Working Paper and Preprint 95/07

THE IMPACT OF PARENT MATERIAL ON SOIL FERTILITY DEGRADATION IN THE COASTAL PLAIN OF TANZANIA

Alfred E. Hartemink
E.M. Bridges

May 1995

ISRIC
INTERNATIONAL SOIL REFERENCE AND INFORMATION CENTRE

Working Paper and Preprint

95/07

THE IMPACT OF PARENT MATERIAL ON SOIL FERTILITY DEGRADATION IN THE COASTAL PLAIN OF TANZANIA

(Submitted for publication in *Land Degradation and Rehabilitation*)

Alfred E. Hartemink
E.M. Bridges

May 1995

ISRIC
PO Box 353
6700 AJ Wageningen
The Netherlands

TABLE OF CONTENTS

FIGURE

TABLES

ABSTRACT

Differences in the vulnerability of soils to fertility degradation are compared for two major soil groups located in the coastal plain of Tanzania and cropped with sisal (*Agave sisalana*). Ferralsols derived from intermediate gneiss of Precambrian age and Cambisols developed in Jurassic and Neogene limestone mixed with Quaternary deposits were selected for comparison. A clear impact of parent material was apparent when soils were continuously cropped with sisal and no fertilizers were applied. Serious soil fertility decline is a problem in Ferralsols but Cambisols are resilient to chemical degradation and the fertility decline in these soils was very low. The differences in degradation rates are explained by the lower initial fertility and low nutrient reserve of Ferralsols, while the Cambisols had higher initial fertility levels and nutrients removed by the sisal crop are replenished by the weathering of the underlying parent material. Sustainable soil fertility management of Cambisols includes NPK fertilization, while heavy dressings of lime, organic manures and/or chemical fertilizers are required to improve the fertility status of the Ferralsols and to produce crops in a sustainable manner.

KEY WORDS: Soil Fertility Degradation, Ferralsols, Cambisols, *Agave sisalana*, Soil rehabilitation, Liming

INTRODUCTION

Human-induced soil degradation is an important cause for the decline of productivity of many soils. Experience in Europe has shown that the vulnerability of soils for a specific type of degradation differs widely. Some soils are vulnerable to erosion by water or wind, others to physical compaction or chemical degradation (Batjes and Bridges, 1993). In large parts of the tropics, chemical soil degradation is caused by the depletion of plant nutrients resulting from agricultural activities. Unless nutrients removed by agricultural crops are replaced, naturally through weathering and bio-geocycling, or through the use of chemical fertilizers or manures, the soil nutrient reserves will gradually be depleted. Human-induced loss of nutrients was estimated to be affecting 45 million hectares in Africa and 135 million hectares worldwide (Oldeman *et al.*, 1991). A semi-quantitative analysis of nutrient depletion was made at a supra-national scale for Africa (Stoorvogel and Smaling, 1990). These authors have shown that nutrient depletion is highest in the eastern part of the continent and that for Tanzania, the balance of all three major plant nutrients was negative: -27 kg N ha^{-1}, -9 kg P ha^{-1} and -21 kg K ha^{-1}.

The vulnerability of a soil to fertility degradation is determined by the initial soil chemical fertility influenced by (palaeo-) climate, mineralogy of its parent material, vegetation and land use. Limited primary data are available about the reduction in fertility of soils from contrasting parent materials. In this paper, fertility degradation is compared for two soils in the coastal plain of Tanzania. For both soils, analytical data of the 1950s and 1960s are compared with recent data from the same fields and land use.

In Tanzania, several large sisal plantations are situated on the coastal plain. Some plantations can be found adjacent to the Indian Ocean coast on soils developed in a mixture of limestone and sediments. However, most plantations are found on deep red soils derived from gneiss. The low initial fertility of these soils is being depleted seriously by the continuous growth of sisal in the absence of fertilizers (National Soil Service, 1988a; Hartemink, 1991; Hartemink *et al.*, submitted) and as a result yields are declining (Hartemink and Wienk, submitted). Sisal imposes a heavy drain on the soil nutrients, even with moderate yields (1.5 t ha^{-1} yr^{-1}. An annual shortfall of 32 kg N ha^{-1}, 4.5 kg P ha^{-1}, 52 kg K ha^{-1}, 127 kg Ca ha^{-1} and 47 kg Mg ha^{-1} was calculated for these deep red soils (Hartemink and Van Kekem, 1994).

