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CASHEW MANAGEMENT AND ITS EFFECT ON SOILS AND INTERCROPS: THE CASE OF SULPHUR DUSTING IN SOUTH EASTERN TANZANIA

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door

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Edward L. NGATUNGA
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Abbreviations and Acronyms

ANOVA	Analysis of variance
ARF	Agricultural Research Fund (Tanzania)
ARI	Agricultural Research Institute
asl	above sea level
BS	Base saturation
BTC	Belgian Technical Co-operation (Agency)
CBT	Cashew nut Board of Tanzania
CEC	Cation Exchange Capacity
CLA	Cashew leaf ash
CNSL	Cashew nut shell liquid
CV	Coefficient of variation
ETO	Evapotranspiration (potential)
FAO	Food and Agriculture Organization of the United Nations
GIS	Geographical information system
GPS	Global Positioning System
ha	hectare
ISRIC	International Soil Reference and Information Centre
ISSS	International Soil Science Society
MDP	Makonde dissected plateau
mg	milligram
MHP	Makonde high plateau
MKL	Mikindani lime
MOA	Ministry of Agriculture of the Government of Tanzania
MRP	Minjingu rock phosphate
N	Nitrogen
NARI	Naliendele Agricultural Research Institute
NSS	National Soil Service
OC	Organic carbon
PMD	Powdery mildew disease of cashew
RIPS	Regional Integrated Project Support (Finnish supported rural project)
S	Sulphur
SAS	Statistical analysis system
Tsh	Tanzania Shilling (national currency)
UNESCO	United Nations Educational, Scientific and Cultural Organization
WRB	World Reference Base for Soil Resources

Abstract

This study examines management of cashew groves in South Eastern Tanzania and the effect of adopting sulphur dusting on soils and on cashew and its intercrops. Production of cashew nuts, an important cash crop in South Eastern Tanzania, is constrained by powdery mildew disease caused by *Oidium anacardii* Noack. To get high yields, farmers have to dust the trees with 90 kg of sulphur per hectare. After a decade of sulphur use, there is widespread concern about future productivity of the soils because buffering capacity of the soils to withstand prolonged sulphur use is not known. Production of cashew nuts is also low due to planting in marginally suitable areas. The other associated problem is the lack of a strategy to address soil acidity arising from sulphur use. The main objective of the study is therefore to find approaches that will ensure sustainable production and management of the cashew–intercrop based farming systems in South Eastern Tanzania.

To evaluate soil suitability for the cashew nut tree, henceforth called the cashew tree, soil profile features and physico-chemical properties of soils of 16 representative cashew groves on the Makonde plateau and 14 in the Inland plains were studied. Soil properties indicate that on the Makonde plateau soils are sandy, highly weathered, deep and devoid of mottles, nodules and hardpans. *Ferralsols* constituted over 60 % of the soil groupings in cashew groves sampled on the plateau. Several soil groupings such as *Acrisols*, *Alisols*, *Plinthosols*, *Cambisols* and *Phaeozems* were found in the plains where soils are generally clayey and often shallow and less weathered.

Through multivariate analysis, the relationship of 19 soil parameters and 20 cashew tree parameters revealed that tree dimensions were larger and had higher yields on deep, strongly weathered soils most common on the Makonde plateaux. On shallow, weakly weathered soils found in the Inland plains, trees had smaller dimensions and low yield. The fact that the plant grew favourably on the plateau, regardless of the low chemical fertility, shows that cashew trees are more sensitive to physical than to chemical limitations of the terrain.

Buffering capacity of cashew growing soils was studied by titrating soil samples from different groves with acid and relating changes in pH to soil properties. Buffering capacity was strongly and positively correlated with percent clay and weakly with percent organic carbon of the soils. Buffering capacity of soils on the Makonde plateau was comparable to that of soils in the Inland

plains. Due to the low initial pH and low clay content of soils of the Makonde plateau, acidification of these soils is more likely to reach to critical levels.

To verify to which extent past sulphur dusting affected the soil of farmers' cashew groves, the pH of 70 sulphur dusted groves was compared to 70 non-dusted groves. The survey indicated that use of sulphur has lowered the pH of soils on the Makonde plateau, while soils of the Inland plains have not been affected.

To predict the effects of sulphur use on annual intercrops of cashew trees, twelve 3-year field experiments in which sulphur was applied on maize, sorghum and cowpeas were conducted at three locations. Sulphur rates varied from 0 to 240 kg ha^{-1}. Results showed that sulphur decreased germination percentage and grain yield of sorghum and maize, beginning from the second year of application of 120 kg ha^{-1} and above. The decrease was most pronounced in soils on the Makonde plateau. Cowpeas were tolerant to sulphur use.

Through an incubation experiment set out to evaluate the ability of Mikindani lime (burned coral lime), Minjingu rock phosphate and ash from cashew leaves to neutralise soil acidity, Mikindani lime was found to be the most suitable material. It raised the soil pH from 3.8 to 6.0 at the rate of 0.3 ton ha^{-1} costing US$ 10 for procurement and application in the field. Both Minjingu rock phosphate and ash required large amounts of materials, resulting in a higher cost.

This study has shown that the most important soil properties to check when planting cashew trees are soil depth and weathering status. Deliberate effort should be made to reduce quantity of sulphur used on the Makonde plateau, as the risk for adverse effects of acidification is highest here. As risk for soil acidification is less pronounced in the Inland plains, sulphur use can be continued, however, periodic monitoring of soil pH is recommended.

To lessen the acidifying effect of sulphur, its use can be reduced by applying crop cultural practises, such as pruning and burning of infected twigs and leaves. Organic fungicides can be an alternative to sulphur but they have the disadvantage of being more expensive and more toxic to humans and animals than sulphur. Although burned lime has proven to be effective to raise the pH of the acidified soils, further research is needed to investigate its effect on the yield of cashew trees and cashew intercrops. An integrated approach to address the mildew problem should also involve a long-term strategy to evaluate/breed for disease resistant tree types.

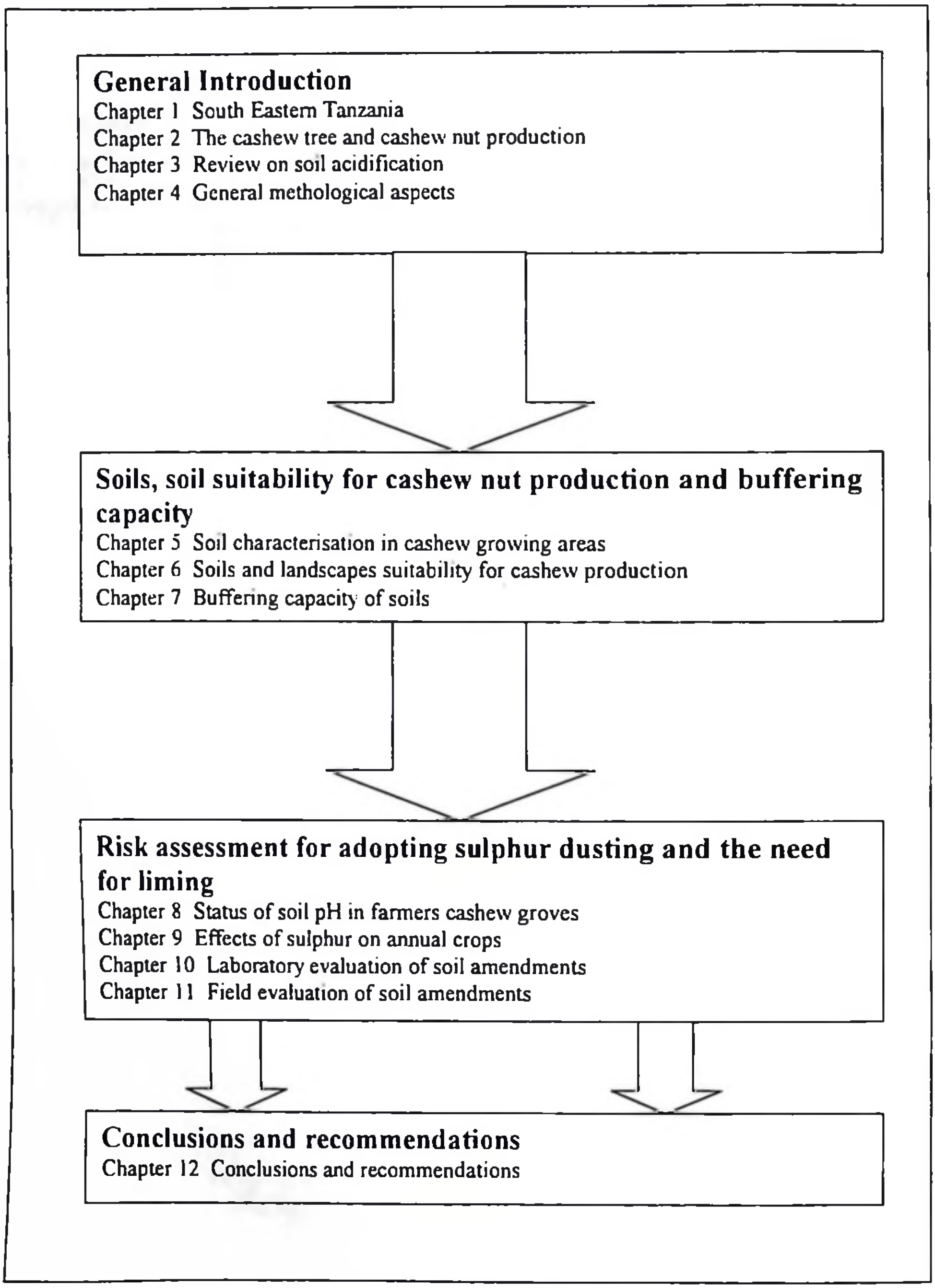
Thesis outline

Chapters 1-4 present background information on the study area and cashew, the principal cash crop in southern Tanzania. It also reviews literature on soil acidification and sulphur, presents objectives of the research and states research hypotheses and general methodological aspects of the study.

Chapters 5-7 provide an inventory of soils, reviews soil suitability and evaluates their buffering capacity.

Chapters 8-11 assesses the risk of sulphur dusting on farmers' cashew groves and discusses the effect of soil applied sulphur on growth and production of selected annual crops often intercropped with cashew trees. It also evaluates the capacity of three soil amendments to neutralise acidity from sulphur use.

Chapter 12 presents the conclusions and recommendations of the study.



Schematic diagram of the thesis

Objectives and Hypotheses

Problem definition

South Eastern Tanzania is the leading cashew nut producing area in Tanzania. It produces about 70 % of the national production. Production is however affected by the fungus *Oidium anacardii* which attacks cashew trees during the reproductive stage of the crop causing serious yield losses. To alleviate this problem, elemental sulphur dust is widely recommended at the rate of 90 kg per hectare per season. After 10 years of sulphur use, concern has been raised regarding future productivity of soils of the areas under prolonged sulphur dusting.

Several knowledge gaps or research issues exist in the cashew farming systems requiring urgent attention. Cashew nuts were introduced in Tanzania during the early 1930's in absence of agronomic knowledge of the crop. Soils used for growing cashew nuts have not been studied adequately and suitability of the various soils to cashew growing and their buffering capacity for sulphur use are not well understood. There are several annual crops grown in association with cashew trees whose response to prolonged sulphur use needs to be evaluated. While sulphur is being used annually, measures to curb the resulting soil acidification are lacking.

General and specific objectives

The primary objective of this research is to find approaches that will ensure sustainable production and management of the cashew–intercrop based farming systems in South Eastern Tanzania.

