years of sampling:	1956-1966		1987-1990		1958-1960		1987-1989	
Number of topsoil samples:	31		25		28		29	
pH (H_2O) 1:2.5	6.1	(5.2-7.3)	4.9	(4.3-5.6)	7.0	(5.5-8.0)	6.6	(5.4-8.1)
Organic C (%)	2.0	(1.7-2.5)†	1.7	(1.4-2.1)	na	-	1.8	(0.6-3.0)
Exchangeable Ca ($\text{mmol}_c\ \text{kg}^{-1}$)	39	(9-113)	14	(3-16)	116	(2-755)	89	(23-633)
Exchangeable Mg ($\text{mmol}_c\ \text{kg}^{-1}$)	25	(1-45)	10	(3-23)	19	(6-43)	15	(2-45)
Exchangeable K ($\text{mmol}_c\ \text{kg}^{-1}$)	2	(1-17)	1	(< 0.5-8)	5	(1-28)	3	(1-9)
Base saturation (%)	56	(36-88)	33	(14-79)	93	(53-100)†	68	(27-100)

na not available
† 6 samples only

All pH data of the topsoils of Ferralsols and Cambisols were plotted (exponential fit) against the sum of exchangeable calcium, magnesium and potassium (FIG. 4.1). The pH and levels of exchangeable cations of the Ferralsol were much lower in the period 1987 to 1990 than in 1956 to 1966. In 1956 to 1966 no topsoil pH was observed below 5.2, and in 1987-1990 no pH was found above 5.6 for the same soils and fields. The pH values of the Cambisols found in the 1958-1960 samples cover the same range as those from the late 1980s, although below pH 6 more recent data points are found than in the earlier period. This agrees with the slight pH decrease as presented in TABLE 4.2. Above pH 7, an increase in the sum of exchangeable cations is observed, caused by the presence of free carbonate which is common in soils with a pH > 7.3. Such a pH might be of advantage as the clay complex is dominated by exchangeable calcium which favours soil physical conditions, but it can also lead to deficiencies of minor elements like iron, as well as creating nutrient imbalances e.g. unfavourable calcium/potassium ratios.

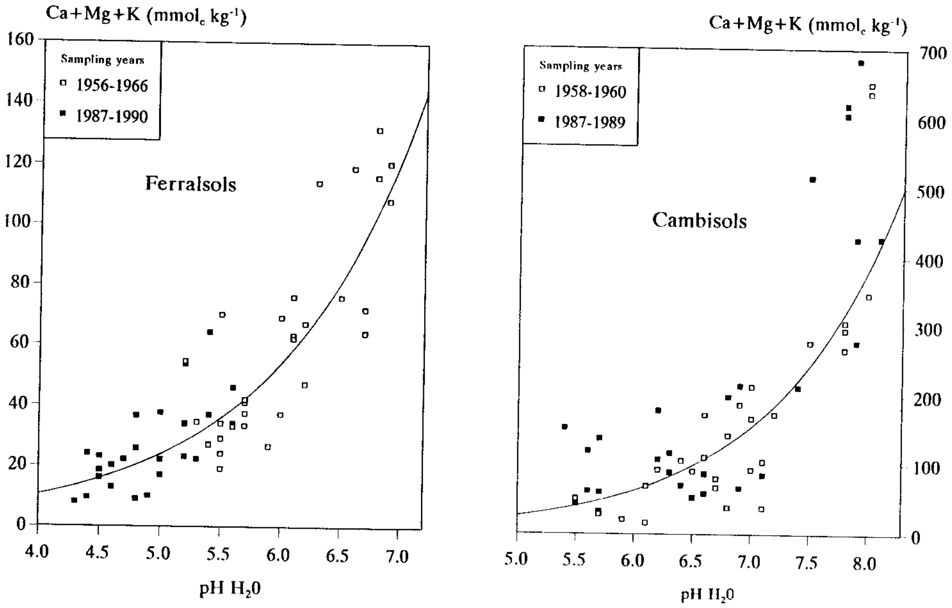

FIG. 4.1 *Relation between pH H_2O and sum of Ca, Mg and K in the topsoil (0-20 cm) of Ferralsols and Cambisols (note different scales on X and Y-axes of Ferralsols and Cambisols). (Hartemink & Bridges, 1995).*

4.2 Effects of Land-Use

Methodology

A simple way of assessing soil fertility changes under sisal cultivation is to take samples from virgin land and compare these with samples from similar soils under continuous sisal. This has been done on a number of plantations and the first ideas about soil fertility decline under sisal cultivation were based on this approach (National Soil Service, 1987b). Composite topsoil samples were taken in a sisal field and in similar soils immediately outside the plantation in land that has never been under cultivation. Such land was usually covered with thick dry and moist woodland locally referred to as "bush", from which at times some firewood was collected. At one location, a sample was taken from virgin land under forest (Bamba estate).

Bush and sisal

At Amboni estate in the Coastal Area, the topsoil pH of a Ferralsol under bush was 1.4 unit higher than in a similar soil under sisal, accompanied by higher levels of exchangeable cations and a higher base saturation (TABLE 4.3). Exchangeable calcium levels were 10 $mmol_c$ kg^{-1} higher in the topsoil and 5 $mmol_c$ kg^{-1} higher in the subsoil. Levels of magnesium and potassium were also higher under bush than under sisal. Absolute levels of exchangeable cations were, however, low in both soils under bush and sisal. Little differences in the organic carbon contents were found. Available phosphorus was lower under sisal (3 mg P kg^{-1} in the topsoil). At Pongwe estate also located in the Coastal Area, two Ferralsols were sampled under bush and sisal. In both examples the pH was lower under sisal, but fertility differences resulted mainly from variations in the organic carbon content. The soil under sisal had a higher organic carbon content resulting in a higher CEC than the Ferralsol under bush. Aluminium saturations in the subsoils under sisal were 41%. Ferralsols at Kwamdulu estate (Uplands) under forest were only slightly more fertile than under sisal. The pH was 0.7 of a unit higher and exchangeable calcium and magnesium levels in the topsoil differed by 11 and 4 $mmol_c$ kg^{-1} respectively between soils under bush and sisal. Levels of available phosphorus in both the topsoil and subsoil under sisal were extremely low. Topsoil pH of a Ferralsol under virgin forest at Bamba estate (Uplands) was 1.0 of a unit higher than in the adjoining sisal field. Organic carbon contents were lower under sisal but levels of available phosphorus did not differ between the forest and sisal. Exchangeable calcium was 68 $mmol_c$ kg^{-1} under forest but only 13 $mmol_c$ kg^{-1} under sisal. Also exchangeable magnesium and potassium were lower under sisal. Levels of exchangeable aluminium were nil under forest but 10 $mmol_c$ kg^{-1} (42% ECEC) in the subsoils under sisal.

The comparison of Ferralsol data under bush and sisal clearly illustrates the variation in chemical fertility within one Major Soil Grouping. Levels of plant nutrients were, however, low to extremely low in all Ferralsols examined. Notwithstanding the variation, it appeared that the Ferralsols under sisal had lower fertility levels than under bush. The difference can easily be explained as little or no nutrients are removed from the bush vegetation whereas sisal land is exposed to a drain of nutrients. Differences in chemical fertility of Ferralsols under bush from Amboni and Pongwe estate, are possibly caused by the soil parent material as the (paleo-) climate has been similar. The Ferralsol at Amboni estate was derived *in situ* from a loamy sandstone whereas the Ferralsol at Pongwe estate developed in clayey sediments. Ferralsols under bush at Amboni, Pongwe and Bamba estate had a slightly acid to neutral soil reaction in the topsoil (pH H_2O 6.2-6.9) but the Ferralsol at Kwamdulu estate was acid (pH H_2O 5.4). Again, this may be due to the nature of the underlying rock. The relatively high available phosphorus level in the Ferralsols of Pongwe estate is remarkable. Phosphorus levels under sisal were even higher than the levels under bush at Amboni, Kwamdulu or Bamba estate. There were no clear differences in organic carbon content between bush and sisal in the Coastal Area (Amboni and Pongwe estate). At Kwamdulu and Bamba estate (Uplands) it was found that the organic carbon levels under sisal were 0.4% point lower in the topsoil, and 0.3% points lower in the subsoils as compared to the soils under bush.

Soil samples under bush and sisal were also taken in Acrisols, Arenosols and Cambisols and the data presented are from two sisal plantations at the coast (Pongwe and Kigombe estate) and one plantation in the Uplands (Kwamdulu estate). Acrisols at Pongwe estate under bush had a topsoil pH that was 1.8 of a unit higher than under sisal (TABLE 4.4). Organic carbon in the topsoil was slightly higher under bush than under sisal, but there was little difference in available phosphorus content. Exchangeable calcium levels differed by 32 $\text{mmol}_c\ \text{kg}^{-1}$ in the topsoil and 17 $\text{mmol}_c\ \text{kg}^{-1}$ in the subsoil. Magnesium levels were also much lower under sisal. The subsoil of the Acrisol under sisal had high aluminium saturation (52% ECEC). Similar differences between Acrisols under bush and sisal were found at Kigombe and Kwamdulu estate. At Kigombe estate, soils under sisal had lower fertility levels than under bush, but levels of exchangeable calcium were higher than in the Acrisols under sisal at Pongwe or Kwamdulu estate. Organic carbon levels were higher under sisal than under bush in both the topsoil and subsoil. Available phosphorus levels were very low in soils under bush and sisal. Arenosols at Kigombe estate had low levels of organic carbon under bush and sisal. Topsoil pH in the Arenosol differed by 1.0 of a unit, and also the exchangeable cations were lower under sisal. At the same plantation, a Cambisol derived from limestone and clayey deposits was sampled. Only the exchangeable magnesium and available phosphorus levels were lower under sisal. Organic carbon and exchangeable potassium were even higher under sisal than in the Cambisol under bush.