MATERIALS AND METHODS

The research was conducted on five sisal plantations of which four were located in Tanga region in the northeast of the country, and the fifth, Mikindani, was located in the Mtwara region in the southeast. Details of the location, elevation, area, annual rainfall and parent materials of each sisal plantation are given in Table 1.

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

						soil parent material (ha)		
plantation	long. S	lat. E	rain (mm yr^{-1})	altitude (m a.s.l.)	area (ha)	gneiss	limestone	unconsolidated material
Bamba	4°55’	39°20’	1044	140-250	1810	1602	0	208
Kwafungo	5°10’	38°50’	1057	210-480	2330	1334	0	996
Kwamdulu	5°20’	39°10’	1136	260-350	4640	3400	0	1060
Mwera	5°40’	39°30’	1295	80-150	2795	0	2620	175
Mikindani	10°15’	40°05’	892	35-140	4285	0	3875	410

Rainfall on the coastal plain of the Tanga region is bi-modally distributed with a yearly mean of 1100 mm, but amounts are slightly higher adjacent to the coast (Mwera Estate). Throughout the coastal plain of Tanzania rainfall is highly unpredictable. In the Tanga region, it exceeds potential evaporation in April and May only, corresponding with the main growing season. In the Mtwara region (Mikindani Estate) the rainfall pattern is mono-modal with a rainy season from December to April and a long dry season from May to November. The mean annual temperature in the coastal plain is 26°C with only minor fluctuations throughout the year.

Coastal plain geology

Elevation on the coastal plain of Tanzania ranges between 0 and 500 m above sea level. The plain can be divided into two areas with distinctly different parent materials. Adjacent to the coast, Jurassic limestone is the predominant rock (National Soil Service, 1988c). In the Upper Jurassic, uplift occurred with tilting towards the east. As a result of the tilting, the weathering products from the hinterland, mainly Basement Complex rocks, were deposited over the coastal plain covering the Jurassic limestone (Halligan, 1958). In some areas the Jurassic limestone is covered by coral limestone laid down during Neogene times (Tertiary). Additional sediments of varying composition were deposited during the Quaternary period. The coral has an irregular surface and consistence and so the depth of soil and weathering vary over short distances. The major constituent of the coralline limestone is calcium with minor amounts of magnesium and iron.

Further inland, Precambrian rocks of the Basement Complex are predominant parent materials which includes schist, granulite, quartzite and gneiss of acid and intermediate composition. Gneiss is the main parent material in the area studied for this paper. This metamorphic rock has a mixture of hornblende and pyroxene quartzo-feldspatic minerals with a granulitic texture (Hartemink, 1991). Upon weathering these minerals may contribute magnesium, calcium, potassium and iron to the soil. Areas of alluvium and sand dunes occur, these constitute the unconsolidated materials in Table 1 and are not considered in this paper.

The soils

Soils derived from the two contrasting parent materials were studied. Soils derived *in-situ* from gneiss are uniform, red, well-drained and very deep (> 4 m) and are the uppermost member of a catenary soil sequence which was first recognized by Milne (1935). The soils have a clayey texture and the predominant secondary minerals are sesquioxides and kaolinite (Nandra, 1977). They are very old and strongly weathered, intensely leached and commonly strongly acid with low levels of exchangeable cations and available phosphorus. Nutrient retention, as represented by the cation exchange capacity (CEC), is low and aluminium saturation may exceed 70%. As a result of the low pH and the high exchangeable Al content, the capacity in these soils for phosphorus fixation is great. In view of their ferralic B horizon (CEC_{clay} < 160 $mmol_c\ kg^{-1}$), and red to dusky red B horizon colours, these soils were classified as Rhodic Ferralsols according to the revised legend of the Soil Map of the World (FAO-Unesco, 1988).

Soils developed over limestone and Quaternary deposits are more heterogeneous and less deep (< 2m). These soils have a variable texture, are mostly well-drained and brown in colour. They are young soils which are less weathered, usually with a neutral soil reaction and a high base saturation. As pH is over 5.5 no exchangeable aluminium occurs. These soils are a complex with either a Cambic B horizon or an argic B horizon (Luvisols) and in this article they are collectively referred to as Cambisols.

Soil sampling and analysis

The selection of sites for sampling on the sisal plantations was based on evidence provided by semi-detailed (1:20,000 or 1:30,000) soil maps. The samples obtained were composites of 10 to 15 randomized mini-pits in an area of uniform soil. The mini-pits were dug with hoes and the soil was taken from the pit with a small spade. Soil samples were taken from 0-20 cm. In addition, soil pits (150 cm depth) were studied of both soils and each horizon was sampled. Analyses of the soil samples was carried out at the National Soil Service Laboratories in Mlingano (Tanzania) following standard methods (Page *et al.*, 1982).