The specific objectives of the study are:

- to study soils and their suitability for cashew production;
- to assess buffering capacity of soils to sulphur application;
- to assess the extent and severity of acidification in farmers' cashew groves originating from sulphur dusting to protect cashew trees from powdery mildew disease;
- to study the effect of sulphur use on growth of cashew and associated intercrops which are important for the food security of the zone; and
- to evaluate soil amendments needed to manage acid affected soils.

Hypotheses

1. Cashew tree size and yield are influenced by the properties of soils on which it grows.
2. Prolonged sulphur dusting of cashew trees leads to soil acidification in farmer's cashew groves.
3. Soil acidification has a negative influence on cashew performance.
4. Prolonged sulphur dusting leads to negative effects on the growth and production of crops grown as intercrops in cashew groves.
5. Locally available base forming materials can raise soil pH of acidified soils and can effectively be used to remedy the acidification caused by sulphur use on cashew.

Chapter 1
South Eastern Tanzania

1.1 Location

Tanzania is located in East Africa and lies between 1^0 and 11^0 50' latitudes south of the Equator and between 29^0 50' and 40^0 30' longitudes east of the Greenwich. It has an area of 945,090 km^2 with a population of 32,793,000 people (FAO, 2000). Administratively, Tanzania is divided into 25 regions. The present study is confined to South Eastern Tanzania which comprises of Mtwara, Lindi regions and Tunduru district of Ruvuma region (shaded area Figure 1.1). In the north (7^0 55'S) it borders with the Coast Region, in the west with Morogoro and Ruvuma regions, in the east with the Indian Ocean and in the south with the Ruvuma river which forms border with neighbouring Mozambique (11^0 50'S). The total area is approximately 103,807 km^2 consisting of Mtwara region (17, 750 km^2), Lindi region (66,950 km^2) and Tunduru district (19,107 km^2).

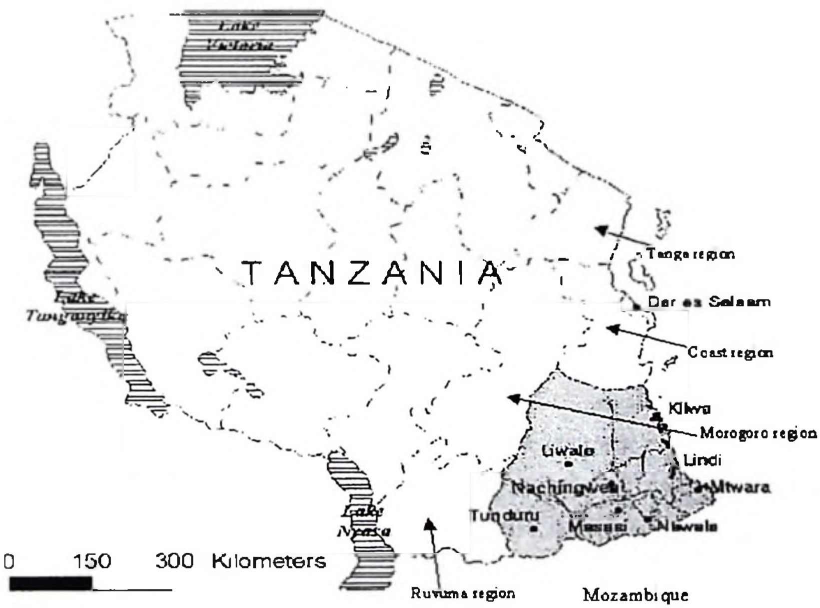


Figure 1.1 Map of Tanzania showing the location of the study area

1.2 Climate

In South Eastern Tanzania, the climate is influenced by the south-east trade winds in mid-year and the north-east tradewinds during the turn of the year. The weather pattern is conditioned by movements of the equatorial trough. This zone of low pressure moves across the equator following the movement of the sun with a lag of 4-6 weeks (Griffiths, 1972). The movement of the airflow from subtropical high-pressure cells into the intervening area of low pressure is not a regular continuous feature: pressure patterns may be distorted, often by movements in the high latitudes, so that both convergence and divergence take place (Kenworthy, 1975). This intricate pattern of airflow produces a distinct wet and dry season.

The rainfall pattern is monomodal but often has a seasonal interruption in some coastal areas and plateaux. Long-term rainfall data indicate that approximately 80 % of the rainfall falls between December and April. On the basis of a minimum of 50 mm rainfall, December to April are defined as wet months (Griffiths, 1972) which coincides with the length of the growing season. According to Bennett *et al.* (1979), the mean annual rainfall in South Eastern Tanzania ranges between 800 and 1250 mm. The mean maximum temperature in December, the hottest month, is 30.5 ^{0}C while the mean minimum temperature in July is 21.7 ^{0}C. According to Dagg *et al.* (1970) and Dagg (1972), potential evapotranspiration (ETo) rates are in the range of 2000-2200 mm per year (Penman method). Rainfall exceeds ETo only during December to April.

1.3 Landscapes, geology and soils

1.3.1 Introduction

The present account on landscape and soils is based on an extensive reconnaissance survey on the physical environment of Mtwara and Lindi regions by Bennett *et al.* (1979). Additional information is from soil profile data by NSS (1987), Ngailo and Kips (1991), Kips and Kimaro (1993), Verwilghen (1996), Wijffels (1997), Cools (1998), Dederen (1998), Majule, 1999 and the Italo-Tanzania Cashew Research Programme (1981). The geological account is based on the report of Kent *et al.* (1971). From east to west, South Eastern Tanzania can be divided into a coastal area, an area of plateaux and floodplains, a central area of plains and a western area of plateaux and uplands (Figure 1.2).

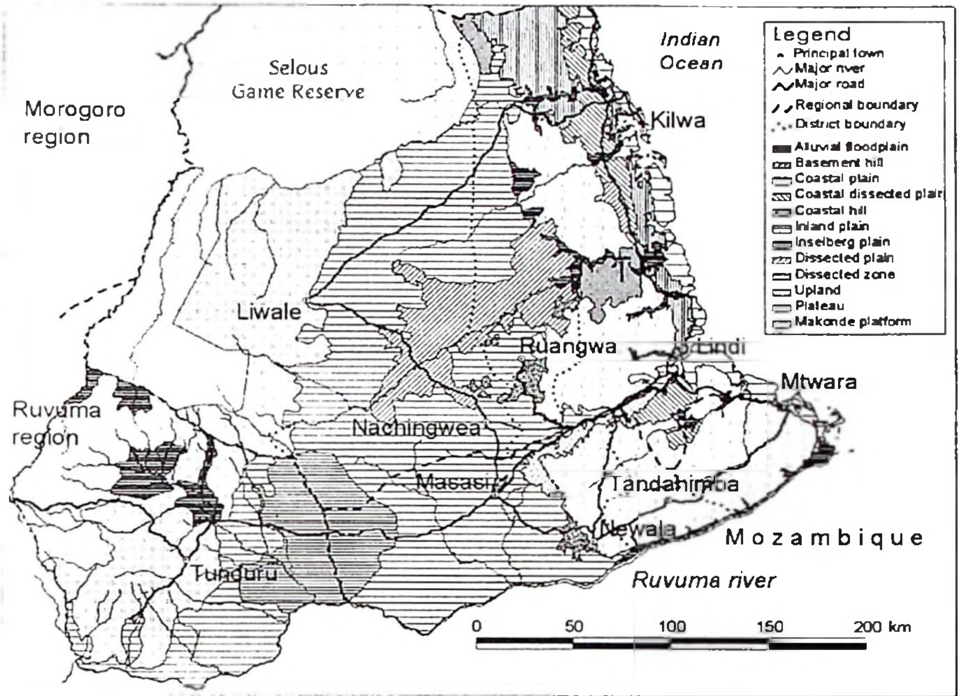


Figure 1.2 Major landscape units of South Eastern Tanzania

1.3.2 The Coastal area

This area is adjacent to the Indian Ocean and comprises of the coastal plains, coastal hills and coastal dissected plains (Figure 1.2). The coastal plain is a narrow, low lying land (roughly 10-20 km in width) running from the north (Kilwa district) to the border with Mozambique in the south. The soil pattern is complex. Soil parent material consists of limestone, sandstone and marl. Dominant soils on flat areas are deep, reddish and highly weathered *Rhodic Ferralsols* and *Haplic Lixisols*. In other areas, less weathered shallow soils such as *Ferralic* and *Dystric Cambisols* are present. In the valley bottoms, dark heavy cracking soils classified as *Calcic Vertisols*, are common. Reaction of soils in the coastal area varies from strongly acidic to mildly alkaline (pH-H_2O 4.5 - 7.5). The exchangeable base content, cation exchange capacity and organic carbon contents of the soils range between 0.6 - 22 $cmol_c\ kg^{-1}$ soil.

The coastal hills consist of the Lindi and Kilwa hills. Lindi hills, which rise to an altitude of 300 m, are located west of the narrow coastal plain and extend 5-15 km inland and northwards of

Lindi town. Altitude decreases in the north where it hardly rises above 75 m asl. The geology consists of Paleogene and marine Neogene deposits mostly limestone and marls (Kent *et al.*, 1971). The common soils are the dark cracking clay soils classified as *Calcic Vertisols*, *Calcaric Vertisols* and *Vertic Cambisols*. The Kilwa hills, located about 10 km north of Kilwa, are low altitude hills strongly dissected by streams and valleys. The geology is mainly marine Jurassic sandstone, limestone shale and other sediments, producing dark cracking clay soils (*Calcic Vertisols*, *Calcaric Vertisols* and *Vertic Cambisols*) over limestone.

Coastal dissected plain lies west of the Lindi and Kilwa hills and extends north-south direction from the border with the Coast Region in the north to the northern border of Makonde dissected plateau (Figure 1.2). Streams to the west dissect this plain, which is wider in the north (20-km) and narrows down in the south. Geology consists of Cretaceous marine deposits of clays, marls, mudstones and shales (Kent *et al.*, 1971). Dominant soils consist of the dark heavy cracking clays classified as *Calcic Vertisols* in valley bottoms and *Vertic Cambisols* on slopes. Soil reaction is neutral to alkaline (pH-H_2O 7.0 - 9.0). Soils have very high contents of exchangeable bases (> 50 $cmol_c\ kg^{-1}$ soil) and very high cation exchangeable capacity (45 - 70 $cmol_c\ kg^{-1}$ soil). The organic carbon content is, however, ranges from low to moderate (0.2 - 2.4%).

1.3.3 The Eastern plateau area

The eastern plateau area is located west of the coastal area and extends from the Matandu river in the north (Kilwa plateau) to Rondo plateau (middle) and finally to the Makonde plateau (close to the border with Mozambique) in the south (Figure 1.2). Located within or in between these plateaux are dissections caused mainly by valleys and rivers. Major rivers (from north to south) are Matandu, Mbwemkuru, Lukuledi and Ruvuma. Other rivers include Mambi and Mbuo. The plateaux tend to restrict the drainage of the major rivers (Lukuledi and Mbwemkuru rivers) giving rise to large alluvial floodplains.

With a width of about 40 km, the Kilwa plateau which rises to about 500 m asl, is narrowest of the three eastern plateaux. Although few scattered cashew trees can be found, soils of Kilwa plateau have not been extensively studied. The Rondo plateau is about 80 km wide and is the highest (870 m asl) of the three eastern plateaux. It has the lowest cashew stands and as for the Kilwa plateau its soils have not been extensively studied. Profile data from the report of Bennett *et al.* (1979), suggests that soils resemble those of the Makonde plateau in the south.