Summarizing TABLE 4.4, it was found that soil fertility was considerably lower in Acrisols and Arenosols under sisal as compared to the same soils under bush. The degree of variation in Acrisols was comparable to the Ferralsols (TABLE 4.3). This variation is most likely due to differences in soil parent material at Pongwe, Kwamdulu and Kigombe estate. The Acrisols at Kwamdulu and Kigombe estate had very low levels of available phosphorus but at Pongwe estate, phosphorus levels were medium, as was also observed in the Ferralsols (TABLE 4.3).

TABLE 4.3 *Soil analytical data of Ferralsols under bush and sisal.*

Plantation:		Amboni†		Pongwe‡		Pongwe‡		Kwamdulu§		Bamba††	
Land-use:	depth (cm)	bush	sisal	bush	sisal	bush	sisal	forest	sisal	forest	sisal
pH (H_2O) 1:2.5	0-20	6.8	5.4	6.9	5.7	6.6	5.0	5.4	4.7	6.2	5.2
	30-50	6.2	4.9	6.4	4.8	6.5	4.3	5.4	4.7	5.7	5.1
Organic C (%)	0-20	0.9	0.8	0.9	2.3	0.8	0.8	1.6	1.2	2.1	1.7
	30-50	0.3	0.3	1.2	0.9	0.3	0.5	0.8	0.5	0.9	0.6
Available P (Bray I) (mg kg^{-1})	0-20	8	3	12	9	11	9	4	< 0.5	3	3
	30-50	1	1	11	7	8	7	< 0.5	< 0.5	1	1
CEC (NH_4OAc pH 7) (mmol$_c$ kg^{-1})	0-20	48	29	134	180	73	56	120	123	125	88
	30-50	26	23	85	na	66	na	100	127	105	60
Exchangeable Ca (mmol$_c$ kg^{-1})	0-20	15	5	84	48	44	12	17	6	68	13
	30-50	9	4	49	7	36	6	6	6	23	9
Exchangeable Mg (mmol$_c$ kg^{-1})	0-20	7	2	16	9	18	3	9	5	26	5
	30-50	4	2	26	7	14	5	5	5	21	3
Exchangeable K (mmol$_c$ kg^{-1})	0-20	4	2	7	1	2	1	3	3	5	1
	30-50	3	< 0.5	4	< 0.5	1	< 0.5	3	3	4	< 0.5
Base saturation (%)	0-20	56	31	80	33	88	30	28	15	80	21
	30-50	65	26	93	-	77	-	21	13	48	20
Exchangeable Al (mmol$_c$ kg^{-1})	0-20	0	0	0	0	0	0	na	na	0	9
	30-50	0	na	0	11	0	13	na	na	0	10
Al saturation (% ECEC)	0-20	0	0	0	0	0	0	-	-	0	32
	3 0-50	0	na	0	41	0	50	-	-	0	42

† data modified from National Soil Service (1987b)
‡ data modified from National Soil Service (1988c)
na not available

§ data modified from Braun (1994)
†† data modified from Hartemink (1991a)

TABLE 4.4 *Soil analytical data of Acrisols, Arenosols and Cambisols under bush and sisal.*

Major Soil Grouping:		Acrisol		Acrisol		Acrisol		Arenosol		Cambisol	
Plantation:		Pongwe†		Kwamdulu‡		Kigombe§		Kigombe§		Kigombe§	
Land-use:	depth (cm)	bush	sisal	bush	sisal	bush	sisal	bush	sisal	bush	sisal
pH (H_2O) 1:2.5	0-20	6.5	4.7	6.1	4.6	6.5	5.5	6.3	5.3	7.5	7.4
	30-50	6.4	4.6	5.6	4.7	6.8	5.2	6.0	5.4	7.5	6.6
Organic C (%)	0-20	1.2	0.8	1.5	1.1	1.5	1.8	0.7	0.7	1.9	3.4
	30-50	1.0	0.5	0.4	0.3	0.9	1.1	0.4	0.4	1.3	1.5
Available P (Bray I) (mg kg^{-1})	0-20	8	10	3	< 0.5	2	1	3	2	9	4
	30-50	8	8	< 0.5	< 0.5	1	1	1	1	4	1
CEC (NH_4OAc pH 7) ($mmol_c$ kg^{-1})	0-20	228	na	157	110	149	137	98	60	310	310
	30-50	219	na	127	97	158	141	80	53	481	221
Exchangeable Ca ($mmol_c$ kg^{-1})	0-20	36	4	38	11	100	71	27	12	161	140
	30-50	24	8	17	11	84	51	28	12	97	107
Exchangeable Mg ($mmol_c$ kg^{-1})	0-20	36	4	23	5	24	5	14	4	70	36
	30-50	22	5	9	5	49	4	16	5	40	23
Exchangeable K ($mmol_c$ kg^{-1})	0-20	8	3	5	3	3	5	3	2	1	3
	30-50	3	1	5	2	4	4	3	1	1	3
Base saturation (%)	0-20	33	-	45	24	87	59	47	28	76	58
	30-50	23	-	31	27	87	43	60	34	29	60
Exchangeable Al ($mmol_c$ kg^{-1})	0-20	0	6	0	na	0	na	0	0	0	0
	30-50	0	16	0	na	0	na	0	0	0	0
Al saturation (% ECEC)	0-20	0	33	0	-	0	-	0	0	0	0
	30-50	0	52	0	-	0	-	0	0	0	0

† data modified from National Soil Service (1988c)
‡ data modified from Braun (1994)
§ data modified from National Soil Service (1987a)

Forest, fallows and sisal

At a sisal plantation in the Uplands of Tanga Region, Ferralsols and Acrisols were systematically sampled to investigate the effects of fallow periods and continuous sisal cultivation on different Major Soil Groupings. In total 24 composite samples of 0-20 cm and 30-50 cm depth were taken of soils: (i) under secondary forest, (ii) which have been fallow for 18 years, preceded by 20 years of sisal cultivation, (iii) which have been continuously cropped with sisal for the past 60 years with little or no fertilization.

Ferralsols under continuous sisal cultivation had a pH of 4.5 in the topsoil and 4.3 in the subsoil accompanied by high aluminium saturations (TABLE 4.5). The pH of Ferralsols under bush fallow was similar to the pH of the soil under secondary forest. Only slight differences were found in the organic carbon contents of Ferralsols between the three land-use systems (range: 1.5-1.8% C). Levels of available phosphorus were very low in all three land-use systems and typically below 3 mg P kg^{-1}.

The sum of exchangeable cations (calcium, magnesium and potassium) was low to very low in the topsoils and did not differ much between the three land-use systems. Exchangeable cations in the subsoils of the Ferralsols were extremely low, and coefficients of variation were high. Aluminium saturation was high in the subsoils under continuous sisal cultivation (60% ECEC), but under bush fallow, aluminium saturation was low in both topsoil and subsoil.

In the Acrisols, the difference in pH between continuous sisal cultivation and 18 years of bush fallow was nearly one unit. The pH under secondary forest was slightly higher than after 18 years of bush fallow. In the subsoils of the 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 carbon contents were higher than in the Ferralsols and around 1.9% in all three land-use systems. Available phosphorus levels under bush fallow and continuous sisal cultivation were very low. Under secondary forest, available phosphorus levels were medium.

The levels of exchangeable calcium in the topsoils of the Acrisols under bush fallow were higher than under sisal, whereas levels of exchangeable magnesium and potassium differed only slightly. Exchangeable cation levels in the subsoils did not differ much between the three land-use systems.

Moderate levels of aluminium saturation were found in the subsoils under continuous sisal cultivation. Aluminium saturation was 8% in the subsoils of bush fallows, but it was zero under secondary forest. In the subsoils of the Acrisols under continuous sisal cultivation aluminium saturation was 17%.

TABLE 4.5 *Soil fertility status of Ferralsols and Acrisols under secondary forest, 18 years of bush fallow and continuous sisal cultivation.*

Major Soil Grouping:		Ferralsols						Acrisols					
Land-use:		secondary forest		18 years of bush fallow		continuous sisal cultivation		secondary forest		18 years of bush fallow		continuous sisal cultivation	
	depth (cm)	(n=3)	cv %	(n=3)	cv %	(n=5)	cv %	(n=5)	cv %	(n=3)	cv %	(n=5)	cv %
pH (H_2O) 1:2.5	0-20	4.9	7	4.8	3	4.5	3	6.2	1	5.9	8	5.0	7
	30-50	4.9	7	4.9	3	4.3	3	5.5	8	5.1	12	4.4	7
pH (1 *M* KCl) 1:2.5	0-20	4.1	3	4.1	2	3.9	3	5.2	5	4.9	9	4.2	8
	30-50	3.9	0	4.1	1	3.9	3	4.5	8	4.3	12	3.8	8
Organic carbon (%)	0-20	1.7	10	1.5	6	1.8	10	1.9	20	1.9	12	1.8	4
	30-50	0.9	9	0.9	9	0.9	7	0.9	56	1.1	12	1.2	6
Available P (Bray I) (mg kg^{-1})	0-20	2	34	1	110	3	49	8	116	4	17	3	16
	30-50	< 0.5	-	1	82	1	67	<0.5	-	1	32	1	17
Exchangeable Ca ($mmol_c$ kg^{-1})	0-20	10	57	12	15	10	37	37	45	31	40	23	25
	30-50	3	57	8	22	3	54	13	46	9	81	16	39
Exchangeable Mg ($mmol_c$ kg^{-1})	0-20	8	25	8	27	7	32	25	11	17	29	15	28
	30-50	3	72	2	73	2	97	13	40	11	43	12	59
Exchangeable K ($mmol_c$ kg^{-1})	0-20	1	71	4	51	2	50	5	38	3	57	2	65
	30-50	< 0.5	-	3	71	1	82	4	26	2	102	1	89
Al saturation (% ECEC)	0-20	na	-	4	-	25	39	0	0	1	141	7	155
	30-50	na	-	10	-	60	28	0	0	8	75	17	63

n number of composite topsoil samples
cv% coefficient of variation (σ/μ*100)
na not available

Number of sisal cycles

In sisal cultivation, cropping years can be expressed in number of cycles, which is the period from planting to flowering. Soil samples were taken in fields which have been under different cycles of sisal cultivation and compared to a soil under virgin forest (TABLE 4.6). The samples were taken at a plantation north of Mlingano in soils derived from gneiss (Ferralsols). Although only a few samples were taken, soil analysis showed that all fertility parameters were highest in the soil under forest and lowest after three cycles of sisal.