Soil research files were consulted from the archives of the Sisal Research Station at Mlingano. These files contained soil analytical data of sisal fields for most plantations in Tanzania. The data related to the 1950s and 1960s and were extremely well documented. Fields of each estate 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 between the two periods of sampling. Only fields which had been continuously under sisal were chosen. The following soil parameters could be used in the comparison as the analytical methods of the 1950s and 1960s were identical to the present methods: pH H_2O (soil:water 1:2.5), organic C (Walkley & Black) and exchangeable Ca, Mg and K (1M NH_4OAc extraction at pH 7.0). Twentyfive to thirty topsoil samples were available from both sampling periods and for each soil. Median values for the soil parameters are reported in this paper; they were preferred to the mean as the distribution was skewed by the presence of extreme values.

RESULTS

The example given of a Ferralsol under continuous sisal cultivation has very low fertility (Table 2) confirming earlier observations (National Soil Service, 1988a, 1998b; Hartemink, 1991).

Table 2 Soil fertility status of a Ferralsol and a Cambisol under continuous sisal cultivation†.

Parent material:	intermediate gneiss			limestone		
Soil type:	Ferralsol			Cambisol		
sampling depth (cm):	0-20	40-60	110-130	0-15	40-60	80-100
pH (H_2O) 1:2.5	4.6	4.2	5.0	6.8	5.8	6.2
pH (KCl) 1:2.5	4.0	4.2	4.5	5.7	4.3	5.0
Organic C (%)	1.8	0.3	0.1	2.0	0.7	0.4
Available P (Bray I) (mg kg^{-1})	3	1	1	2	1	1
Exchangeable Ca (mmol$_c$ kg^{-1})	7	< 0.5	< 0.5	101	66	78
Exchangeable Mg (mmol$_c$ kg^{-1})	5	< 0.5	< 0.5	21	17	12
Exchangeable K (mmol$_c$ kg^{-1})	1	< 0.5	< 0.5	1	< 0.5	< 0.5
CEC (NH_4OAc pH 7) (mmol$_c$ kg^{-1})	89	51	50	164	153	133
Base saturation (%)	14	<5	<5	76	55	68
Exchangeable Al (mmol$_c$ kg^{-1})	8	5	2	0	0	0
Al saturation (% CEC)	9	10	4	0	0	0

† data obtained from profile pits

The soil reaction is very strongly acid in the topsoil (pH 4.6), with very low base saturation (14%). The pH H_2O in the 40-60 cm soil horizon is similar to the pH KCl indicating that there is a variable charge. Levels of available phosphorus are low throughout the profile, and exchangeable cations (calcium, magnesium and potassium) are severely depleted. The capacity of the soils to retain nutrients (CEC) is very low. As a result of the very strongly acid soil reaction, exchangeable aluminium levels are moderate. When expressed as percentage of the effective cation exchange capacity (ECEC) aluminium saturation reached 38% in the topsoil (0-20 cm) and over 70% in the subsoil (40-60 cm). Such high levels are only tolerated by a few crops (e.g. pineapple or tea) and certainly have an adverse affect on the growth of sisal.

The example of a Cambisol under continuous sisal cultivation given in Table 2, has a neutral soil reaction (pH H_2O 6.8) in the topsoil (0-15 cm) and is slightly acid (pH 6.2) in the subsoil (80-100 cm). Amounts of organic carbon are higher than in the Ferralsol, but in the subsoil of the Cambisol they are considerably higher which may be an indication of a lower mineralization rates. Levels of available phosphorus are also very low in the Cambisol but exchangeable calcium and magnesium levels are high throughout the profile, and so is the nutrient retention capacity. Exchangeable potassium levels are very low (< 1.5 mmol$_c$ kg^{-1}) and base saturation is high (76%) in the topsoil but decreases with depth. Partly weathered limestone rock is found below 110 cm depth.

A comparison of 59 topsoil samples from the 1950s and 1960s with 54 samples from 1987 to 1990 revealed that the pH had declined by 1.4 of a unit in the Ferralsols and only by 0.4 of a unit in the Cambisol (Table 3).