The Makonde plateau is about 140 km wide and reaches about 800 m asl at its highest point. It is divided into the Makonde eastern plateau (120-350m) also called Makonde dissected plateau and Makonde high plateau (350-800m asl) also called Makonde western plateau. The geology is terrestrial Lower Cretaceous and continental Neogene sandstone deposits (Bennett *et al.*, 1979). Besides the study of Bennett *et al.* (1979), soils of the Makonde plateau have been studied by the Italo-Tanzania project (1981); Verwilghen (1996) and Cools (1998). Soils are deep, well-drained with sandy topsoil and sandy loam or sandy clay loam in the subsurface horizons. The dominant soil units on the Makonde plateau are *Xanthic* and *Haplic Ferralsols*. Soils are acidic in reaction (pH-H_2O 4.5 - 6.5) and have very low exchangeable base contents (0.5 - 1.5 $cmol_c$ kg^{-1} soil), very low cation exchange capacity (2 - 6 $cmol_c$ kg^{-1} soil), as well as very low levels of organic carbon (0.5 - 1%)

River valleys that dissect the plateaux have floodplains consisting of Quaternary alluvial deposits or, locally, of lacrustine and marine deposits as the Kitere and Mambi plains. Soils are poorly drained and, depending on the origin of the deposits, are dark heavy cracking clays (*Eutric Vertisols*) or lighter textured and clearly stratified *Eutric* and *Mollic Fluvisols*. In backswamps of the Ruvuma river, very poorly drained soils (*Eutric Gleysols*) as well as organic soils (*Fibric Histosols*) are found (Verwilghen, 1996). Soil reaction of these soils varies from slightly acidic to alkaline (pH-H_2O 5.5 - 8.5). These soils have low to high exchangeable base contents (16 - 77 $cmol_c$ kg^{-1} soil) with equally low to high cation exchange capacity (20 - 60 $cmol_c$ kg^{-1} soil) and organic carbon contents (0.2 - 2.5%). According to Verwilghen (1996), percent organic carbon of *Fibric Histosols* along the swamps of the Ruvuma river can be as high as 23%.

1.3.4 The Central plains area

The central area comprises the plains in Masasi and Nachingwea districts and eastern part of Liwale district. Geologically the plains in Masasi and Nachingwea districts belong to the Precambrian Basement zone while the Liwale plain falls under the western Sedimentary zone. The altitude ranges between 175 to 450 m asl. The central plain area has several undulating interfluves and wide valleys in varying degrees of dissections. It is famous for isolated inselbergs that are more common in the south and less and smaller in size and height in the north.

In the Precambrian Basement zone (Nachingwea-Masasi plain) soils are derived from gneiss. Several soil groupings are found in the zone but their occurrence and distribution is complex. Soil changes reflect variations in lithology, drainage and erosional history (Bennett *et al.*, 1979).

On the interfluvial crest, least affected by erosion, the dominant soils are the highly weathered red soils (*Rhodic Ferralsols*). These are deep soils with sandy clay loam topsoil and sandy clay or clay subsoil. On the slopes, less weathered and shallow soils occur. They may be less than a metre deep and are mostly *Chromic Luvisols*, *Chromic Cambisols* or *Humic Cambisols*. Soils of the south and western Masasi district have not been extensively studied. In south and south-west of the basement zone and extending into Tunduru district, inselbergs dominate the landscape with the highest reaching 800 m close to Masasi town. Soils have not been studied in detail.

The eastern part of Liwale district has sandy soils derived from Continental Neogene sandstone deposits resembling soils of the Makonde plateau. These are classified as *Haplic Ferralsols* and *Luvic Arenosols*. Soil reaction is mostly acidic, but can be alkaline on poorly drained sites (pH-H_2O 4.5 - 8.2). The exchangeable base content is usually very low (<5 $cmol_c$ kg^{-1} soil), as is the cation exchange capacity (0.2 - 15 $cmol_c$ kg^{-1} soil) and the organic carbon content (0.5 - 1%).

Located adjacent to the west of Rondo and Makonde plateaux are hills dominated by shallow and sometimes stony soils. Those located close to the escarpment of the Makonde plateau have quartzite rocks and very shallow soils.

1.3.5 The Western plateau and uplands area

The western area consists of Liwale uplands and Tunduru plateau and uplands (Figure1.2). (Bennett *et al*., 1979; Dondeyne *et al*., 2001) described the Liwale uplands as a complex of flat plateaux, sloping, slumped and dissected plateaux and highly dissected terrain of ridges and valleys. The uplands consist of sandstone of Karoo age, overlying basement rocks. Soils are well drained *Haplic* and *Rhodic Ferralsols*. Soil reaction is acidic (pH-H_2O 4.7 - 6.5), with very low levels of exchangeable bases (<5 $cmol_c$ kg^{-1} soil) and cation exchange capacity (<5 $cmol_c$ kg^{-1} soil). The organic carbon content is equally very low (0.4 - 0.9%).

Based on the topography, the uplands of Tunduru can be separated into flat-topped *plateaux* and *dissected uplands*. The plateaux, mostly between 800 and 900 m, are separated from the dissected uplands by an escarpment with its base at 700 m. Detailed information on the soils of this area is however not available. Soil profile data available from the plateaux and uplands of Tunduru show that the topsoil is sandy while the subsoil is sandy clay.

1.4 Occupation of the people of South Eastern Tanzania

South Eastern Tanzania has a population of about 2 million people with an average growth rate of 1.7 % (Tanzania Population Census, 1988). It is inhabited by a number of ethnic groups including Makonde, Makua, Matambwe, Matumbi, Mwera, Ngindo and Yao. The history of origin and settlement of these tribes is given in Murdock (1959) and Wembah-Rashid (1975). The presence of tsetse flies in large areas, particularly in the northwest and west, and the Selous Game Reserve in the northwest (Figure 1.2) have contributed to congestion of population in habitable areas particularly on the Makonde plateaux and central Inland plains.

More than 98 % of the population is engaged in agricultural production (small-scale farming) (Tanzania Population Census, 1988). Cashew nut (*Anacardium occidentale* L.) is important as a cash crop in South Eastern Tanzania where about 70 % of the Tanzanian cashew production comes from (Martin *et al.*, 1997; Topper *et al.*, 1998c). Sesame is the second most important cash crop grown mainly in the Inland plains. Mponda *et al.* (1993) have reported that South Eastern Tanzania produces 80% of the national sesame production of about 30 ton. Cassava, maize, rice, sorghum and different types of peas and bambara nuts as well as groundnuts are grown for food crops. Some of these crops are intercropped with cashew trees. Common annual crops for intercropping with cashew trees, in order of preference, are cassava, maize, cowpea, sorghum, pigeon pea, bambara nut, upland rice and groundnuts. Besides agriculture other income generating activities include livestock (mainly goats and chicken), fishing, mining, harvesting forest products, wage labour, trading and craft.

1.5 Constraints for agricultural production and general development

Rainfall distribution in South Eastern Tanzania is very uneven. Crops requiring high rainfall or reliable distribution are at risk. Best-suited crops are sorghum, bulrush millet, cassava, sesame, pigeon pea, cowpea and cashew nut. Less adapted crops include maize (performs poorly under high night temperatures and poor rainfall distribution), upland rice and groundnut (sensitive to uneven rainfall distribution). Cashew trees perform poorly in areas with low average temperature particularly areas located above 800 m.

The abundant natural resources in the area (fish, forests and minerals) are not fully utilised because of poor physical infrastructure that leads to both internal and interregional isolation. Transport problems arise from poor road conditions. The only tarmac road connects the port town of Mtwara to Masasi town about 200 km inland. The most important outlet road from Mtwara to

Dar Es Salaam passes through areas of *Vertisols*, which are extremely sticky during the wet season rendering the road impassable. This affects the transport of inputs (sulphur, fertilizers, farm implements) and produce (cashew nuts and food crops) to and from Dar Es Salaam. It is worth noting that a deep natural harbour exists at Mtwara town, however, this infrastructure is not fully utilised due to a limited supply of goods from the hinterland.

Chapter 2
The cashew tree and cashew nut production

2.1 The Cashew tree

The taxonomic classification of the cashew tree is as follows:

Division	Magnoliophyta
Class	Magnoliopsida
Order	Apindales
Family	Anacardiaceae
Genus	Anacardium
Species	*Anacardium occidentale*

The family Anacardiaceae comprises about 64 genera and over 400 species consisting mostly of trees and shrubs (Singh, 1968; Johnson, 1973b) which grow abundantly in the tropics and semi-tropical climates. This family is characterised by a resinous bark (Ohler, 1979). Members of this family include mango (*Mangifera indica* L.), buchanania tree (*Buchanania latifolia* Roxb) and pistachio (*Pistacia vera* L.) (Purseglove, 1968). The cashew tree (*Anacardium occidentale* L.) falls under the genus Anacardium which is native to Latin America. Its primary centre of diversity lies in the Amazonia and its secondary centre in the Planalto in Brazil (Mitchell and Mori, 1987). The cashew tree was one of the first fruit/nut trees from the new world to be widely distributed to the tropics in Africa and Asia by the Portuguese in the 16th and 17th centuries (Ohler, 1979).

Under good conditions, the cashew tree can grow up to a height of 20 m (Behrens, 1996). The cashew tree is a low-branched and spreading evergreen plant, which produces several lateral branches thereby forming a bushy canopy. Old, overgrown and unpruned branches often reach the ground. Purseglove (1968) describes the leaves as alternate, simple, leathery, obovate, and glabrous with lamina growing to 6-20 cm in length and 4-15 cm in width. The leaves are rounded and often notched at their apex, tapering at their base with prominent main and laterally spreading veins.

The tree produces both male and bisexual flowers with male flowers predominating in the first flowering month. Period of flowering varies with climate, but usually lasts 3-4 months. The flowers are greenish and reddish, radially symmetrical with 5 sepals, 5 petals and 10 stamens.

Cashew flowers are cross-pollinated primarily by insects, particularly bees, although wind may also disperse pollen (Johnson, 1973a). Extensive use of insecticides in cashew groves is therefore discouraged.

An interesting feature of the cashew tree is that the nut develops first and when full-grown but not yet ripe, its peduncle or, more technically, receptacle, enlarges quickly to become the cashew apple (Figure 2.1). The cashew apple is a fleshy, juicy pear-shaped stalk (or accessory) which can be white, yellow, or red. The apple is about 10 cm long and 5 cm wide when ripe and often weighs 5 to 10 times more than the nut (Morton, 1987). Cashew apples have an astringent taste, due to tannins (0.1-0.7 %) (Sastry *et al.*, 1962) and traces of cashew nut shell oil. Cashew apples are rich in vitamin C.