TABLE 4.6 *Soil fertility status of Ferralsols under forest and after two or three cycles of sisal cultivation.*

	Forest		2 cycles of sisal		3 cycles of sisal	
Soil depth (cm):	0-20	30-50	0-20	30-50	0-20	30-50
pH (H_2O) 1:2.5	6.2	5.7	5.7	5.2	5.2	5.1
pH (1 *M* KCl) 1:2.5	5.7	4.4	4.5	4.0	4.0	4.0
Organic C (%)	2.1	0.9	1.7	0.6	1.7	0.6
Total N (%)	0.19	0.08	0.13	0.05	0.14	0.06
C:N	11	11	13	12	12	10
Available P (Bray I) (mg kg^{-1})	3	1	2	1	3	1
CEC (NH_4OAc pH 7) ($mmol_c\ kg^{-1}$)	125	105	117	98	88	60
Exchangeable Ca ($mmol_c\ kg^{-1}$)	68	23	32	18	13	9
Exchangeable Mg ($mmol_c\ kg^{-1}$)	26	21	16	10	5	3
Exchangeable K ($mmol_c\ kg^{-1}$)	5	4	6	3	1	< 0.5
Base saturation (%)	80	46	48	32	21	20
Exchangeable Al ($mmol_c\ kg^{-1}$)	0	0	0	5	9	10
Al saturation (% ECEC)	0	0	0	14	31	43

An exception is the available phosphorus content which was very low in all three soils. The pH decreased by 0.5 of a unit in the topsoil with an extra cycle of sisal. Soil organic carbon contents did not differ between two and three cycles of sisal. Organic carbon contents under forest were 0.4% points higher than under sisal accompanied by a lower C/N ratio. The exchangeable cation contents decreased with an extra cycle of sisal, particularly in the subsoil. Exchangeable potassium was exhausted after three sisal cycles. The decrease in pH resulted in an increase of exchangeable aluminium, and aluminium saturation was 43% in the subsoils after three cycles of sisal.

Hybrid 11648 effects

After a number of detailed soil surveys, the National Soil Service (1988d) tentatively concluded that a decline in soil fertility may have been promoted by the planting of hybrid 11648. They noted that the hybrid has a higher nutrient demand as compared to *Agave sisalana*, and that the ratio years immature/years mature of the hybrid is lower by which eventually more nutrients are removed per cycle. This hypothesis was further investigated for some Major Soil Groupings which were planted at different years with hybrid 11648 (TABLE 4.7). Before they were planted with hybrid 11648, the soils were cultivated with *Agave sisalana* for at least 30 years.

A Ferralsol at Kwamdulu estate planted with hybrid 11648 in 1980, had lower levels of exchangeable cations than a Ferralsol planted with hybrid 11648 in 1987. There were no differences in pH and organic carbon contents between the two planting years but aluminium saturation was 75% in the subsoil of the field planted in 1980. On the same plantation, Acrisols were sampled. The pH of the Acrisols planted with hybrid in 1980 was 0.8 of a unit lower and also levels of exchangeable cations were lower. Similar effects were recorded in Acrisols at the coast (Mwera estate) where longer periods of hybrid 11648 cultivation resulted in lower fertility levels. This was particularly observed in the exchangeable cation levels, which decreased with ten extra years of hybrid 11648 cultivation. Also a Cambisol at Mwera estate had lower magnesium and potassium levels when it was cultivated with hybrid 11648 for a longer time. Exchangeable calcium and pH of Cambisols were not influenced by the period of hybrid cultivation.

Although the results presented here are only few, it seems that hybrid 11648 does accelerate soil fertility decline and in particular reduces the levels of exchangeable cations in both topsoil and subsoil. The accelerated process of a declining fertility is presumably first noticeable in soils with low mineral reserves like Ferralsols and Acrisols.

4.3 Nutrient Balance

A nutrient balance (budget) is a useful tool in research and extension studies, and may provide insight in the sustainability of an agro-ecosystem from a nutrient perspective. Frequently, the balances are used to plan nutrient management or to estimate an unknown output of a system. The merit of a nutrient balance largely depends on the exact quantification of the individual input and output records. Some are simple to quantify (e.g. nutrient removal by the harvested product); others are hard to measure (e.g. denitrification) and may explain the difference between input and output.

TABLE 4.7 *Soil analytical data of some Major Soil Groupings under continuous sisal cultivation and different periods of hybrid 11648.*

Major Soil Grouping:		Ferralsol		Acrisol		Acrisol		Luvisol		Cambisol	
Plantation:		Kwamdulu†		Kwamdulu†		Mwera‡		Mwera‡		Mwera‡	
Hybrid 11648 since:	depth (cm)	1980	1987	1980	1987	1965	1975	1972	1978	1970	1986
pH (H_2O) 1:2.5	0-20	4.3	4.4	5.0	5.8	5.3	6.7	6.6	5.5	7.8	7.9
	30-50	4.2	4.0	4.9	4.5	4.7	6.1	5.1	5.2	7.7	8.1
Organic C (%)	0-20	1.8	1.7	1.9	1.6	1.0	1.7	0.8	1.4	2.0	2.0
	30-50	0.8	0.9	1.3	1.3	0.6	0.7	0.5	0.8	0.9	0.9
Available P (Bray I) (mg kg^{-1})	0-20	3	< 0.5	3	3	1	1	2	1	1	2
	30-50	< 0.5	1	1	2	1	1	1	1	3	1
CEC (NH_4OAc pH 7) ($mmol_c$ kg^{-1})	0-20	na	na	na	na	140	147	108	121	320	242
	30-50	na	na	na	na	125	175	151	90	386	287
Exchangeable Ca ($mmol_c$ kg^{-1})	0-20	4	14	25	55	24	99	44	40	272	226
	30-50	3	4	20	15	18	88	23	37	282	196
Exchangeable Mg ($mmol_c$ kg^{-1})	0-20	3	8	13	16	9	23	12	8	20	42
	30-50	2	1	10	6	1	16	16	12	8	44
Exchangeable K ($mmol_c$ kg^{-1})	0-20	2	1	1	6	1	1	2	2	2	8
	30-50	1	< 0.5	< 0.5	2	< 0.5	1	1	1	1	3
Base saturation (%)	0-20	-	-	-	-	26	85	55	42	92	100
	30-50	-	-	-	-	16	61	27	57	76	85
Exchangeable Al ($mmol_c$ kg^{-1})	0-20	5	5	3	0	0	0	0	0	0	0
	30-50	18	3	6	6	na	0	0	0	0	0
Al saturation (% ECEC)	0-20	36	18	7	0	0	0	0	0	0	0
	30-50	75	35	16	20	-	0	0	0	0	0

† soils were sampled in 1987 and had been cultivated with *Agave sisalana* for at least 30 years, data modified from National Soil Service (1988b)
‡ soils were sampled in 1987, and had been cultivated with *Agave sisalana* for at least 30 years, data modified from National Soil Service (1988a)

na not available

For their supra-national study of nutrient depletion in sub-Saharan Africa, Stoorvogel & Smaling (1990) considered five input and five output factors. Nutrient input includes: mineral fertilizers, animal manure, atmospheric deposition, biological nitrogen fixation and sedimentation. Output of nutrients includes: harvested crop parts, crop residues, leaching, denitrification and water erosion.

For the nutrient balances presented in this account, deposition, biological nitrogen fixation and harvested crop parts are considered. Mineral fertilizers, manure and sedimentation were all nil since sisal was neither fertilized nor flooded. Crop residues were not removed from the field and were not considered in the nutrient balance. Erosion may occur on sloping lands where the sisal is clean weeded. Ngatunga *et al.* (1984) found, however, that runoff and erosion on Ferralsols in Mlingano were effectively controlled by a grass cover. As sisal is a perennial crop which gives better protection than annual crops (Ahn, 1977) and as it is always grown with a grass cover, losses of nutrients by erosion are considered negligible and they are therefore not included in the nutrient balances.

Methodology

The nutrient balance was calculated for a sisal field in the Uplands of Tanga Region, and was compared to changes in soil nutrient contents over a 25 years period. The sisal field was located at the foot of the East Usambaras and the soils were red, very deep, uniform and classified as Rhodic Ferralsols (Hartemink, 1991a). Topsoil (0-20 cm) clay content was 35% increasing to 50% at 50 cm depth. The natural forest at the site was cleared mechanically in 1956 and the first sisal (*Agave sisalana*) was planted in 1957. Of this first planting, leaves were cut till 1965 and by then most of the sisal plants had poled. The land was cleared again mechanically, and replanted in 1966. In 1976, a third sisal crop (hybrid 11648) was planted which was harvested up to the late 1980s. From 1966 to 1990, sisal yields (t ha^{-1} yr^{-1}) and rainfall (mm d^{-1}) were recorded.

In this sisal field, a composite topsoil sample (0-20 cm) was taken by E.C. Diekmahns of the Sisal Research Station at Mlingano prior to the second cycle in 1966. Analysis showed the topsoils to contain: 2.5% organic C, 0.22% total N, 20 mg P kg^{-1} (Bray I), 19 $mmol_c$ Ca kg^{-1}, 11 $mmol_c$ Mg kg^{-1} and 3.6 $mmol_c$ K kg^{-1}. The pH H_2O was 5.5 and base saturation was 45%. In the same sisal field, a new composite soil sample was taken by the present writer in 1990. Now the topsoil contained 1.5% organic C, 0.12% total N, 3 mg P kg^{-1} (Bray I), 6 $mmol_c$ Ca kg^{-1}, 3 $mmol_c$ Mg kg^{-1} and 0.8 $mmol_c$ K kg^{-1}. The pH H_2O had decreased to 5.0 and base saturation to 16%.