Table 3 Soil fertility status (0-20 cm) of sisal fields on Ferralsols and Cambisols at different sampling times (median values).

parent material:	intermediate gneiss		limestone	
Soil type:	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	4.9	7.0	6.6
Organic C (%)	2.0	1.7	na	1.8
Exchangeable Ca (mmol$_c$ kg^{-1})	39	14	116	89
Exchangeable Mg (mmol$_c$ kg^{-1})	25	10	19	15
Exchangeable K (mmol$_c$ kg^{-1})	2	1	5	3
Base saturation (%)	56	33	93	68

na = not available

More important, however, is the relative decrease. The pH in the Ferralsols reached 4.9 while in the Cambisols it was still near neutral (pH 6.6) after 30 years of continuous sisal cultivation. The organic carbon contents in the Ferralsols decreased from 2.0 to 1.7% and this is commonly observed with a prolonged cropping period (Nye and Greenland, 1960). Exchangeable calcium in the Ferralsols decreased from 25 to 10 mmol$_c$ kg^{-1}, and in the Cambisols from 116 to 89 mmol$_c$ kg^{-1} which are still favourable calcium levels. The weathering of the underlying limestone which is found within 2 m depth, and the transport of calcium by capillary rise (potential evaporation is greater than the rainfall) may have resulted in topsoil calcium levels remaining high. Magnesium levels were, however, higher in the Ferralsols than in the Cambisols in the 1950s and 1960s. The decrease in magnesium is larger in the Ferralsols (from 25 to 10 mmol$_c$ kg^{-1}) than in the Cambisols (from 19 to 15 mmol$_c$ kg^{-1}). Base saturation at pH 7 decreased in both soils and reached low levels in the Ferralsols (33%), but remained fairly high in the Cambisols (68%).

All pH data of the topsoils of Ferralsols (3 plantations) and Cambisols (2 plantations) were plotted (exponential fit) with the sum of exchangeable calcium, magnesium and potassium (Fig. 1).