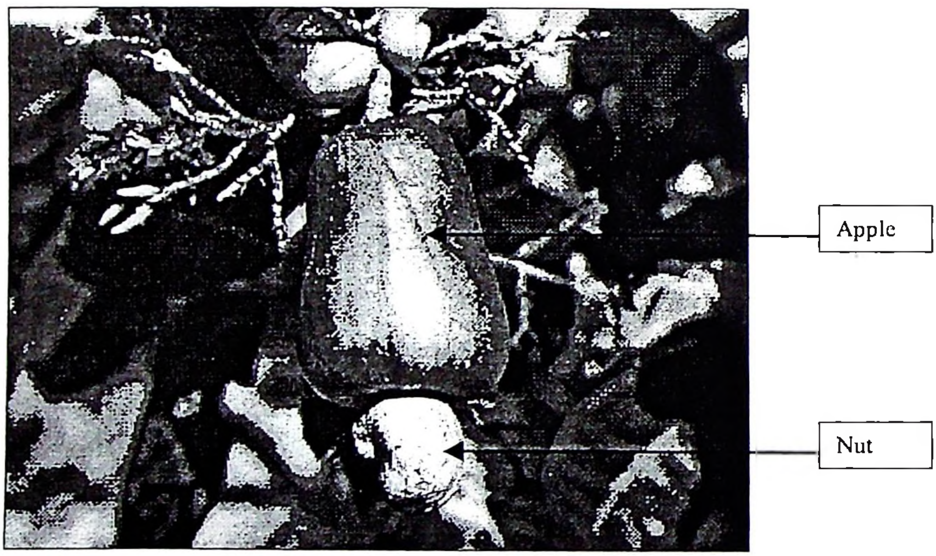


Figure 2.1 A cashew apple and nut

The nut is kidney-shaped (Figure 2.1) enclosing the kernel which is composed of two large white cotyledons and a small embryo. The kernel is sweet, oily and nutritious and is protected by a double-shelled tissue (mesocarp) containing a caustic phenolic resin in honeycomb-like cells. This resin is poisonous often causing allergenic skin reactions in humans. The various coatings around the kernel are indicated in Figure 2.2.

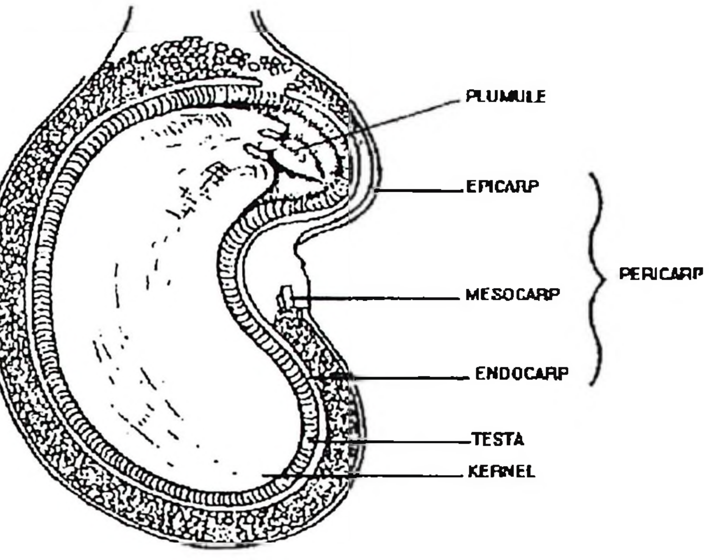


Figure 2.2 Cross-section of the cashew nut showing the various coatings protecting the kernel

(Source: Behrens, 1996)

2.2 Ecological requirements

2.2.1 Soil conditions

The cashew tree has a preference for deep, well drained, light textured soils (Ohler, 1979) which facilitates extensive lateral root extension (Tsakiris and Northwood, 1971) thereby contributing to drought resistance. Therefore soils with hard consistency and hardpans within the rooting zone are not very suitable for cashew production. High chemical fertility is not necessary for optimum cashew production (Falade. 1977; Mishra, 1984; Falade, 1984). However, the tree is less tolerant to saline soil than most coastal plants (Johnson, 1973b).

2.2.2 Climatic conditions

Cashew tolerates high temperatures and drought, but cannot grow and produce favourably in cold areas. A tropical climate with a distinct wet and a pronounced dry season of 5-7 months is important for flowering and fruit setting (Wait and Jamieson, 1986). The optimum average monthly temperature for cashew growing is 27^{0}C. Cool temperatures, associated with high altitude, interfere with the reproductive cycle of the tree. Cashew nut trees are particularly sensitive to low temperature, as they do not withstand frost. The first symptom of low temperature is delayed flowering (Behrens, 1996). The cashew tree is an unusual plant in that it flowers and sets fruit and maintains a full leaf cover during the driest part of the year. However, rainfall lower than 500 mm can not be tolerated (Behrens, 1996).

2.3 World production

Currently, cashew trees are grown in tropical and sub-tropical areas in America, Africa, Asia and Australasia. Table 2.1 shows countries leading in cashew nut production (metric ton) in the world. India is the world's leading producer and Tanzania ranks fourth. The four leading countries in cashew nut production in Africa are Nigeria, Tanzania, Mozambique and Guinea-Bissau. In Asia leading producers include India, Indonesia, Vietnam and Thailand. Brazil is the only country in America in the first 15 world producers. Current world production is around 1.2 million ton.

Data on area (hectares) under harvest (Table 2.1) shows that India also leads in area under cashew nut harvest. Other countries with high area under harvest are Brazil, Tanzania, Nigeria, Indonesia Vietnam and Guinea-Bissau. Production per hectare ranges from 0.17 to 5.71 ton/ha, which differs markedly among producing countries reflecting different farming systems and management of the crop. In a study of prospects and potentials of cashew production, Behrens (1996) concludes that "Increases in nut yields from currently 0.4 ton/ha to 2.3 ton/ha should be achievable within the next 10-15 years and that potential maximum nut yield will not be more than 6-7 ton/ha until at least 2020". This means that current production of 0.5 ton/ha and above should however be considered with caution.

Table 2.1 Cashew nut production (ton) and area under harvest (ha) for 15 producing countries of the world in the year 2000

Rank	Country	Production (ton)	Area under harvest (ha)	Production (ton/ha)
1	India	450000	730000	0.62
2	Nigeria	176000	278000	0.63
3	Brazil	153921	597813	0.26
4	Tanzania	130000	400000	0.33
5	Indonesia	75000	250000	0.30
6	Vietnam	68717	195000	0.35
8	Guinea-Bissau	42000	106000	0.40
7	Mozambique	35000	50000	0.70
9	Côte d'Ivoire	28000	95000	0.29
10	Thailand	22000	22000	1.00
14	Senegal	15000	55000	0.27
11	Malaysia	13000	7000	1.86
13	Philippines	7000	17000	0.41
12	Kenya	4000	700	5.71
15	China	1000	5800	0.17
	Total	1220638	2809313	

Source: FAO, 2000

2.4 Commercial products

The cashew tree is grown for its nuts, cashew nut shell liquid (CNSL), apples, gum and wood. Among these, the most important economic product is the kernel obtained from the nut after processing either in mechanised factories and by hand driven machines. Roasted and salted kernels have a pleasant taste and flavour forming an important component of the snack market. In 1995 snacks from cashew nuts accounted for 70% of the total kernel consumption in the world (Jafee *et al.*, 1995). In the snack market, the principal competitors are almonds (*Prunus communis*), hazelnuts (*Corylus avellana*) and peanuts (*Arachis hypogea*). Kernels are also used in confectionery where they compete with almonds, hazelnuts, walnuts (*Juglans regia*) and pistachios (*Pistacia vera* L.). The cashew kernel is also used for desserts and in the preparation of sweets. It is rich in proteins, calcium, phosphorus and vitamins (NOMISMA, 1994). Not surprisingly the kernel is one of the ingredients in many dishes along the east African coast.

The largest consumers (importers) of cashew nuts are the USA followed by the EU (Figure 2.3). According to Jaffee *et al.* (1995), within the EU the main importers are the UK, the Netherlands, Germany, France, Belgium and Sweden.

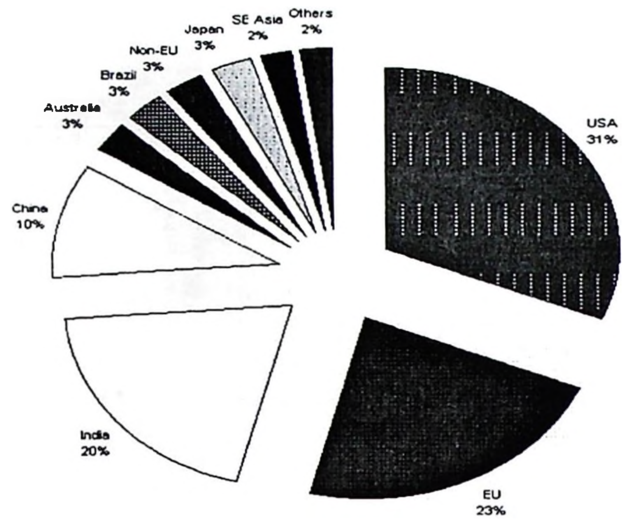


Figure 2.3 World consumers (importers) of cashew nuts

The second most important product of the cashew tree is the CNSL which is obtained through mechanical processing of raw nuts. It is used in the manufacture of brake linings, industrial belting and clutches. reinforcing synthetic rubber, in lacquers, in electrical insulation material, as an anti-corrosive material, for waterproofing and as an adhesive. The main producer of CNSL is India. It is mainly exported to Japan, Korea and Australia.

Cashew apples do not attract international trade due to the short production period, low transportability, natural astringency and lack of infrastructure. Cashew apples have a low local commercial value in Tanzania where they are consumed raw or squeezed and fermented to produce a local liquor known as "Uraka" or distilled into an alcoholic drink called "Nipa" popular in South Eastern Tanzania. Cashew apple juice is also popular in Brazil (Johnson, 1973a).

Other additional products of low commercial value include cashew wood, bark and gum. Wood is used in furniture making, boat building, packing cases and in the production of charcoal. Bark is used in tanning. Stems exude a clear gum used in pharmaceuticals, for bookbinding and as substitute for gum arabic.

2.5 Cashew nut production in Tanzania

2.5.1 History

Local inhabitants in Newala district in Mtwara region (Figure 1.1) claim that parent material for cashew came from Mozambique in the early 1920s and 1930s. It is also claimed that the first planting was done at Samora village in Newala district in Mtwara Region (Mpinda, personal communication). With time, cashew tree planting and production spread to other areas on the Makonde plateau, the coastal plains stretching from Mtwara to Lindi and to the inland plains west of the plateaux (Figure 1.2). Further expansion to the coastal plains of the northern regions in Tanzania occurred during the 1950s and 1960s (Northwood and Kayumbo, 1970). After its introduction, cashew remained a crop for local consumption until the late thirties. In 1938 about 210 ton of cashew nuts were shipped to India (Northwood and Kayumbo, 1970). These exports stimulated further planting and within twenty years cashew had established itself as an important cash crop for smallholder farmers in South Eastern Tanzania.

Cashew nut production in Tanzania has fluctuated over the years. Production grew steadily during the 1960s and early 1970s reaching a peak of 145,000 ton of nuts in 1974 (Figure 2.4) but then fell dramatically and remained extremely low for almost a decade before rising again in the mid 1990s. In mid 1970s, Tanzania was the second largest producer of cashew nuts in the world, after Mozambique (Martin *et al.*, 1997; Cumbi, 1998). This production encouraged the government to invest in the construction of 12 processing factories spread over the main cashew producing areas.