Ring samples (100 mL) were taken in soil pits in 1990 for the determination of the bulk density (ρ_D). Topsoil bulk density was 1.31 kg dm^{-3} (mean of three replicates) and this value was used to calculate the soil nutrient content(1) in kg ha^{-1}. For the calculation of nutrients in kg ha^{-1}, the measured bulk densities of 1990 were also used for the 1966 soil analytical data. As the soils in 1966 were already ten years under cultivation, it is assumed that their bulk densities have not changed significantly between 1966 and 1990.

Nutrient inputs and outputs

Nutrients in the wet deposition (IN_{rain} in kg ha^{-1} yr^{-1}) were calculated with the regression equation developed for sub-Saharan Africa by Stoorvogel & Smaling (1990). The equation uses the square-root of the total annual rainfall (P) multiplied by a factor f:

$$IN_{rain} \text{ nutrient } = f * \sqrt{P}$$

The factor f is estimated to be: 0.14 for nitrogen, 0.023 for phosphorus and 0.092 for potassium (Stoorvogel & Smaling, 1990). At the site, annual rainfall varied from 599 to 1,669 mm between 1966 and 1990. Nitrogen deposited with the rainfall hence varied from 3.4 to 5.8 kg ha^{-1} yr^{-1} (mean 4.6 kg N ha^{-1} yr^{-1}), phosphorus deposits ranged from 0.6 to 0.9 kg ha^{-1} yr^{-1} (mean 0.8 kg P ha^{-1} yr^{-1}) and potassium deposition was on average 3.0 kg ha^{-1} yr^{-1} (range: 2.3-3.8 kg K ha^{-1} yr^{-1}). These values correspond fairly well with the scarce literature on NPK contents in wet deposition (e.g. Poels, 1987; Pieri, 1989a; Stoorvogel & Smaling, 1990).

No equation could be found which links annual rainfall with calcium or magnesium deposition. As the site is about 60 km from the coast of the Indian Ocean and the rainwater is mainly derived from sea-evaporation, a relative high calcium and magnesium concentration may be expected. Parker (1983) gives as world average values for calcium and magnesium in the rainwater 0.82 and 0.40 mg L^{-1} respectively, which is based on a large number of rain samples. These concentrations are equivalent to 0.82 kg calcium and 0.40 kg magnesium ha^{-1} per 100 mm of rain. At the site, average annual rainfall is 1,044 mm, and the average input was estimated to be: 8.5 kg Ca ha^{-1} yr^{-1} and 4.2 kg Mg ha^{-1} yr^{-1}. Annual rainfall input of calcium and magnesium in Ghana (1,850 mm rain yr^{-1}) was 12.8 and 11.3 kg ha^{-1} respectively (Nye, 1961). Bruijnzeel (1990) compiled data from various sources and gives for Venezuela (1,500 mm rain yr^{-1}) 5.6 kg Ca ha^{-1} yr^{-1} and 5.2 kg Mg ha^{-1} yr^{-1}.

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(1) Organic C and total N data can be simply multiplied with the bulk density to arrive at kg ha^{-1}, because the measurements are of the total C and N pools in the soil. Available P and exchangeable Ca, Mg and K are only a fraction of the total pool in the soil. There were, however, no data available on the total P and cation content of the soil. The ratio total cation to exchangeable cation can be 4 for calcium, 8 for magnesium and up to 10 for potassium (Nye & Greenland, 1960).

Nonsymbiotic nitrogen fixation occurs in most soils but its contribution to the nitrogen balance is hard to quantify. Stoorvogel & Smaling (1990) used the following equation for the rainfall-dependent contribution of nonsymbiotic nitrogen fixation:

$$A = 2 + (P - 1350) * 0.0005$$

in which A is kg N ha^{-1} yr^{-1} and P is mm rain yr^{-1}. Rainfall at the site varied from 599 to 1,699 mm yr^{-1} (1966-1990). Hence nonsymbiotic nitrogen fixation ranged from 0 to 2.2 kg N ha^{-1} yr^{-1} (mean $<$ 0.5 kg N ha^{-1} yr^{-1}).

An important source of nutrient inputs for the sisal is the planting material, as at the beginning of a cycle thousands of small sisal plants (ca. 2 kg each) are brought to the field. These plants are raised in a nursery at a density of 80,000 ha^{-1}. Nutrient removal from such nursery is 257 kg nitrogen, 78 kg phosphorus, 283 kg potassium, 699 kg calcium and 102 kg magnesium per ha (Osborne, 1967). At the site, plant densities of field sisal were 5,000 ha^{-1}. Input of nutrients with the planting material (IN_{plant}) was estimated to be: 16 kg nitrogen, 5 kg phosphorus, 18 kg potassium, 44 kg calcium and 6 kg magnesium per ha for each cycle.

The only output of nutrients which could be quantified, was the removal with the harvested products (OUT_{yield}). Annual yield data (t fibre ha^{-1} yr^{-1}) were multiplied with nutrient removal data (kg ha^{-1}) to arrive at kg nutrient per t fibre ha^{-1} yr^{-1}. The removal data of Osborne (1967, see TABLE 2.2) were used here as they refer to sisal growing on deep red soils in Tanga Region. Total fibre yield of the sisal field between 1966 and 1990 was 18.5 t ha^{-1} of which 12 t ha^{-1} was harvested in the first cycle (1966-1976). In the second cycle, only 6.5 t fibre ha^{-1} was harvested, mainly due to poor field maintenance in that period.

The balance

Differences between input with planting material and rainfall, and output by the harvested product (yield), were calculated for the five major nutrients. In the absence of fertilizers and manure the balance is negative for each nutrient (TABLE 4.8).

Total input of nitrogen in the period 1966 to 1990 was 166 kg N ha^{-1} of which the major part was added with the rainfall. The output of nitrogen with the harvested product was about three times larger than the sum of inputs, and the total difference between 1966 and 1990 was -316 kg ha^{-1}. Little phosphorus is deposited with the rainfall ($<$ 1 kg ha^{-1} yr^{-1}) but the output of phosphorus is also low (65 kg P ha^{-1} in 25 years). Although fair amounts of cations are deposited in the rainfall and supplied with the planting material, there is a large shortfall for the three cations. The removal of potassium is nearly eight times larger than the input. For calcium and magnesium the removal is about five times larger than the input. These figures clearly illustrate the depletion of cations under sisal cultivation.

TABLE 4.8 *Nutrient balance of a sisal field during the period 1966 to 1990 (kg ha^{-1}).*

	Nutrient				
	nitrogen	phosphorus	potassium	calcium	magnesium
IN_{plant} 1966+1976†	32	10	35	87	13
IN_{rain} 1966-1990‡	134§	19	75	213	105
OUT_{yield} 1966-1990††	482	65	816	1,520	575
$\Sigma\ IN_{1966\text{-}1990} - \Sigma\ OUT_{1966\text{-}1990}$	−316	−36	−706	−1,220	−457

† input with sisal planting material in 1966 and in 1976
‡ input from rainfall (see text for calculations)
§ includes 19 kg N ha^{-1} from a-symbiotic fixation (see text for calculations)
†† yield in t fibre ha^{-1} multiplied with nutrient removal in kg t^{-1} fibre (see TABLE 2.2)

Soil nutrient contents

Topsoil nutrient contents were calculated for 1966 and 1990 using the soil analytical data and bulk density values as given above (TABLE 4.9). In 1966, the topsoil of the Ferralsol contained 5,764 kg N ha^{-1} but this had decreased to 3,144 kg N ha^{-1} in 1990. Differences in the available phosphorus contents between the two periods was −44 kg, and only 8 kg P ha^{-1} was available in the topsoils in 1990. Potassium, calcium and magnesium contents

TABLE 4.9 *Soil nutrient contents of a sisal field sampled in 1966 and in 1990 (kg ha^{-1} for 0-20 cm).*

	Nutrient				
	nitrogen	phosphorus	potassium	calcium	magnesium
$SOIL_{1990}$†	3,144	8	82	271	97
$SOIL_{1966}$†	5,764	52	369	996	355
$SOIL_{1990} - SOIL_{1966}$	−2,620	−44	−287	−725	−258

† calculated with ρ_D = 1.31 kg dm^{-3}.

in 1990 were less than 30% of their 1966 contents. It must be remembered that especially for phosphorus and potassium the loss will be partly made good from the non-exchangeable forms (Nye & Greenland, 1960).

Nutrient balance vs soil nutrient contents

The input-output balance was compared with the difference in soil nutrient contents between 1966 and 1990. Both approaches show that there is a negative balance for each of the five nutrients (TABLE 4.10).

TABLE 4.10 *Nutrient balance based on the input-output balance, and on difference in soil nutrient contents between 1990 and 1966 (kg ha^{-1} yr^{-1}).*

	Nutrient				
	nitrogen	phosphorus	potassium	calcium	magnesium
$(\Sigma\, IN_{1966\text{-}1990} - \Sigma\, OUT_{1966\text{-}1990})/25$	−13	−1.4	−28	−49	−18
$(SOIL_{1990} - SOIL_{1966})/25$	−104	−1.8	−11	−29	−10

More nitrogen has disappeared from the topsoil than was calculated from the input-output balance. Mean annual losses can be calculated as the net difference in soil nitrogen content *minus* the difference between nitrogen input and output:

$$\text{net annual N loss} = ((SOIL_{1990} - SOIL_{1966})/25) - ((\Sigma\, IN_{1966-1990} - \Sigma\, OUT_{1966-1990})/25)$$

which becomes: $-104 - -13 = -91$ kg N ha^{-1} yr^{-1}.

These mean annual losses are high, particularly when taking into account that the data are from unfertilized conditions. Nitrogen losses may have increased when the process of soil fertility had proceeded and other nutrients (e.g. potassium, calcium) were limiting sisal growth. It may have been lost from the topsoil through leaching, and there is a fair possibility during April and May when the rainfall surplus is on average about 75 mm. Leaching losses may have occurred at the time of land preparation when no uptake occurs (Sanchez *et al.*, 1983), and if land preparation takes place at the beginning of the rainy season when mineralization is enhanced, nitrate leaching losses can be very high (Poss & Saragoni, 1992; Cahn *et al.*, 1993b).