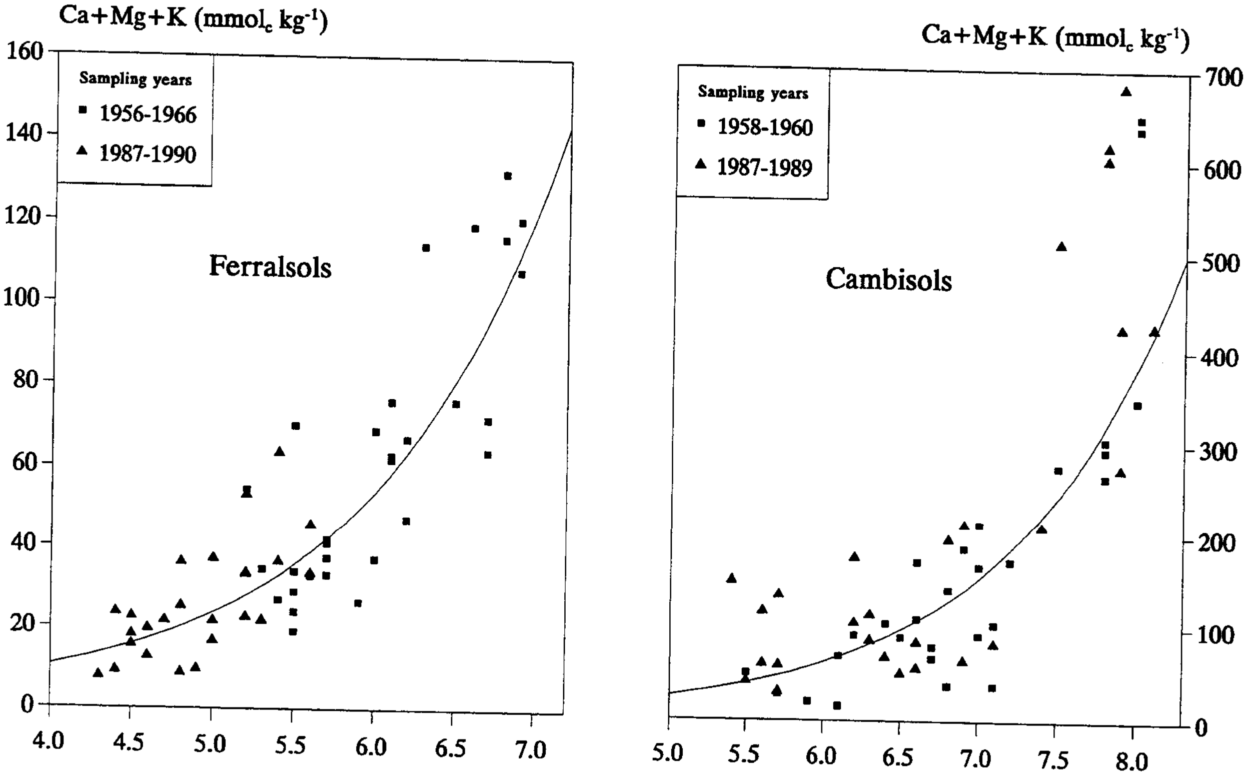

Fig. 1 Relation between pH H_2O and sum of Ca, Mg and K in the topsoil (0-20 cm) of Ferralsols and Cambisols. (Note different scales on X and Y-axes of Ferralsols and Cambisols).

The data of the Ferralsol clearly revealed the increasing amount of exchangeable bases with decreasing acidity. It also shows that the pH H_2O and levels of exchangeable bases were much lower in 1987 to 1990 than in 1956 to 1966. In 1956 to 1966 no topsoil pH was found below 5.2, and in 1987-1989 no pH was found above 5.6 for the same soils and fields. The pH trend in the topsoil of the Cambisols was very different (Fig. 1, note different scales of X and Y axes). In these soils, the pH values found in the 1958-1960 cover the same range as those from 1987-1989, although below pH 6 more recent data are found than in the earlier period. This confirms the slight pH decrease as presented in Table 3. Above pH 7, an increase in the sum of exchangeable bases can be seen, this is caused by the presence of free carbonate which is common in soils derived from limestone with a pH > 7. Such pH might be of advantage as the clay complex is dominated by exchangeable calcium which favours soil physical conditions, but it can lead to deficiencies of minor elements (iron) as well as creating nutrient imbalances e.g. unfavourable calcium/potassium ratios.

SOIL FERTILITY MANAGEMENT

Liming, fertilization and/or organic manuring are important measures for sustainable soil fertility management in the coastal plain of Tanzania, but the soils studied have not been limed or fertilized for long periods. Some appropriate measures are reviewed below.

The Ferralsols require liming: (i) to increase the pH and thus to eliminate the harmful effects of exchangeable aluminium, (ii) to increase the P availability and, (iii) to supply Ca and Mg as they are important nutrients for sisal. Kamprath (1970) suggested exchangeable Al 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 Al is given by the equation:

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

This $CaCO_3$ equivalent will reduce the Al saturation to approximately zero according to Kamprath (1984). 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 required Al saturation, as suggested by Cochrane *et al.*, (1980) for optimal growth, is therefore assumed to be zero. To reduce the Al saturation to zero in the topsoil of the Ferralsol in Table 2, 1.2 t $CaCO_3$ ha^{-1} is required ($\approx$0.15*8 Al $mmol_c$ kg^{-1}). To diminish exchangeable aluminium in the whole profile, larger amounts of lime are needed. Tanzania Sisal Growers Association (1965) recommended 2 to 5 t ha^{-1} of agricultural lime which consists largely of $CaCO_3$ and up to 3% Mg. It is usually applied before planting and its effect lasts for the whole sisal cycle of 10 years (TSGA, 1965). As sisal may remove about 1215 kg Ca 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 Ca removed with the harvested leaves assuming all the Ca supplied is taken up. To rectify the chemical degradation of many of the Ferralsols in the coastal plain of Tanzania, application rates of 4 to 5 t $CaCO_3$ ha^{-1} are needed.

Alternatively, old partly decomposed sisal waste may be applied and this contains per 50 tons about 300 kg N, 50 kg P, 40 kg K, 1230 kg Ca and 80 kg Mg. There is a cost in returning the bulky waste to the fields and at present it has not been considered worthwhile to do so although its has also beneficial effects on the organic matter contents and soil physical properties.

NPK fertilizers are needed for sustainable soil fertility management in both major soil groups. Regarding the mineralogy and very strongly acid soil reactions of the Ferralsols, phosphorus fixation is large. The use of rock-phosphate and banded applications are recommended. Nitrogen fertilizers may induce potassium deficiency in the Ferralsols and should therefore always be applied together with potassium (Rijkebusch and Osborne, 1965).