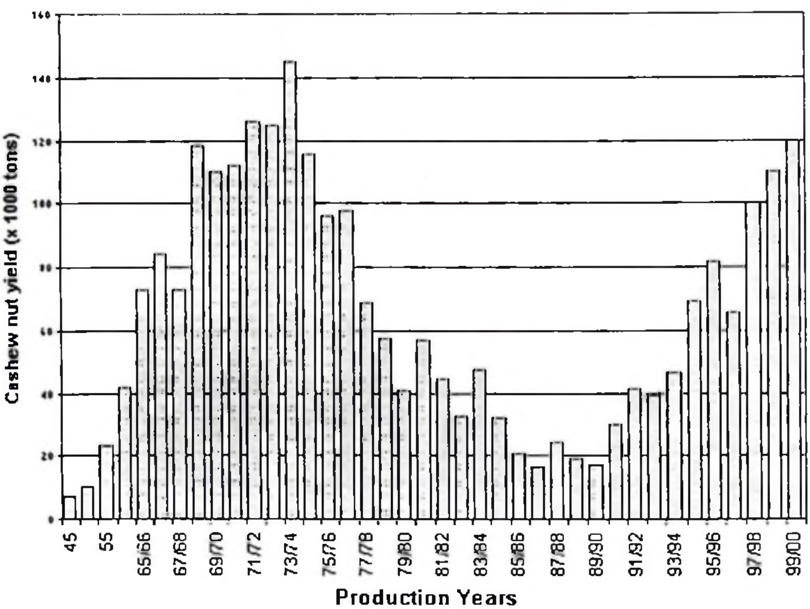


Figure 2.4 National cashew nut production statistics for the period 1945-2000 (Cashew nut Board of Tanzania 2000)

2.5.2 Cashew nut producing regions

Figure 2.5 presents the contribution (%) of different regions to national cashew nut production between 1973/74 to 1996/97. South Eastern Tanzania, which comprises Mtwara (47 %), Lindi (18 %) and Tunduru district (Ruvuma region 7 %), leads with 72% of the national production.

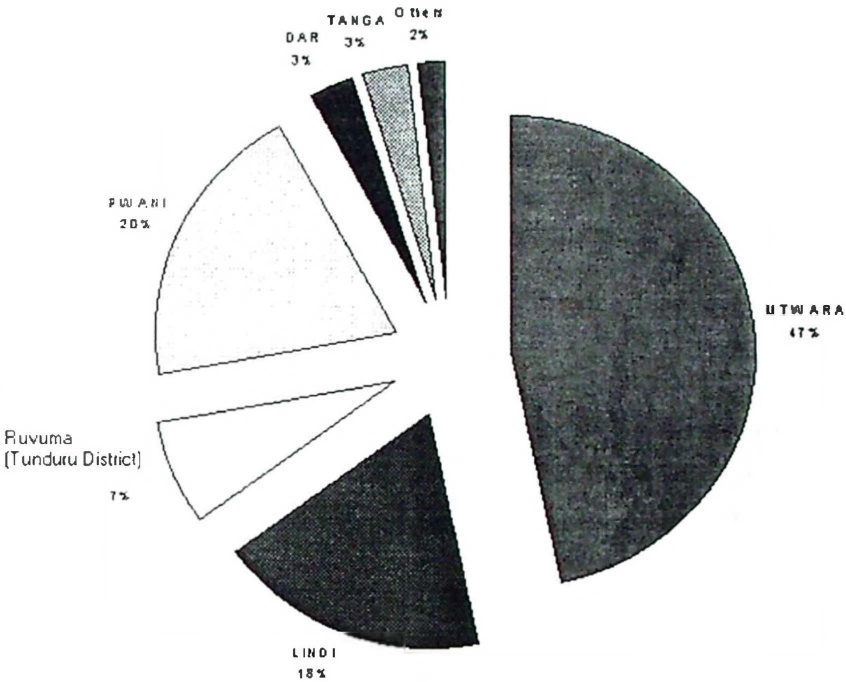


Figure 2.5 Cashew nut production per region in Tanzania (CBT, 1998)

Cashew nut production in South Eastern Tanzania between 1987/88 and 1996/97 is shown in Table 2.2. Newala district, which produced a total of 120,704 ton in 11 marketing seasons is leading in cashew nut production. In 1997 Newala was divided into two districts, Newala and Tandahimba. Other districts in decreasing order of production are Masasi, Mtwara, Tunduru and Lindi. In terms of landscapes, Makonde plateau leads in cashew production followed by Inland plains and Tunduru Uplands and Plateau.

Table 2.2 Cashew nut production in various districts in South Eastern Tanzania between 1987 and 1997

Landscapes	Districts	Marketing year (ton)										
		1987/88	1988/89	1989/90	1990/91	1991/92	1992/93	1993/94	1994/95	1995/96	1996/97	Total
Makonde Plateau	Mtwara	1793	1184	1169	2684	4531	4950	3039	2987	11038	5754	39129
	Newala	7457	7621	4429	7885	11985	7033	10901	13754	27749	21890	120704
												159833
Inland Plain	Masasi	3173	2203	2950	3783	5609	5960	7894	10722	10319	8612	61225
	Nachingwea	436	289	135	451	1344	1764	2356	3732	4684	4443	19634
	Liwale	227	622	54	374	654	665	675	1410	45	860	5586
												86445
Coastal areas (Rondo Plateau + Ruangwa district)	Lindi	1191	507	856	1614	3399	4800	2711	2964	5983	5173	29198
Coastal areas +Kilwa Plateau	Kilwa	738	196	250	660	516	206	202	957	874	758	5357
Tunduru Uplands and Plateau	Tunduru	550	1354	319	1336	2854	5165	4981	6640	7997	7214	38410

Source: Cashewnut Board of Tanzania, (1999).

2.5.3 Cropping systems

About 280,000 cashew farmers grow cashew on mono or mixed crop production systems in South Eastern Tanzania (Shomari, 1996; 1999). Most production comes from small plots varying in size from 1.6 to 5 hectares often mixed with staple food crops. Cashew groves with over 10 hectares occupy a small percentage of the total area under production, mostly in Mtwara and Lindi regions (Cashew Research Report, 1998/99).

In farmers' groves, trees are established from 3 seeds per hill of which one seedling is left after germination. Planting has to be done in situ because cashew seedlings do not transplant easily. Seeds for planting are stored in a dry place to maintain seed dormancy which remains viable for one year. The best time for seeding is during the onset of rains in December. By the end of the rainy season the young cashew plants have developed a taproot and sufficient lateral roots to ensure survival during the dry season. In recent years vegetative propagation has become common in South Eastern Tanzania (Shrestha, 1989). Seeding of rootstock is done in seed gardens and grafting involving scions takes place at the seed gardens. Transplanting of grafted seedlings is usually delayed till January when the soils have gained sufficient soil moisture.

In South Eastern Tanzania, the reproductive cycle starts with leaf flushing in May–June and flowering extends from June to September coinciding with periods of low or no rainfall (Martin *et al.*, 1997). Nuts mature 3 months after pollination. A cashew tree seedling takes 3 years to produce its first crop and about 10 years to reach its optimum production.

Cashew groves in South Eastern Tanzania are often intercropped with annual crops (Bennett *et al.*, 1979; Martin *et al.*, 1997). Therefore farmers prefer a wider spacing than the recommended 12 m × 12 m to allow intercropping with annual crops particularly in young cashew groves or where land for these crops is scarce. In some farmers' groves trees are grown irregularly making it difficult to ascertain size of groves by counting the tree numbers. Annual crops preferred for intercropping include cassava (Figure 2.6), maize, sorghum, cowpea, groundnut and bambara nut. Intercropping is also practised in other cashew growing countries. In Brazil's Northeast region for example, cashew is intercropped with coconut, citrus and banana (Johnson, 1973a). Intercropping with annual crops helps to keep weeds under control especially during the early growth stages of the cashew trees.

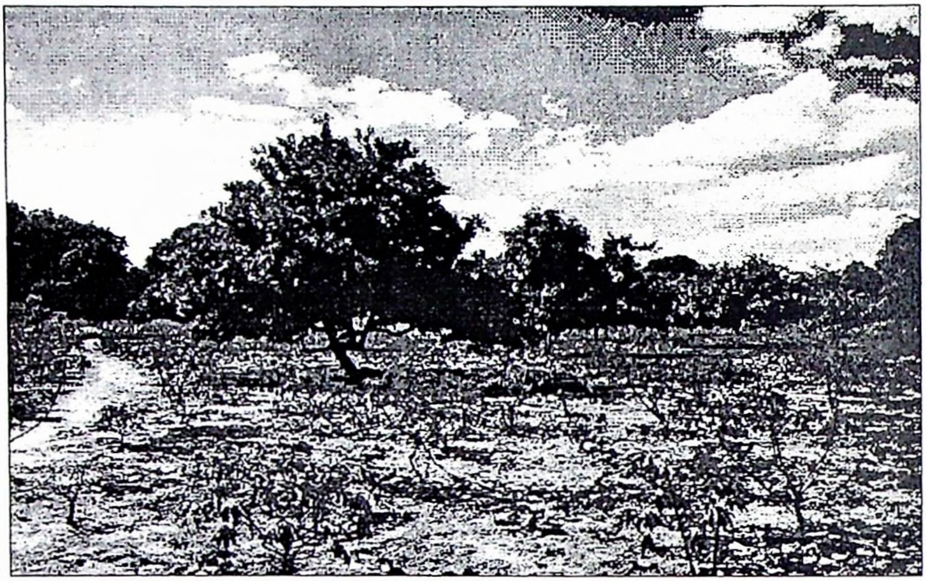


Figure 2.6 A young cashew grove in Newala district intercropped with cassava

2.5.4 Cashew production per tree

Cashew nut yield ranges from 0–48 kg/tree/year (Behrens, 1996) and depends among others on soil type, rainfall pattern, crop management, genotype and age of the tree. Cumbi (1998) has reported that the average nut yield per tree in Mozambique is 1.5 kg. At Pacajus (Ceara, Brazil) the average nut yield is 17.4 kg/year with a few trees reaching 48 kg/year (Duke, 1983 quoting Johnson, 1973a). Average nut yield recorded from smallholder farmers' cashew groves in South Eastern Tanzania ranges from 1 to 15 kg/tree/year (Kasuga, personal communication). It has been reported that during the mid 1970s when Tanzania recorded a peak production of 145,000 ton of cashew nuts, the average national tree yield was 4 kg per tree (World Bank, 1989) equavalent to 0.28 tons ha^{-1}. The present average yield per tree is estimated to be the same.

2.5.5 Management of cashew groves

Weeds are a major problem in southern Tanzania because they conceal fallen nuts and constitute a fire hazard. Bush fires are common particularly in the Inland plains. A hand hoe is normally used for weeding but slashing is also practised. Pruning of excess branches is an important agronomic practice since it improves air circulation and light penetration into the canopy. Increased air circulation and light reduces disease infestation and spreading of harmful insects.

Harvesting starts as soon as nuts fall on the ground usually from August to November. The nut and the apple drop together and are separated manually through a twisting action. The apples are processed the same day by squeezing and fermenting the juice for a local brew. Apples can also be sun-dried and later distilled into an alcoholic drink. Nuts are sun dried for several days before grading and bulking ready for sale. In wet periods, nuts are gathered daily otherwise apples decay and nuts germinate

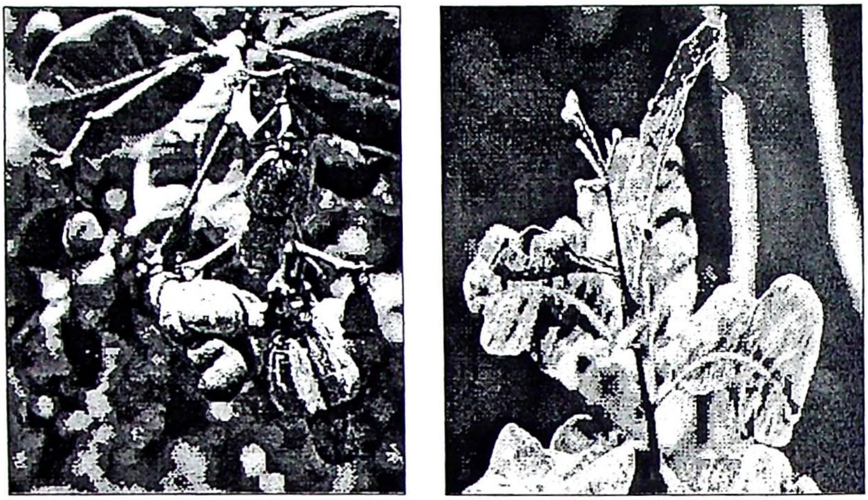
2.5.6 Constraints to cashew nut production

2.5.6.1 Powdery mildew disease

Powdery mildew disease (PMD) of cashew is caused by a parasitic fungus called *Oidium anacardii* Noack (Casulli, 1981). This fungus belongs to the class Ascomycetes and sub-class Hymenoascomycetes (Agrios, 1988; Bold *et al.*, 1987). The full classification of this species is indicated below:

Class:	Ascomycetes
Sub-class:	Hymenoascomycetes
Order:	Hyphales
Sub-order:	Erysiphales
Family:	Erysiphaceae
Genera:	Erysiphe
Species:	*Oidium anacardii*

PMD is characterised by the appearance of spots or patches of white to grayish, powdery, mildew growth on young plant tissues and parts (Figure 2.7). The whitish material represents hyphae growing from mycelia. PMD is a major constraint in the production of the crop in South Eastern Tanzania (Castellani and Casulli, 1981; Casulli, 1981; Intini and Sijaona, 1983; Sijaona, 1984; Sijaona and Shomari, 1987; Sijaona, 1997).