The leached nitrate from the topsoil is apparently not retrieved by the sisal roots and recycled to the topsoil as occurs under some other perennials (Seyfried & Rao, 1991). Indeed most sisal plants concentrate their roots in the upper 30 cm and have very few roots at depth (Lock, 1969).

Nitrate leached below the rooting zone of the sisal is not necessarily lost. It may be adsorbed by positively charged soil particles which retards leaching to greater depths (Kinjo & Pratt, 1971; Arora & Juo, 1982; Wong *et al.*, 1990). On the other hand, the strongly acid soil conditions favouring nitrate adsorption, limit the rooting depth of sisal for utilizing subsoil nitrate. Although leaching may be one way of nitrogen loss under sisal cultivation, other ways are perhaps equally important but from this study no conclusive answer can be provided.

Differences in topsoil phosphorus contents (-1.8 kg ha^{-1} yr^{-1}) were about the same as the input-output balance (-1.4 kg ha^{-1} yr^{-1}). It suggests that very little phosphorus is lost from the topsoil, and that the input-output balance explains most of the measured differences in available phosphorus.

The annual decrease in exchangeable cations of the topsoil is lower than was calculated from the input-output balance. Part of the difference may be explained by the weathering of soil particles releasing cations and affecting the exchangeable cation contents. It should be borne in mind that contributions from mineral weathering are probably very low in this highly weathered soil. Secondly, it may imply that although roots are concentrated in the upper 30 cm, the subsoil was an important source of cations for the sisal crop despite its shallow root system. Although nitrate leaching is a likely explanation for the nitrogen losses, leaching of cations from the topsoil is an improbable process to explain the difference in soil cation contents between 1966 and 1990.

4.4 Trends and Effects

In the first sections of this chapter, differences in soil fertility decline between, and within, Major Soil Groupings were presented. Despite the substantial variation found, this section discusses the overall trends in soil fertility decline with their effects on crop growth: increase of soil acidity, loss of organic matter and nitrogen, decreased phosphorus availability and loss of cations.

Increasing acidity

In many soils in Tanga Region acidity increased under continuous sisal cultivation but some soils in the Coastal Area showed little or no decrease in pH with time. The increase in acidity was particularly observed in soils derived from Precambrian rocks (Ferralsols, Acrisols), from sandstone (Ferralsols) and soils from sandy deposits (Arenosols). Hartemink & Wienk (1995) have shown that the topsoil pH of Ferralsols of three sisal plantations decreased from an average of 6.1 in the late 1950s to 4.9 in the late 1980s ($r^2=0.549^{***}$). Difference in pH between soils under bush and sisal were 1.0 to 1.5 of a unit in many Major Soil Groupings. The main cause for the increase in acidity is of course the removal of cations by the sisal crop, and this process was possibly enhanced by the cultivation of hybrid 11648 since it removes larger amounts of calcium than *Agave sisalana.*

Increasing acidity has a number of direct and indirect effects which are unfavourable for calcicole plants like sisal. Islam *et al.* (1980) have shown that at low pH and low calcium concentrations damage to root membranes occurs which results in leakage of ions from the roots. Also the uptake of calcium, magnesium and potassium is suppressed in the presence of high H^+ concentrations which is particularly problematic in soils with very low CECs (Kamprath, 1984). As the acidity increases, aluminium is released from the soil particles into the soil solution where it has effects similar to H^+ i.e. inhibiting calcium uptake and injuring roots. Also manganese becomes soluble and may be found at toxic levels inducing chlorotic mottling in sisal leaves (Muller, 1964). Another disadvantage of subsoil acidity is the decrease in rooting depth limiting deep nutrient and water uptake (Ritchey *et al.*, 1980).

Loss of organic matter

Organic carbon contents ($\approx$ organic matter $*$ 0.58) declined under continuous sisal cultivation. This was particularly observed in Ferralsols and Acrisols (Uplands) where a decline of 0.3 to 1.0% points was recorded. In soils of the Coastal Area, no apparent relation between organic carbon and sisal cultivation was observed, but is should be added that fewer samples were available from soils in the Coastal Area.

The decrease in organic carbon levels has important consequences for crop production because organic matter supplies most of the nitrogen and half of the phosphorus taken up by unfertilized crops (Sanchez, 1976). Furthermore, organic carbon is important for the retention of cations in highly weathered soils like Ferralsols and Acrisols (ca. 2500 to 3500 $\text{mmol}_c\ \text{kg}^{-1}$ C). Reduction in organic carbon content therefore greatly reduces the CEC which may enhance the leaching of cations. Phosphorus immobilization may also increase when organic matter contents decrease and leaching losses of micronutrients may be accelerated because organic matter forms complexes with them. Furthermore a decrease in organic matter may result in an increased susceptibility to erosion and decrease the water holding capacity of the soil.

From the soil nutrient contents presented in the previous section, some basic calculations can be made on the dwindling organic carbon contents. The topsoil (0-20 cm) carbon content of the Ferralsol sampled in 1966 was 65,500 kg ha^{-1}, and 39,300 kg ha^{-1} in 1990. From the decrease in organic carbon contents, an average annual decomposition rate (k) can be calculated, thereby using the exponential decay curve of carbon (Ladd & Amato, 1985):

$$C_t = C_0 * e^{-kt}$$

where C is the organic matter content (kg ha^{-1}), k is the decomposition rate (%) and t is time (years). For calculating the value of k, the formula is rewritten as:

$$\ln C_t = -k * t + \ln C_0$$

Substituting the 1990 and 1966 organic carbon values for C_t and C_0, and 25 for t (1966 to 1990), gives an average net decomposition rate (k) of 2.0% per annum.

Greenland & Nye (1959) give 2.5% as decomposition factor for an ustic tropical forest, and 1.3% for a tropical savanna, both located in Ghana. The average decomposition rate of 2.0% calculated for the sisal field located in the ustic Uplands of Tanga Region, falls within this range.

Loss of nitrogen

The decomposition rate provides also information on the natural supply of nitrogen. The total amount of nitrogen released between 1966 and 1990 can be calculated with:

$$N_t = (1-k)^t * N_0$$

in which N_t and N_0 is the nitrogen content of the soil (kg ha^{-1}), and t is time (yr). From the difference between the two periods, the total nitrogen mineralized can be calculated as:

$$N_{total} = N_t - N_0$$

in which N_{total} is the total amount mineralized in time t.

Substituting 2.0% for k, and 5,764 kg N ha^{-1} for N_0 (total N content in the topsoil in 1966, see TABLE 4.9), gives as total nitrogen mineralized 2,286 kg ha^{-1}. This is 334 kg ha^{-1} lower than was calculated from the difference in total nitrogen content in the soil. The net decomposition rate of 2.0% proved fairly correct for the decrease in soil organic carbon, but slightly overestimates the amount of nitrogen which is mineralized.

More important than the total amounts released between 1966 and 1990, is the amount of nitrogen released in a year. Based on an average organic matter decomposition of 2.0%, 115 kg N ha^{-1} yr^{-1} was released in 1966, but only 63 kg N ha^{-1} yr^{-1} in 1990. This clearly shows that dwindling organic carbon contents severely reduce the natural nitrogen supply.

Decreasing phosphorus availability

Many of the soils presented in Chapter 3 and 4 have phosphorus levels below 10 mg kg^{-1} (Bray I) but more often below 5 mg kg^{-1} and in some soils available phosphorus was hardly traceable ($<$ 0.5 mg P kg^{-1}). Soils with high phosphorus levels were the Cambisols and Vertisols at the footslopes of the West Usambaras and some soils developed in deposits over limestone at Pongwe estate.

In many sisal fields with extremely low phosphorus levels, weeds like thatching grass (*Hyparrhenia rufa*) showed characteristic purple colouring which is a sign of phosphorus deficiency. Such signs were, however, not encountered in the sisal plants. The sisal plant has a modest phosphorus requirement and the input-output balance has shown that the average shortfall was -1.4 kg P ha^{-1} yr^{-1} (TABLE 4.10). A possible explanation for the absence of phosphorus deficiency symptoms in sisal is that for the current low yields, sufficient phosphorus becomes available with the mineralization of the organic matter. In many tropical soils, most of the phosphorus is in the organic form and becomes available with mineralization of the organic matter (Sanchez, 1976; Stewart & Sharpley, 1987). The combination of increasing acidity resulting in phosphorus immobilization, with the decrease in soil organic matter, may severely reduce the phosphorus availability to levels where even moderate sisal yields (≈ 1.5 t ha^{-1} yr^{-1}) might be unobtainable.

Loss of cations

The loss of cations was clear in soils with low mineral reserves like the Ferralsols, Acrisols and Arenosols. The main cause for the decrease in cations is the removal by the sisal crop. The nutrient balances have shown that the annual shortfall is large, particularly for calcium and potassium. The shortfall based on the input-output balance was larger than the difference in topsoil contents over the 25 years period, which may indicate that cations also were taken up from the subsoil.

The effect on sisal yields

Clear trends in soil fertility decline were found. Both national sisal production and estate yields have declined (see FIG. 2.2 & 2.4), but relating the decline in soil fertility to sisal yields is another question. Although total production records of the FAO-Production Yearbooks confirm reasonably well with other sources (e.g. Guillebaud, 1958; Lock, 1969; Kimaro *et al.*, 1994), the area under sisal in the FAO yearbooks shows large variations making accurate yield calculations at a national level a hazardous undertaking. At the plantation level, yield data are usually only recorded for the entire plantation allowing no link between yields and soil fertility parameters of individual fields.

Hartemink (1991a) linked soil chemical data of Ferralsols with sisal yields of individual fields of a plantation in Tanga Region (TABLE 4.11).