CONCLUSIONS

In both Ferralsols and Cambisols the chemical fertility has been reduced, under continuous sisal cultivation as demonstrated by decreased values for pH and the amounts of exchangeable bases. The impact of parent material is clear. Ferralsols derived from gneiss have low reserves upon which to draw and started off at a lower fertility level than the Cambisols derived from limestone. As a result, Ferralsols have been severely depleted and have become an example of human-induced soil degradation. Cambisols have been able to resist the process of depletion by drawing upon reserves. The study clearly showed that fertility degradation cannot be assumed uniformly in an area and under the same land-use.

Acknowledgements. The authors wish to acknowledge the kind cooperation of director and staff of the Agricultural Research Institute Mlingano in Tanzania. Mr Ph.A. Kips kindly provided some of the soil analytical data. Mr N.H. Batjes and Mr J.H.V. van Baren are thanked for their constructive comments on the draft version of this paper.

REFERENCES

Batjes, N.H. and Bridges, E.M., 1993. Soil vulnerability to pollution in Europe. *Soil Use and Management* **9**:25-29.

Cochrane, T.T., Salinas, J.G. & Sanchez, P.A. 1980. An equation for liming acid mineral soils to compensate crop aluminium tolerance. *Tropical Agriculture*, **57**:133-140.

FAO-Unesco 1988. Soil Map of the World, Revised Legend. *World Soil Resources Report No. 60*, FAO, Rome.

Halligan, R. 1958. *Geology of the Tanga area*. Records of the Geological Survey of Tanganyika, Vol. VI. Government Printer, Dar es Salaam.

Hartemink, A.E. 1991. *Soils of Bamba Estate and their suitability for sisal, teak and cashew*. Chillington Corporation London/Ralli Estates Ltd, Tanga.

Hartemink, A.E. and Van Kekem, A.J. 1994. Nutrient depletion in Ferralsols under hybrid sisal cultivation in Tanzania. *Soil Use and Management* **10**:103-107.

Hartemink, A.E. and Wienk, J.F. —. Sisal production and soil fertility decline in Tanzania. Submitted for publication in *Outlook on Agriculture.*

Hartemink, A.E., Osborne, J.F. and Kips, Ph.A. —. Soil fertility decline and fallow effects in Ferralsols and Acrisols of sisal Plantations in Tanzania. Submitted for publication in *Experimental Agriculture*.

Kamprath, E.J. 1970. Exchangeable aluminium as criterion for liming leached mineral soils. *Soil Science Society of America Proceedings* **24**:252-254.

Kamprath, E.J. 1984. Crop Response to Lime on Soils in the Tropics. pp 349-368 in *Soil acidity and liming*. Agronomy Monograph No. 12, ASA-CSSA-SSSA, Madison.

Milne, G. 1935. Some suggested units of classification and mapping, particularly for East African soils. *Soil Research* **4**:183-198.

Nandra, S.S. 1977. Soil fertility status of sisal growing areas in Tanzania. *African Soils* **19**:58-66.

National Soil Service, 1988a. *The Potential for Hybrid Sisal Cultivation of Four Amboni Estates in Tanga region*. Publication M8, Agricultural Research Institute, Mlingano, Tanzania.

National Soil Service 1988b. *Soils of Pongwe Estate and their Suitability for Hybrid Sisal Cultivation*. Detailed Soil Survey Report D13, Agricultural Research Institute, Mlingano.

Nye P.H. and Greenland, D.J. 1960. *The Soil under Shifting Cultivation*. Technical Communication No. 51, Commonwealth Bureau of Soils, Harpenden.

Oldeman, L.R., Hakkeling, R.T.A. and Sombroek, W.G., 1991. *World Map of the Status of Human-induced Soil Degradation: an explanatory note*. Second revised edition. International Soil Reference and Information Centre, Wageningen.

Page, A.L., Miller R.H. and Keeney D.R. (eds.) 1982. *Methods of Soil Analysis, part 2. 2nd edition*. ASA-SSSA, Madison.

Rijkebusch, P.A.H. and Osborne J.F 1965. Interpretation of Soil Analysis in Relation to the Manuring of Sisal Fields. *Research Bulletin No. 39*. Tanganyika Sisal Growers' Association, Mlingano.

Stoorvogel, J.J. and Smaling, E.M.A. 1990. *Assessment of Soil Nutrient Depletion in Sub-Saharan Africa 1983-2000*. Winand Staring Centre for Integrated Land, Soil and Water Research (SC-DLO), Wageningen.

Tanzania Sisal Growers Association (TSGA), 1965. *Handbook for Sisal Planters*. Sisal Research Station, Mlingano.