(A) (B)

Figure 2.7 Cashew nuts and apples (A) and leaves (B) infected by Powdery mildew disease

Oidium anacardii develops from conidia which are tiny spores floating in the air and within the canopies of cashew trees. Conidial germination usually occurs when temperature of 20-30^{0}C sets in within the tree canopies. When temperature is below 15 and above 30^{0}C conidial germination percentages are significantly lowered (Shomari and Kennedy, 1998). Conidial germination occurs at all humidities but tends to increase with increasing humidity. After germination the conidium establishes an appendage called haustorium that penetrates into the epidermal cells of the host tissue where it obtains nourishment. The mycelium then develops dense white hyphal cells which are uninucleate (Sijaona, 1999). Through asexual reproduction these hyphal cells produce conidia which are spreading by air currents to establish secondary infections when conditions are favourable. Unless treated with fungicides, this cycle of infection and re-infection will continue.

Oidium anacardii infects terminal buds, young shoots, flower buds, flowers and young fruits and nuts (Casulli, 1981; Castellani and Casulli, 1981) (Figure 2.7). Infection starts on less exposed parts of the target (shaded or interior) parts of the canopy and progresses rapidly with time to other areas (Shomari and Kennedy, 1998). Severe infections on leaves may cause necrosis (Figure 2.7) and defoliation. When young nuts are severely infected, they become shrivelled and deformed (Shomari, 1996) resulting in downgrading and reduced market value. Young flowers are very susceptible to infection. Severely infected flower buds fall before anthesis thereby significantly reducing yield (Masawe, 1994). In South Eastern Tanzania, cashew nut yield reductions of up to 70-100 % have been reported (Sijaona and Shomari, 1987).

Extensive surveys in cashew groves in South Eastern Tanzania by Shomari (1999) has shown that initial inoculum originates on immature shoots and flowers within the canopies of trees produced during off-season. Here conidia are continually produced and based on Shomari (1999) about 4-6 % of conidia concentrations can be monitored at a distance of 180 m from the source. Destruction of these sources during off-season will help reduce the inoculum but since large numbers of cashew trees are unattended, this measure alone can not eradicate the mildew problem (Shomari, 1999).

It seems likely that PMD came from northern Mozambique, where cashew trees were neglected for a long time due to several years of civil strife (Cumbi, 1998). In Tanzania the villagisation (ujamaa) programme of mid 1970's has aggravated the spread of the fungus. By resettling farmers in new villages, this programme had the effect of distracting management of farms in traditional villages including cashew groves leading to declining yields (Brown *et al.*, 1984; Raikes, 1986; Poulton *et al.*, 1997). The disease is now widely spread in most of the cashew nut producing areas in Tanzania. Nathaniels and Kennedy (1996) and Shomari (1999) have reported that incidence of the disease is higher on the coastal areas where humidity is higher than in the hinterland.

The exact origin of the fungus *Oidium anacardii* has not been established. It could be possible that it co-evolved with the crop in Latin America where currently it has no economic importance. The disease is also of minor economic importance in India. These observations support the view that long-term neglect of cashew groves in eastern Africa has created a conducive environment for its present status (Kasuga –personal communication).

2.5.6.2 Other diseases and pests of cashew trees

Besides powdery mildew, other diseases but of less economic importance in Tanzania include anthracnose (*Colletotrichum gloeosporides* Penz), dieback (*Phomopsis anacardii* Early and Punith), cercospora leaf spot (*Pseudocercospora anacardii* Nova), pestalotia leaf spot (*Pestalotia heterocornis* Guba) and wilting syndrome (Intini, 1987; Sijaona, 1997).

In recent years insect pests have become a problem. The main insect pests in South Eastern Tanzania are *Helopeltis* spp. (Order Heteroptera, family Miridae), *H. anacardii* Miller and *H. schoutedeni* Reuter) and coconut bugs (*Pseudotheraptus wayi* Brown) (Order Hemiptera, family Coreidae) Others include thrips (*Selonothrips rubrocinctus* Giard) and mealybug (*Pseudococcus* spp.) (Order Homoptera. family Pseudococcidae) (Cashew Research Report, 1997/98). *Helopeltis* and *Pseudotheraptus spp.* suck tender parts of the plant (new shoots, flowers and nuts) causing lesions and dieback of these parts. Thrips and mealybugs attack leaves, shoots, inflorescences and flowers. Currently these pests are controlled by application of Karate (l-cyhalothrin ULV 6). Work on biological control of *Pseudotheraptus wayi* and *Helopeltis* bug involving the African weaver ants (*Oecophylla longinoda*) is in progress at Naliendele.

2.5.6.3 Market related and input supply constraints

Involvement of private traders in crop purchases in previous marketing seasons (1992/93-1999/00) managed to raise producer prices of raw nuts from 250 to 800 Tshs/kg (800 Tsh is approximately US$ 1). However during 2000/01 marketing season, the price of cashew nuts went down to 350 Tsh per kilogram. This decline is attributed to over supply of cashew nut kernels in the traditional consumer countries in Western Europe and America. It is also caused by competition from other nuts particularly almonds and hazelnuts. Producer countries are therefore forced to make market adjustments. One obvious option would be the local processing of raw nuts in order to diversify end products that have the added advantage of creating employment opportunities.

Entry into commercial production of cashew nuts presents problems due to lack of credit for purchasing sulphur, sulphur dusters and pesticide. Purchase of sulphur on credit is restricted since it is perceived as risky in view of problems of loan repayment from farmers.

2.5.7 Sulphur dusting

The catastrophic decline of cashew nuts in Tanzania (Figure 2.4) has been attributed mainly to the outbreak of powdery mildew disease and partly to socio-economic factors linked to the resettlement programme in the 1970s and to market related problems (Brown *et al.*, 1984; Poulton *et al.*, 1995). In the early 1980s, research at the Naliendele Agricultural Research Institute in Tanzania, led to the identification of sulphur as a suitable chemical for controlling powdery mildew disease (Sijaona, 1984). Sulphur has been widely adopted by farmers (Partel, 1988; Poulton *et al.*, 1995) and during the last three years (1997-1999) sulphur imports to South Eastern

Tanzania (regions of Lindi, Mtwara and Tunduru district) went up from 2,500 to 7,000 ton (Cashewnut Board of Tanzania, 1999). As a result of sulphur dusting and the recent market liberalisation, production is increasing and during the 1999/2000 marketing season 120,000 ton of nuts were marketed (Figure 2.4).

The standard recommendation is to dust 1.25 kg of sulphur per tree per season. For the recommended spacing of 12 by 12 m per tree, this represents approximately 90 kg ha^{-1} of S. Sulphur is dusted onto the trees by using motorised blowers in five rounds at the rate of 250 g per tree; the first application coinciding with the initiation of flower buds. As the interval between sulphur applications is two weeks, the last application is done eight weeks later. Flower buds, flowers, young leaves and young shoots of untreated trees become seriously attacked by the mildew resulting in poor harvest and inferior nut quality.

Smith *et al.* (1998) however reported that up to 78% of the sulphur dusted onto cashew trees drifts away. When sulphur gets to the soil, under moist aerobic conditions it gets oxidised unto sulphuric acid by autotrophic bacteria (Brady, 1990). It can thus be said that although sulphur dusting alleviates the problem of declining yield, it creates acidity in soils. Majule *et al.* (1997) and Ngatunga *et al.* (1998) have also reported declining pH on cashew groves under S dusting in South Eastern Tanzania.

2.5.8 Micro-economic considerations for using sulphur

2.5.8.1 Is sulphur dusting profitable?

Field trials comparing the performance of sulphur dusted and non-dusted plots have indicated that sulphur significantly decreases PMD infection and improves yield of cashew trees (Boma *et al.*, 1998, Topper *et al.* 1998b) (Tables 2.3 and 2.4). Cashew nut yield data in Table 2.3 show that <1 kg/tree (or 0.07 ton/ha) was harvested from the control plots while over 7 kg/tree (0.49 ton ha^{-1}) were obtained from sulphur applied plots. This is a gain of 6 kg of nuts per tree or 0.36 ton ha^{-1}. Assuming the current price of US$ 437.50 per ton and a plant population per hectare of 70 trees, this is equivalent to a net revenue of US$ 157.50. The actual net revenue will be slightly lower due to inputs such as sulphur, transport and bags (Annex II).

Table 2.3 Comparison of 4 mildew control strategies at Newala in 1993

Treatments*	Mildew score** (North direction))	Mildew score (South direction)	Yield (kg/tree)
Sulphur (on best 50% of trees)	21.1 c	43.1 b	9.13
Sulphur (on best 100% of trees)	12.7 bc	30.7 b	7.56
Bayfidan (on best 50% of trees)	1.2 a	1.3 a	14.36
Anvil (on best 50% of trees)	3.4 ab	4.0 a	12.14
Control	83.6	85.9	< 1

* Means with the same letter in the same column do not differ significantly at $p > 0.1$

** Mildew score is the percent of leaf area affected by mildew

(Source: Topper *et al.*, 1998b)

Table 2.4 Effect of different fungicides (4 sulphur types and 1 organic) on mildew scores at Kibiti

Treatments*	Mildew score** (North direction)	Mildew score (South direction)
Arabian sulphur (Palm brand)	23.2 ab	27.5 b
Tanzanian sulphur (TFC brand)	24.0 b	27.4 b
Fluidosoufre-spray	28.4 c	32.0 c
Solfo-spray	23.0 ab	26.8 b
Bayfidan-organic fungicide	20.3 a	21.0 a
Control	39.3	43.1

* Means with the same letter in the same column do not differ significantly at $p > 0.1$

** Mildew score is the percent of leaf area affected by mildew

(Source: Boma *et al.*, 1998)

2.5.8.2 Trade off of cashew versus intercrops

For a farmer who manages 5 ha of cashew and intercrops with cassava, maize, sorghum, cowpea and ground nut. net revenue from cashew and cost of producing intercrops are shown in Table 2.5 for 70 cashew trees per ha and Table 2.6 for 50 trees per ha. A list of inputs required and corresponding costs are shown in annex II. For a cashew grove with 70 trees per ha the cost per ha is estimated US$ 71.25 if hired labour is used or US$ 38.13 when own labour is used. For trees yielding 1 kg of cashew nuts. revenue per ha (at US$ 437.50 per ton) is estimated at US$ 153.13. This revenue increases as production per tree increases as shown in Table 2.5. It should be noted that farmers usually intercrop to satisfy food security requirements for the family. If the farmer has to forgo intercropping, the assumption is that net revenue from cashew has to be used to meet food security requirements.