TABLE 4.11 *Sisal yields and soil fertility status of three sisal fields (Ferralsols) at one plantation in Tanga Region (Hartemink, 1991a).*

Yield (t ha^{-1} yr^{-1}):	2.3		1.8		1.5	
Soil depth (cm):	0-20	30-50	0-20	30-50	0-20	30-50
pH (H_2O) 1:2.5	6.5	5.3	5.4	5.2	5.0	4.9
pH (1 *M* KCl) 1:2.5	5.3	4.2	4.1	4.1	3.9	3.9
Organic C (%)	1.6	0.8	1.9	0.6	1.5	0.5
Total N (%)	0.11	0.05	0.16	0.07	0.12	0.04
C:N	15	16	12	9	13	13
Available P (Bray I) (mg kg^{-1})	5	1	4	< 0.5	3	1
CEC (NH_4OAc pH 7) ($mmol_c$ kg^{-1})	93	73	111	70	64	50
Exchangeable Ca ($mmol_c$ kg^{-1})	46	22	19	12	6	6
Exchangeable Mg ($mmol_c$ kg^{-1})	17	9	6	3	3	2
Exchangeable K ($mmol_c$ kg^{-1})	7	4	2	1	1	< 0.5
Base saturation (%)	79	51	25	23	16	17
Exchangeable Al ($mmol_c$ kg^{-1})	0	3	7	6	11	13
Al saturation (% ECEC)	0	10	20	26	50	59

Although the data are only few, they show that the highest yield (2.3 t ha^{-1} yr^{-1}) was obtained in a field with the highest pH, levels of exchangeable cations and base saturation levels in both topsoil and subsoil. The lowest yield (1.5 t ha^{-1} yr^{-1}) was obtained in a field with a topsoil pH of 5.0, a low base saturation and an aluminium saturation in the subsoil of 59%.

5 SOIL FERTILITY MANAGEMENT

Soil fertility management has been an important area of research at the Sisal Research Station Mlingano from the 1940s to 1970s. Many dose-effect trials with fertilizers and lime were conducted, often related to plant density and soil type. With the reduced interest in sisal growing, research on soil fertility management ceased and little recent information is available. Management options discussed in this chapter are therefore mainly based on the early Mlingano work combined with some recent knowledge. General fertilizer recommendations for sisal are given in: Tanzania Sisal Growers Association (1965), Acland (1971), De Geus (1973), Samki & Harrop (1984), Ahn (1993), Kalumuna (1993), and Mowo *et al.* (1993),

5.1 Fertilizers and Lime

It is manifest that hard and fast rules for fertilizing sisal cannot be laid down because these depend on the kind of soil and its previous cropping. A common feature to all the field trials conducted on land under continuous sisal, is a response to nitrogen and this is more marked in low rainfall areas (Lock, 1969), where mineralization rates are lower (Rijkebusch & Osborne, 1965). Responses to nitrogen fertilizer applications have been recorded up to 0.19% total N. It is generally economic to apply nitrogen fertilizer in medium to high rainfall areas if the target is an average yield of over 2 t ha^{-1} yr^{-1} and provided there are no other nutrient deficiencies.

The Tanzania Sisal Growers Association (1965) recommends 150 kg N ha^{-1} per cycle when nitrogen levels are low and 300 kg N ha^{-1} for very low nitrogen levels. Kalumuna (1993) recommends 100 kg N ha^{-1} for mature sisal on soils which are very low in N (< 0.10%) to be given in split applications. Ahn (1993) recommends 50 to 100 kg ha^{-1} for soils with a marked nitrogen deficiency. Based on the work of Samki & Harrop (1984), Mowo *et al.* (1993) advise 50 kg ha^{-1} for sisal on Ferralsols in Tanga Region. Nitrogen fertilisers must be applied to bare soil near the sisal plants (Acland, 1971).

Nitrogen fertilizers may acidify the soil. Care should therefore be taken in the selection of nitrogen fertilizers, as sulphate of ammonia and urea may lower the pH and increase soil solution aluminium concentration (Schwab *et al.*, 1990; Heenan & Taylor, 1995), which is unfavourable for many soils under sisal cultivation. For example, about 1.8 kg $CaCO_3$ should be applied to neutralize the acidity produced by 1 kg nitrogen in the urea form (Parish, 1993). Calcium ammonium nitrate (20.5% N) is a suitable fertilizer on acid soils in the Uplands, whereas urea (46% N) might be applied on slightly acid soils. Nitrogen fertilizers may induce potassium deficiency ('banding disease') and they should always be applied together with potassium. This is particular recommended for low fertility soils like the Ferralsols and Acrisols in the Uplands which have been under prolonged periods of sisal cultivation.

Phosphorus is not needed in large amounts by sisal and it is probably of greatest value when the plants are young. Acid soils may have very low levels of available phosphorus and immobilization may be high (Sanchez & Uehara, 1980). For such soils, ground rock phosphate (ca. 13% P) is a suitable fertilizer whereas Triple Super Phosphate (ca. 20% P) can be used on slightly acid soils. The effects of phosphorus applications can be long lived as was found in Kenya and Brazil (Boswinkle, 1961; Yost, *et al.* 1981), but the residual value may differ widely and is not always related to soil properties (Le Mare, 1974).

The Tanzania Sisal Growers Association (1965) recommends for most soils about 13 g phosphorus in the planting hole, which is equivalent to 65 kg P ha^{-1} at a density of 5,000 plants per ha. Kalumuna (1993) recommends 25 kg P ha^{-1} for soils with available phosphorus levels below 7 mg P kg^{-1}, and 13 kg P ha^{-1} for soils with phosphorus levels up to 20 mg P kg^{-1}.

Potassium is essential where the soil is low in this nutrient and 'banding disease' develops. A common fertilizer for sisal is Muriate of Potash (ca. 50% K), and the Tanzania Sisal Growers Association (1965) recommends about 25 kg K ha^{-1} for five years where the soil potassium status is low, and 250 kg K ha^{-1} per sisal cycle where potassium levels are very low. Kalumuna (1993) recommends 200 kg K ha^{-1} for loamy and clay soils and 20 kg K ha^{-1} on sandy soils when the exchangeable potassium level is below 1.5 $mmol_c$ kg^{-1}. For soils with potassium levels between 1.5 and 2.9 $mmol_c$ K kg^{-1} the recommended application is 20 kg K ha^{-1} (Kalumuna, 1993).

Liming

Calcium is a major nutrient for sisal and deficiencies may easily develop as the crop removes large amounts of it and as many soils under sisal cultivation have low calcium reserves. Calcium is commonly supplied to the soil with liming which has a number of direct and indirect effects. On acid soils liming is needed to: (i) increase the pH and thus eliminate the harmful effects of exchangeable aluminium and manganese, (iii) supply calcium and magnesium as they are important nutrients for sisal, and (iii) increase the phosphorus availability (Coleman *et al.*, 1985).

Kamprath (1970) suggested exchangeable aluminium as the criterion for determining the amount of lime to apply to acid soils. The relationship between the amount of $CaCO_3$ required to neutralize a given amount of exchangeable aluminium is given by the equation:

$$CaCO_3\text{-equivalent (t ha}^{-1}) = 0.15 * \text{Al mmol}_c\ \text{kg}^{-1}$$

This $CaCO_3$-equivalent will reduce the aluminium saturation to approximately zero according to Kamprath (1984). Liming to pH 5.5 and above also sufficiently decreases the solubility of manganese to eliminate its toxicity to plant growth, and the International Fertilizer Association (1992) therefore recommends that the soil pH for sisal should be 5.5 to 6.5. As sisal grows naturally on soils derived from limestone with a high pH and base saturation, it is very sensitive to low pH and the presence of exchangeable aluminium. The plant-specific aluminium saturation, as suggested by Cochrane *et al.*, (1980) for optimal growth, is therefore assumed to be zero.

The Tanzania Sisal Growers Association (1965) recommends 2 to 5 t ha^{-1} of agricultural lime which consists largely of $CaCO_3$ and up to 3% magnesium. Kalumuna (1993) recommends 5 t lime ha^{-1} for Ferralsols. Lime is usually applied before planting and its effect lasts for the whole sisal cycle of 10 years (Tanzania Sisal Growers Association, 1965). As sisal may remove about 1215 kg calcium ha^{-1} per cycle (15 t fibre ha^{-1}), 3 t $CaCO_3$ ha^{-1} ($\approx$ 1200 kg Ca ha^{-1}) is sufficient to replenish the calcium removed with the harvested leaves assuming all the calcium supplied is taken up.

The positive effects of lime on pH exchangeable aluminium and phosphorus are only obtained if the lime is thoroughly mixed with the soil as was recently demonstrated for Ferralsols in Ghana (Osei, 1995). Lime incorporated in the topsoil moves only slowly through the soil profile and may have little effect on the subsoil acidity which is the main problem in many soils. One possible way of ameliorating the subsoil acidity is to apply lime and high rates of acidifying fertilizers to the topsoil (e.g. Cahn *et al.*, 1993a). The lime and fertilizers can provide excess HCO_3 capable of moving into the subsoil to neutralize the acidity. However, results sofar have been mixed (Sumner, 1995). Another way to decrease acidity is to incorporate the lime in the subsoil using a deep limer and a subsoiler. A limitation of these methods of liming is that a relatively low volume of soil is ameliorated for the high operational costs and power requirements (McGray & Sumner, 1990). It is only attractive if subsoil acidity occurs together with a hard pan at shallow depth which is rarely found in sisal fields.

An alternative for lime may be gypsum, and Reeve & Sumner (1970) showed the beneficial effects of gypsum on subsoil acidity. Surface-incorporated gypsum moved through a Ferralsol and reduced the level of exchangeable aluminium in the subsoil more effectively than surface-incorporated lime. A problem encountered with gypsum application on highly weathered soils is the removal of potassium and magnesium from the surface soil (Ritchey *et al.*, 1980; Sumner, 1993). It would thus be advisable to include potassium and magnesium amendments if gypsum is applied.