To get a balance (after purchasing crops) of a least US$ 100 ha^{-1} when 70 trees per ha are cropped (Table 2.5), the farmer needs to have trees that yield at least 6 kg nuts/tree if labour is hired or 5 kg nuts/tree if own labour is used. When 50 trees per ha are cropped (Table 2.6), which resembles a typical farmers' situation, and a balance of US$ 100 ha^{-1} is required, trees need to produce 7 kg nuts/tree if labour is hired or 6 kg nut/tree when own labour is used. Production costs per ha and for 5 ha for cashew and for intercrops are shown in annexes II and III respectively. Considering that farmers in the study area have low yielding trees, the implication of these scenarios is that farmers need to intercrop to meet their food requirements. Intercropping will have to continue until such time when trees with a minimum capacity to produce 5 kg nuts/tree or more are obtained. Also in view of food security of remote cashew growing areas it would be unwise to sacrifice the intercrops for obtaining high short-term cashew yields.

Based on data in Table 2.1, current average national production per hectare stands at 0.33 ton ha^{-1} reflecting an estimated average yield of 4-5 kg per tree. As shown above for a 5-ha grove, 5 kg/tree can bring a net return of US$ 409.38 which is only sufficient to cater for the family food requirement. There is need to increase average yield per tree to realise increased profits. Production of 1 ton/ha of cashew nuts, equivalent to 10-15 kg/tree, can bring a net return of US$ 1831.25 and a balance of US$ 1425.60 after offsetting food requirements. This is US$ 285.12 per ha equivalent to Tsh. 228,096. The drop of cashew nut price from 800 Tsh (US$ 1) in the 1998/99 marketing season to 350 Tsh (US$ 0.44) in the following season has greately reduced profitability of the crop. At constant costs of production and food crops, a high price of cashew nuts and a stable market will make cashew farming a lucrative enterprise.

2.5.9 Current research issues

While marketing and institutional problems are improving, cashew nut production is still being propagated from low yielding and disease susceptible tree types, insect pests are on the increase and environmental pollution from sulphur dusting continues to worry the industry and the small farmer. A cashew nut breeding programme has been initiated and sixty crosses of local cashew nut clones have been produced and germplasm imported. Preliminary results show that some of the hybrids flower early which provides possibilities to select tree types that escape powdery mildew disease (Masawe *et al*., 1999b)

Alternative fungicides to sulphur are being screened and a range of pesticides is available for screening against pests of cashew (Cashew Research Report, 1999/00). Work on biological control of cashew nut bugs (*Pseudotheraptus wayii*) and Helopeltis bugs (*Helopeltis* spp) is in progress. Implication of dusting 90 kilograms of sulphur on cashew trees on soils and growth of crops is being assessed. Agronomic research work has concentrated on improving yield through upgrading cashew orchards including management of tree stumps (Topworking) and optimisation of plant population (Martin and Kasuga, 1998).

Table 2.5 Partial budget for a 5-hectare cashew grove with 70 trees per hectare

Labour status	Yield/tree (kg)	Yield (ton)*	Gross revenue (US$)**	Cost of production (US$)	Net revenue (US$)	Cost of intercrops (US$)	Balance (US$)
Hired labour	1	0.35	153.13	356.25	-203.13	405.65	-608.78
	2	0.70	306.25	356.25	-50.00	405.65	-455.65
	3	1.05	459.38	356.25	103.13	405.65	-302.53
	4	1.40	612.50	356.25	256.25	405.65	-149.40
	5	1.75	765.63	356.25	409.38	405.65	3.73
	6	2.10	918.75	356.25	562.50	405.65	156.85
	7	2.45	1071.88	356.25	715.63	405.65	309.98
	8	2.80	1225.00	356.25	868.75	405.65	463.10
	9	3.15	1378.13	356.25	1021.88	405.65	616.23
	10	3.50	1531.25	356.25	1175.00	405.65	769.35
	14	5.00	2187.50	356.25	1831.25	405.65	1425.60
	15	5.25	2296.88	356.25	1940.63	405.65	1534.98
Own labour	1	0.35	153.13	190.65	-37.53	405.65	-443.18
	2	0.70	306.25	190.65	115.60	405.65	-290.05
	3	1.05	459.38	190.65	268.73	405.65	-136.93
	4	1.40	612.50	190.65	421.85	405.65	16.20
	5	1.75	765.63	190.65	574.98	405.65	169.33
	6	2.10	918.75	190.65	728.10	405.65	322.45
	7	2.45	1071.88	190.65	881.23	405.65	475.58
	8	2.80	1225.00	190.65	1034.35	405.65	628.70
	9	3.15	1378.13	190.65	1187.48	405.65	781.83
	10	3.50	1531.25	190.65	1340.60	405.65	934.95
	14	5.00	2187.50	190.65	1996.85	405.65	1591.20
	15	5.25	2296.88	190.65	2106.23	405.65	1700.58

* Yield in ton = (yield per tree (kg) × number of trees per ha)/1000 × 5 (ha)
** Price of 1 ton of cashew nuts = US$ 437.50
Details of computations of costs of inputs for cashew and intercrop production are shown in annexes II and III

Table 2.6 Partial budget for a 5-hectare cashew grove with 50 trees per hectare

Labour status	Yield/tree (kg)	Yield (ton)*	Gross revenue (US$)**	Cost of production (US$)	Net revenue (US$)	Cost of intercrops (US$)	Balance (US$)
Hired labour	1	0.25	109.38	262.50	-153.13	405.65	-558.78
	2	0.50	218.75	262.50	-43.75	405.65	-449.40
	3	0.75	328.13	262.50	65.63	405.65	-340.03
	4	1.00	437.50	262.50	175.00	405.65	-230.65
	5	1.25	546.88	262.50	284.38	405.65	-121.28
	6	1.50	656.25	262.50	393.75	405.65	-11.90
	7	1.75	765.63	262.50	503.13	405.65	97.48
	8	2.00	875.00	262.50	612.50	405.65	206.85
	9	2.25	984.38	262.50	721.88	405.65	316.23
	10	2.50	1093.75	262.50	831.25	405.65	425.60
	14	3.50	1531.25	262.50	1268.75	405.65	863.10
	15	3.75	1640.63	262.50	1378.13	405.65	972.48
Own labour	1	0.25	109.38	140.65	-31.28	405.65	-436.93
	2	0.50	218.75	140.65	78.10	405.65	-327.55
	3	0.75	328.13	140.65	187.48	405.65	-218.18
	4	1.00	437.50	140.65	296.85	405.65	-108.80
	5	1.25	546.88	140.65	406.23	405.65	0.58
	6	1.50	656.25	140.65	515.60	405.65	109.95
	7	1.75	765.63	140.65	624.98	405.65	219.33
	8	2.00	875.00	140.65	734.35	405.65	328.70
	9	2.25	984.38	140.65	843.73	405.65	438.08
	10	2.50	1093.75	140.65	953.10	405.65	547.45
	14	3.50	1531.25	140.65	1390.60	405.65	984.95
	15	3.75	1640.63	140.65	1499.98	405.65	1094.33

* Yield in ton = (yield per tree (kg) × number of trees per ha)/1000 × 5 (ha)

** Price of 1 ton of cashew nuts = US$ 437.50; Details of computations of costs of inputs for cashew and intercrop production are shown in annexes II and III

Chapter 3

Literature review on soil acidification

3.1 Soil acidification and alkalisation

Soils become acidified when the concentration of H^+ ions exceeds OH^- ions. This occurs through a complex set of processes that generate net H^+ ions in a system leading to soil acidification. These processes can be natural and/or man-made (Krug and Frink, 1983). In an ecosystem, natural acidifying processes include base cation uptake (by plants or microbes); natural leaching by carbonic, organic, or nitric acid; and humus formation (Van Breemen *et al.*, 1984). Man-made acidifying processes include biomass harvesting (Binkley *et al.*, 1987), fertilisation (Van Breemen *et al.*, 1984) as well as atmospheric inputs of acidifying compounds (Reuss and Johnson, 1986). Acidification through natural processes is caused by the dissociation of carbonic and organic acids to provide protons and anions (Krug and Frink, 1983). Protons displace exchangeable base cations that can be transported down the profile with anions. External inputs of acidifying compounds add to the effect of natural acidifying reactions and so increase the rate of acidification.

Van Breemen *et al.* (1984) offers another way of understanding the concept of acidification. Soil acidification is defined as a decrease of its acid neutralising capacity (ANC). It occurs when the input of protons exceeds output. There are several reactions that produce or consume protons in soils (Breedemeier *et al.*, 1990). For example when there is a net export of base cations (Ca^{2+}, K^+, Na^+ and Mg^{2+}) in drainage water and in harvested crop, ANC of the system declines. Loss of base cations in drainage water is often accompanied by loss of anions mainly Cl^-, NO_3^-, SO_4^{2-} and HCO_3^-.

Soil alkalisation is the opposite of acidification. It is defined as an increase in the ANC and takes place when there is an increase of cationic components such as CaO, Ca $(OH)_2$ and $CaCO_3$ (Van Breemen *et al.*, 1984). Helyar (1976) reports that during the processes of alkalinisation, a proton is consumed or a hydroxyl ion is produced. Thus alkalinisation of the percolating soil solution becomes complete when free protons are neutralised resulting in the formation of unprotonated anions such as HCO_3^-. On the basis of the relative concentrations of H^+ and OH^- ions, soils are grouped into acid or alkaline.

3.2 Intensity and capacity factors in soil acidification

Components that comprise ANC can be divided into processes that are relatively fast (approach equilibrium rapidly) and slow (Gower *et al.*, 1995). Processes approaching equilibrium fast are referred to as *intensity factors* (Reuss and Johnson, 1986). Such processes have an immediate impact on the composition of the soil solution. Soil components involved are predominantly the soil solution and those soil surfaces that react rapidly to changes in the soil solution (e. g. cation and anion exchange capacity) including soluble compounds.

Slow processes are referred to as *capacity factors* and essentially reflect an integration of changes in the soil system over time. These processes, which are controlled by the buffer capacity of the soil (Bloom and Grigal, 1985), include cation and anion plant uptake, mineralisation, oxidation and reduction, and primary and secondary mineral weathering (Gower *et al.*, 1995). Over the long term, capacity factors control the range in intensity factors since ion pools that comprise them greatly exceed those of the intensity factors and the inputs from acidic deposition (Reuss and Johnson, 1986). These relatively large pools of ions in already acid soils are the basis for the assumption that the impact from acidic deposition will be small compared to natural acidification processes (Krug and Frink, 1983). Substantial periods of time will be required before detectable changes in these bulk soil chemical properties can take place (Binkley *et al.*, 1987).