5.2 Sisal Waste

Organic matter levels of many soils have decreased under continuous sisal cultivation with adverse effects for soil fertility. Raising soil organic matter contents is not an easy task. For the sisal plantations, old decomposed sisal waste is plentiful and is a good source of organic manure. It also contains large amounts of nutrients (TABLE 5.1).

TABLE 5.1 *Nutrient contents (kg ha^{-1} per 10 tonnes) of fresh and old sisal waste (after Lock, 1969).*

	10 tonnes of sisal waste	
	fresh	old
nitrogen	13	60
phosphorus	5	10
potassium	10	8
calcium	38	246
magnesium	10	16

Fresh sisal waste effluent is acid (pH 4.8-5.2) but it becomes slightly alkaline within about ten days. Experiments have shown that applications of old sisal waste give excellent responses on almost all soils (Berger, 1969; Acland, 1971; De Geus, 1973). The positive effect of sisal waste on soil properties was demonstrated by Osborne (1967). Exchangeable calcium levels increased from 10 to 39 mmol$_c$ Ca kg^{-1} if 50 t ha^{-1} fresh waste was applied, and from 10 to 100 mmol$_c$ Ca kg^{-1} if 50 t ha^{-1} old waste was used. The weight of sisal plants raised in a nursery increased seven-fold when old waste was applied.

Lock (1969) mentioned that the effects of sisal waste applications do not last for much more than three years after which most of the plant nutrients become mineralized. Therefore, sisal waste is particularly suitable for manuring nurseries, particularly as the bulbils remove large amounts of nutrients.

For field sisal it is difficult to cover all nutrient requirements using sisal waste, and therefore sisal growers 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).

5.3 Fallow Periods

Sisal is mostly grown in rotation with fallow periods during which sisal land is left to bush after the last cutting of leaves. Most sisal growers anticipate that during the fallow period soil fertility is sufficiently restored for a new cycle of sisal.

Hartemink *et al.* (1996) took samples in Ferralsols and Acrisols which had been under 18 years of fallow preceded by two to three cycles of sisal, and compared these values to soils under continuous sisal cultivation (TABLE 4.5). The effect of a bush fallow on the chemical soil fertility differed per parameter and soil type. The most dramatic effect was the increase in soil pH, accompanied by a decrease in aluminium saturation. This is probably the main impact of a fallow period on the chemical soil fertility. Bush fallows did not increase the organic carbon contents in both Ferralsols and Acrisols. There were no fallow effects on the exchangeable magnesium content but exchangeable calcium and potassium levels slightly increased.

Hartemink *et al.* (1996) concluded that 18 years of fallow are insufficient in restoring the soil fertility for a new cycle of sisal, and this agrees with earlier findings by Nye & Greenland (1960) and Charreau (1974).

5.4 Strategies

Several strategies for sustainable soil fertility management under sisal can be developed. An important consideration is the scale on which sisal is grown i.e. large areas with little or no inputs and thus low yields, or intensively well-managed areas with high inputs and high yields. Both systems have their advantages and the final choice for any particular cultivation system is beyond the scope of this account. It should be added, however, that from a soil nutrient perspective a system with nutrient inputs is of course preferable and approaches the goal of sustainable sisal cultivation.

The current soil fertility management strategy is the rotational system which includes fallow periods and the absence of external nutrient inputs. The heavy drain of nutrients in the cropping period and the limited effect of the fallow period mean that the current system is *soil mining* as was shown in the previous chapter. The rotational system is appropriate for some soils in the Coastal Area where cations removed are replenished by the weathering of underlying limestone rock. For optimal yields these soils also need NPK fertilizers as they suffer from nutrient imbalances (Hartemink & Bridges, 1995).

A second nutrient management strategy is the use of an improved or managed fallow as was suggested for the low fertility soils in South America (Sanchez & Salinas, 1981) and more recently for sub-Sahara Africa (Balasubramanian & Blaise, 1993). Research in Uganda showed that improved fallows with elephant grass (*Pennisetum purpureum*) were much more effective in restoring fertility than natural bush fallows (Stephens, 1967). Lock (1969) mentioned, however, that after two years of fertilized fallow with elephant grass and guinea grass (*Panicum maximum*), the growth of sisal was not as good as that on the virgin soil. Improved fallows may be inadequate to restore the fertility when the subsoil is severely depleted and very few nutrients have remained to recycle. The removal of nutrients by sisal cannot be remedied through the medium of plants alone, i.e. nutrient cycling with bush/grass or improved fallows. There is also a cost in establishing improved fallows and it may only be a serious option for intensive sisal cultivation systems, and in soils which are not completely depleted.

The most promising option for sustainable sisal cultivation is integrated nutrient management which combines an input of fertilizers, lime and/or sisal waste with leguminous cover crops. This option is particularly valid for the acid soils in the Uplands. The productivity of these soils cannot be maintained or improved solely by the use of fertilizers and lime because organic inputs are required as well (Pieri, 1989b). Integrated nutrient management is particularly suitable when sisal is grown on an intensive scale, but since each situation is unique, the optimum mixture of organic and mineral fertilizers is always site-specific (Janssen, 1993).

Leguminous cover crops with sisal may contribute significantly to the nitrogen demand of sisal (Lock, 1969; De Geus, 1973). There is not much competition between cover crops and sisal and sisal with cover crops yields better than with a grass-cover between the rows (Hopkinson, 1969, 1971). Nevertheless, cover crops were never extensively planted since they overgrow the sisal when field maintenance is poor. Intensive sisal cultivation systems with proper field maintenance justify the re-introduction of these crops.

Similar to on-farm soil fertility research with smallholders, sisal growers could establish simple trials with different inputs (lime, fertilizers, sisal waste) to assess the effects on sisal yields on their own plantations. The detailed soil maps which are available for many plantations in Tanga Region, could serve to identify suitable fields for such trials.

6 SUMMARY AND CONCLUSIONS

Sisal production of Tanzania has decreased from about 230,000 t yr^{-1} in the 1960s to 30,000 t yr^{-1} at the end of the 1980s. Both the area grown with sisal and the yield per area decreased. Yields declined because of poor agronomic practices including the lack of fertilization and manuring.

Sisal grows best with about 1,200 mm of rain per annum, and in soils with a neutral pH and a high base saturation. In Tanga Region, sisal is grown in a variety of climate and soils. It is cultivated near the coast with 1,300 mm of annual rainfall, and in the uplands at 600 m a.s.l. with only 400 mm of rain per year. Soils under sisal cultivation vary from shallow and gravelly with an alkaline reaction, to very deep and extremely acid with a high aluminium saturation. Sisal is grown in extremes of texture such as loose sandy soils (Arenosols) and black heavy clays (Vertisols), but it is commonly grown on clayey ferralitic soils (Ferralsols, Acrisols). Parent material is an important factor for the fertility of the soils under sisal cultivation. Soils near the coast, derived from a mixture of limestone with clay, fluvial sediments had generally favourable fertility levels, whereas soils in the uplands, developed *in situ* from metamorphic rocks had generally low fertility levels.

Three approaches were used to investigate the effects of continuous sisal cultivation on soil chemical properties in different Major Soil Groupings. Firstly, a large number of soil samples from the 1950s and 1960s were compared with samples from the 1980s and 1990s of the same fields which had been continuously cultivated with sisal. There was a strong decline in exchangeable cations and pH in Ferralsols and Acrisols in the absence of fertilizer applications. The decline was more severe in the Ferralsols because of a lower initial fertility and less weatherable minerals as compared to the Acrisols. Also organic carbon contents decreased under sisal cultivation. Little or no changes in soil fertility were found in Luvisols, Phaeozems, Leptosols or Cambisols between the 1950s and 1990s. In these soils, nutrients removed by the sisal crop were replenished by the weathering of the underlying limestone rock.

Secondly, samples were taken in soils under bush (woodland) that have never been under sisal, and these were compared to soils which were continuously cultivated with sisal. Ferralsols under bush had a higher fertility than Ferralsols under continuous sisal cultivation, but variation between plantations was large. None of the Ferralsols under bush, however, had lower soil fertility levels than the highest fertility under sisal. Some

Ferralsols under sisal had extremely acid soil reactions and high aluminium saturations which is unfavourable for the crop. Also Acrisols and Arenosols under bush had higher fertility levels than under sisal. Soil fertility levels of Acrisols under sisal were higher than Arenosols under bush. Soil fertility levels of Cambisols under bush and sisal were similar.

Thirdly, a nutrient balance of the "black-box" type was constructed and compared to the measured difference in the nutrient contents of a Ferralsol over a 25 years period. The nutrient balance showed a shortfall of all major nutrients in the absence of fertilization, and this was estimated to be was 13 kg N ha^{-1} yr^{-1}, 1.4 kg P ha^{-1} yr^{-1}, 28 kg K ha^{-1} yr^{-1}, 49 kg Ca ha^{-1} yr^{-1} and 18 kg Mg ha^{-1} yr^{-1}. The removal of the sisal crop accounted for only 13% of the reduction in topsoil nitrogen contents. It suggests that nitrogen losses occur and these were estimated to be 91 kg N ha^{-1} yr^{-1}. The input-output balance for phosphorus was similar to the measured difference in available phosphorus contents over 25 years, indicating that most of the phosphorus removed by the sisal crop is supplied by the topsoil. The input-output balance for cations was much higher than the calculated removal of cations from the topsoil. The difference implies that sisal plants extract a notable proportion of their cation requirements from the subsoil.

All the approaches to the study of soil fertility decline have shown that there is a profound fertility decline in many soils under sisal cultivation in Tanga Region. There were trends in most Major Soil Groupings although soil fertility decline is far from uniform and as spatial and temporal variable as soils and agro-ecosystems themselves. The main cause for the soil fertility decline is of course the drain of nutrients by the sisal crop and the lack of nutrient inputs. The process might have been accelerated by the cultivation of hybrid 11648 which was introduced in the 1960s. The hybrid removes larger amounts of nutrients particularly calcium. Although it is commonly believed that many soils of the tropics are acid and infertile by nature, soil acidity and low fertility of soils under sisal cultivation is a man-made syndrome.

Many of the soils under sisal cultivation require nutrient inputs to sustain and improve production. It is difficult to cover all nutrient requirements with organic inputs, and therefore sisal growers have to aim at integrated nutrient management which implies that both organic and inorganic nutrient inputs should be used.

What has happened to many of the soils under sisal cultivation might also take place on smallholders' farms. There is, however, a vital difference between sisal growers and smallholders. Sisal growers are not farming for subsistence, and they have the resource ability for nutrient inputs. However, they have been reluctant sofar to make these inputs. As the soil fertility declines under sisal cultivation, there is an urgent need to change this attitude. The first study has to be conducted showing that inputs of nutrients on sisal are economically unsound.

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PHOTOGRAPHS⁽¹⁾

Plate 1

The picture was taken at Ras Kikogwe (Mwera estate) where the first sisal of Tanzania was planted in 1893 by the Dane Lautherborn. A large commemorative stone was constructed under the baobab trees possibly by the *Deutsch Ostafrikanische Gesellschaft* (now Amboni Ltd). At some meters from the statue we found the commemorative tablet in the middle of a maize field, depicting:

CHRISTIAN LAUTHERBORN
Plantageleder Kikogwe Mwera
** Aalborg V-VII 1859*
† Kikogwe X-XII 1907
Er war einer der ersten welche hier den
Pflug der Kultur in die reiche Erde
Afrikas setzten.
Danske Frænder mindes ham i Kærlighed.

Plate 2

The slightly undulating Coastal Area seen from Mabokweni hill (ca. 140 m a.s.l.) at Amboni estate. The view is towards the south and the Tanga Bay and Indian Ocean can be clearly seen. Mangrove vegetation and coconuts are dominant directly along the coast, whereas sisal is grown inland. On sisal plantations south of Tanga town (i.e. Kigombe estate), sisal is nearly planted on the beach.

Plate 3

Sisal fields in a typical undulating landscape of the Uplands. The photograph was taken on Bamba estate (*'nyumba yangu'*) at the foot of the East Usambara mountains at an altitude of 180 m a.s.l. The soils constitute the typical Ferralsol-Acrisol catena which was formed on intermediate gneiss. Small shrubs were abundant in this field and many sisal plants had poled. The nutrient balance presented in section 4.3 was calculated for this field.

Plate 4

A well drained Alisol in the Uplands of Tanga Region. The picture was taken at Lanconi estate which is one of the oldest sisal plantations at the foot of the East Usambaras. The rooting system of a one year old teak tree (*Tectona grandis*) is shown. Teak grows very fast on these soils due to the combination of high rainfall

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(1) All photographs by the author. Plate 1 - June 1987; plate 2 - December 1987; plate 3 - May 1990; plate 4 - July 1990; plate 5 - September 1987; plate 6 - September 1989.

(ca. 1,200 mm y^{-1}) and the reasonable soil fertility levels. Many sisal growers in Tanga Region consider the planting of teak on a large scale a suitable alternative for sisal cultivation.

Plate 5

The footslope of the typical 'Milne' catena as was discussed in section 3.3. The picture was taken at Kwamdulu estate and reveals a thin reddish topsoil over a plinthitic subsoil. The plinthite hardens to ironstone when exposed to air, and was removed for roadbuilding on the plantation.

Plate 6

A D8 Caterpillar clears 15 years old fallow vegetation at Bamba estate in the Uplands of Tanga Region. Sisal growers refer to this as 'brushcutting'. The water ballasted rollers, each weighing five tonnes, flatten and crush the vegetation. Sisal boles (there is one in the lower corner of the picture) are also crushed and segmented which forms a thick mulch on the soil. The mulch is left to dry and decompose for some time and finally is burned to clear the field completely. In order to avoid too rapid burning leading to very high temperatures and risks of estate fires, the fires are started in the opposite direction of the winds. After burning, the soil is tilled with a heavy harrow plough pulled by a D8, whereafter a D4 usually continues with disc-harrows passing several times in different directions. Then the land is planted. Many sisal growers assume that the soil fertility is restored during the fallow period so that no fertilizers need to be applied.

Plate 1

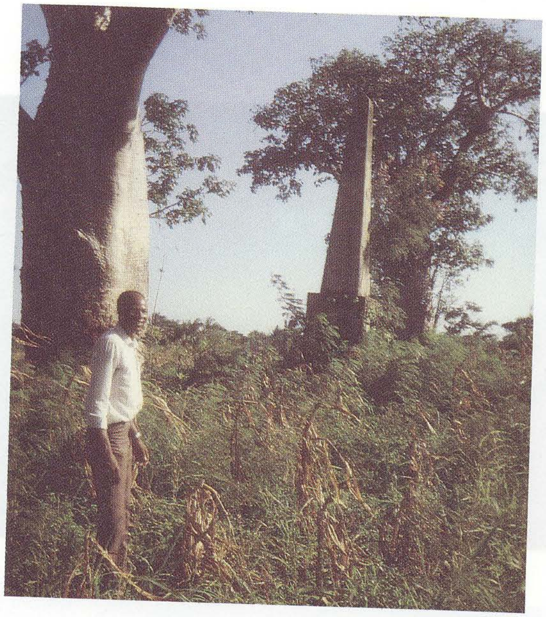


Plate 2

Plate 3

Plate 4

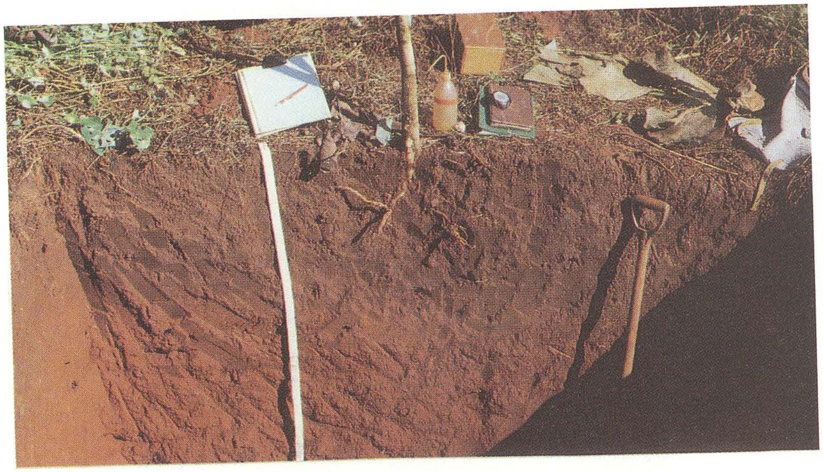
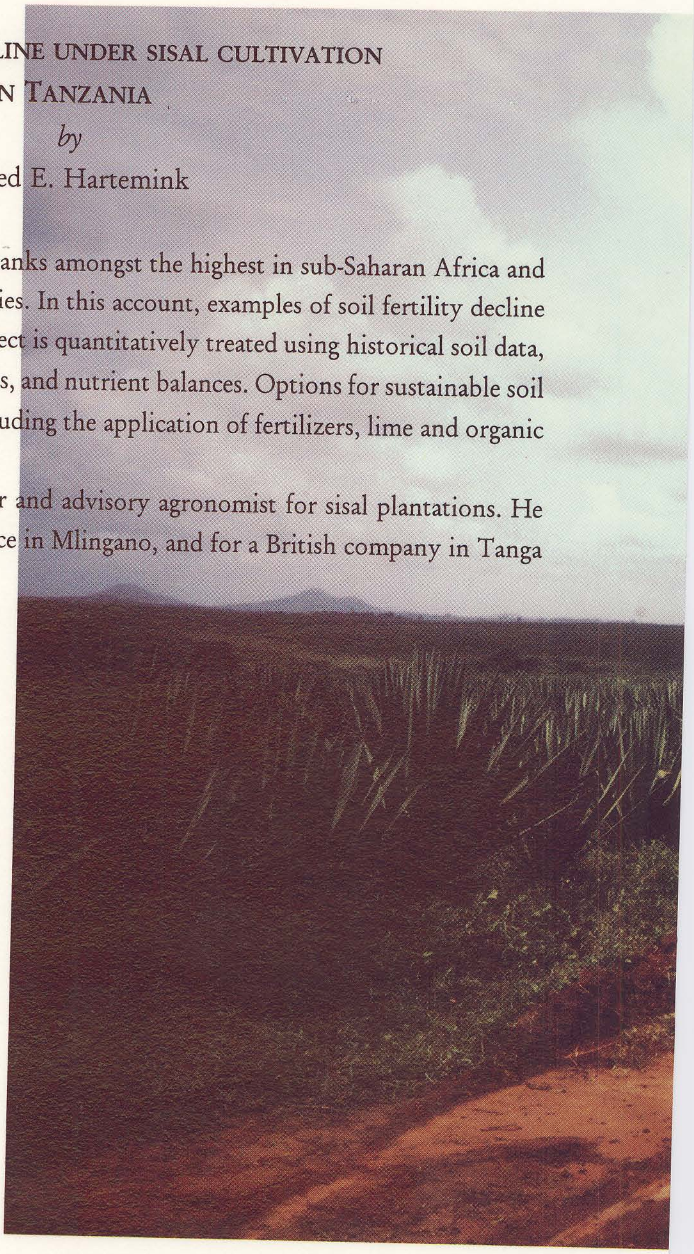


Plate 5

Plate 6



SOIL FERTILITY DECLINE UNDER SISAL CULTIVATION IN TANZANIA

by

Alfred E. Hartemink

Soil fertility decline in East Africa ranks amongst the highest in sub-Saharan Africa and is mainly caused by agricultural activities. In this account, examples of soil fertility decline on sisal plantations are given. The subject is quantitatively treated using historical soil data, soil data from different land-use systems, and nutrient balances. Options for sustainable soil fertility management are discussed including the application of fertilizers, lime and organic manures.

The author has been a soil surveyor and advisory agronomist for sisal plantations. He has worked for the National Soil Service in Mlingano, and for a British company in Tanga region, in Zaire and Indonesia.

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