3.3 Quantification of soil acidification

Van Breemen *et al.* (1984) suggests quantifying acidification of the soil as the sum of basic components minus the strong acidic components. This can be presented as follows:

$$ANCs = 6[Al_2O_3] + 6[Fe_2O_3] + 2[FeO] + 4[MnO_2] + 2[MnO] + 2[CaO] + 2[MgO] + 2[Na_2O] + 2[K_2O] - 2[SO_3] - 2[P_2O_5] - [HCl] \quad \text{Eq. 2.1}$$

Thus, acidification is said to increase when basic components are taken away from the soil system. As indicated above, a decrease in the cationic components (such as CaO) could occur through biomass uptake or leaching. Increase of acidification can also arise from addition of acidic inputs such as HCl. According to Binkley and Richter (1987) the ANC approach emphasises the mass of acidic input as equivalents of H^+ or NO_3^- and SO_4^{2-} rather than intensity of inputs as measured by pH. Accordingly, Reuss and Johnson (1986) note that it is the difficulty associated with quantification of ANC by this method that renders the soil pH approach practical (Reuss and Johnson, 1986)

3.4 Types of soil acidity

The degree of ionisation and dissociation in the soil solution determines the nature of soil acidity. Exchangeable H^+ ions are the reasons for development of potential or reserve of soil acidity. The magnitude of the latter can be determined by titration of the soil. The free H^+ ions create the active acidity. Active acidity includes all titratable acidity in the soil that is associated with the solution phase (Thomas and Hargrove, 1984; Rowell, 1994). Rowell (1994) has pointed out that exchangeable acidity is associated with the loosely bound H^+ and Al^{3+} in soil solution. Non-exchangeable acidity consists of bound H^+ and Al^{3+} and is usually associated with weak acid groups on humus, organically complexed Al strongly retained at mineral surface (Thomas and Hargrove, 1984). Reserve acidity has been reported by Sakala (1998) to be the form of titratable soil acidity and is associated with the soil solid phase.

3.5 Factors of soil acidification

Any proton (H^+ ions) producing processes influences formation of soil acidity (Van Breemen *et al* 1984. Rowell. 1994). For example, as organic matter decomposes, both organic and inorganic acids are formed thereby releasing protons in the system. Large application of ammonium sulphate fertiliser $(NH_4)_2SO_4$ especially on slightly buffered soils results in higher concentrations of HNO_3 and H_2SO_4 (Alexander, 1965). High concentrations of H_2SO_4 and very low soil pH values can result from the oxidation of pyrite (FeS_2) leading to a low soil pH. In highly weathered and acidic soils containing free Al^{3+} and Fe^{3+}, protons can be generated when these metal ions are hydrolysed (Thomas and Hargrove, 1984). Hydrolysis occurs when the charge/size ratio (or acidity) of the cation is so great as to cause rupture of H-O bonds. The result is ionisation of the hydrate to yield hydronium ions. For Al^{3+} this can be illustrated as follows.

$$Al^{3+} + 6H_2O \rightarrow [Al(H_2O)_6]^{3+} + H_2O = H_3O^+ + [Al(H_2O)_5OH]^{2+} \qquad \text{Eq.2.2}$$

Sulphuric and nitric acids are formed from organic decay processes and from the microbial action on materials containing S and N such as elemental sulphur, ammonium nitrate and ammonium sulphate. These acids are also formed in the atmosphere from oxides of nitrogen and sulphur emitted from different sources (such as industries, coal mine, thunderstorms).

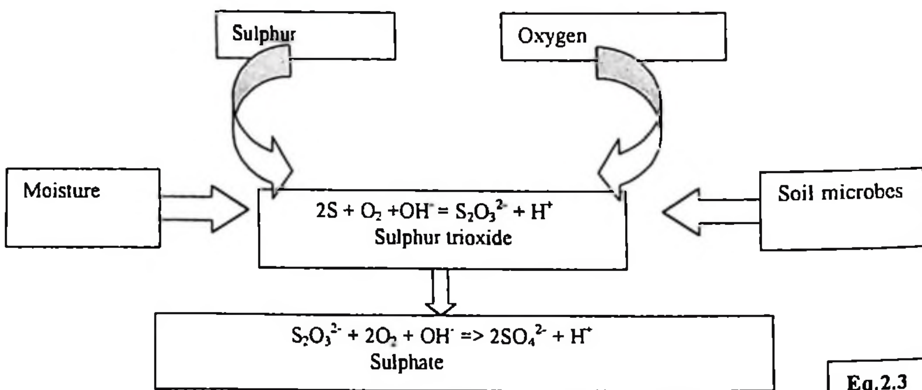
Leaching of bases also encourages acidity because it removes base forming cations that might compete with hydrogen and aluminium on the exchange sites (Brady, 1990).

3.6 Forms of sulphur compounds in soils

In soils, sulphur is present in inorganic and organic forms. The quantity and type of forms of sulphur in soils depend on physical and chemical soil conditions (Breemen *et al.*, 1984). Inorganic forms are more abundant than organic ones (Aulakh and Chihbba, 1992). Inorganic S in the soil is mainly made up of SO_4^{2-} while the organic fraction consists of a range of compounds such as ester sulphate, sulphonate, bonded-S and biomass-S (Castellano and Dick, 1988). Inorganic S can exist in oxidation states of -2 to +6 (Trudinger, 1986). Some of the important oxidation states of sulphur are sulphide (S^{2-}, -2), bisulphite (S_2^{2-}, -1), sulphur (S, 0), disulphuroxide (S_2O, +1), sulphur monoxide (SO, +2), thiosulphate ($S_2O_3^{2-}$, +2), dithionate ($S_2O_4^{2-}$, +3), sulphur dioxide (SO_2, +4), sulphur trioxide, SO_3, +6) and sulphate (SO_4^{2-}, +6).

3.7 Sulphur as an acidifying agent

In most aerated soils sulphur is oxidised to produce sulphuric acid according to the reactions indicated on Figure 3.1. For every sulphur atom oxidised, two hydrogen ions are formed which may lower soil pH (Nortcliff and Wong, 1995). The overall product of this oxidation process in soils is sulphuric acid (Beverly and Anderson, 1987; Abo-Rady *et al.*, 1988).



Eq.2.3

Figure 3.1 Sulphur oxidation

In the soils, elemental S and other reduced forms of sulphur are oxidised to sulphates through both chemical (abiotic) and microbiological (biotic) processes (Wainwright, 1984; Konopka *et al.*, 1986). Abiotic oxidation of S to sulphate is extremely slow at prevailing room temperature in any medium. Watkinson and Bolan (1997) have reported that in industry, oxidation of S requires heating S at high temperature (1200 -1600°C) in the presence of a catalyst. In contrast to abiotic oxidation, microbial oxidation of S in soils occurs at ambient temperature and is therefore the dominant oxidative process (Wainwright, 1984; Chapman, 1989).

In most agricultural soils, chemoautotroph and heterotroph bacteria as well as actinomycetes play a major role in the oxidation of sulphur. Autotrophs require energy for their survival and activity from the oxidation of S and use CO_2 as their carbon source while heterotrophs require the supply of available carbon to support their life (Lawrence and Germida, 1991). Some of the autotrophic bacteria that are important in the oxidation of S include *Thiobacillus. thiooxidans*, *T. ferrooxidans* and *T. denitrificans* (Singh *et al.*, 1997; Watkinson and Bolan, 1997). Heterotrophs include bacteria of genus *Streptomyces* spp., *Bacillus* spp., *Anthrobacter* spp., *Acromobacter* spp. and *Micrococcus* spp. (Watkinson and Bolan, 1997). Biological oxidation of elemental S is considered to require direct contact of the microbial cells with S particles, and the extent of contact is important in controlling the rate of microbial oxidation.

The after-effects of acidification include decreased soil pH, increased solubility, mobility and potential toxicity of aluminium and heavy metals, such as nickel and copper (Agrawal *et al.*, 1985; Nyborg and Malhi, 1991; Nortcliff and Wong, 1995). In south eastern Tanzania, elemental S is the most important proton-producing source since it is widely used for controlling PMD of cashew (Nortcliff and Wong, 1995; Majule *et al.*, 1997). Soil acidification through sulphur use and its effect on other soil chemical properties, annual crops and natural vegetation has been observed widely (Agrawal *et al.*, 1985; Nyborg and Malhi, 1991).

3.8 Factors affecting the oxidation of elemental sulphur

There is a negative relationship between particle size and the rate of S oxidation. Li and Caldwell (1966) have shown that oxidation of sulphur is faster with particle sizes of < 100 μm than those exceeding this size. This supports the findings of Ghani *et al.* (1997) who found that oxidation of S is greater with particles of mesh size 75-125μm than with particles of mesh size 125-150 μm. The smaller the particle sizes the larger the specific surface area and the higher the reactivity. Being a surface reaction, the rate of S oxidation depends on the abundance of S-oxidising micro-organisms, the availability of substrate and removal of products (Li and Caldwell, 1966; Janzen and Bettany, 1987).

Soil temperature influences the activity of S-oxidising soil microbes and thereby the rate of S oxidation. Sulphur is oxidised over a wide range of soil temperatures (4°-40°C) with an optimum for *Thiobacilli* of 28°-30°C (Watkinson and Bolan, 1997). It has been observed that S oxidation is optimum at soil moisture near field capacity and tends to decrease at contents both below and above this point (Watkinson and Bolan, 1997). This effect of moisture is probably mediated through both activity of S oxidisers and the transport of nutrients to and products of S oxidation away from the zone of S oxidation (Watkinson and Bolan, 1997). In some soils, a second application of elemental S after one year has been reported to produce a higher oxidation rate. Lee *et al.* (1988) has however refuted this finding.

3.9 Consequences of soil acidification

Soil acidification is one of the major constraints to crop production in many parts of the world (Sanchez and Salinas, 1981; Kamprath, 1984). It affects crop production by reducing the availability of the chemical elements important for the nutrition of plants and soil microbes. In acidified soils, some of the nutrients such as phosphorus and molybdenum become unavailable, as they are more strongly retained in acid soils. There is increased solubility of toxic metals (primarily aluminium and manganese), which may influence root growth, nutrient availability, water uptake (Kennedy, 1992; Brady, 1990) and a change in microbial populations and activities (Binkley *et al.*, 1987). Such changes will often be accompanied by changes in overall soil pH, but the degree of change will depend on a combination of properties within a given soil system. The availability of nitrogen, sulphur and molybdenum is somewhat restricted at low pH values, whereas that of phosphorus is enhanced at intermediate pH levels (Brady, 1990).

Most bacteria and actinomycetes are active at intermediate and high pH values but according to Binkley *et al.* (1989) fungi seem to be particularly versatile, flourishing satisfactorily over a wide pH range. The activity of fungi tends to predominate in acid soils but at intermediate and high pH, fungicides meet competition from actinomycetes and bacteria.

3.10 Soil buffering capacity

The pH buffering capacity of a soil is defined as its resistance to changes in pH when an acid or a base is added. It always acts to stabilise the soil pH when chemical inputs are administered. This depends among other factors on base saturation (Magdoff and Bartlett, 1985; Brady, 1990), cation exchange capacity (McFee, 1983) and presence of weatherable minerals. Soil components that constitute buffering mechanisms also include clay and humic fractions. In general, the higher the clay and organic matter content of the soil, the more lime is required to for a given change in soil pH. The clay mineralogy of the soil also plays an important role in influencing the buffering capacity. The dominant clay in cashew growing areas on the Makonde plateau is kaolinite (Majule, 1999).

Magdoff and Bartlett (1985) and Godefroy and Dormoy (1990) indicate that soils are poorly buffered between pH 4.5 and 6.5 and that soils are well buffered below pH 4 and above pH 7. At low pH buffering is increased through dissociation of oxides and hydroxides of aluminium while at high pH through increased content of base cations. Soil buffering is important for two primary reasons. First, it tends to assure reasonable stability in the soil pH, preventing drastic fluctuations that might be detrimental to plants and to soil micro-organisms. Secondly, it determines the amount of soil amendments such as lime that are required to change the soil pH.

3.11 Control of soil pH

Lime (calcium Oxide or Calcium Hydroxide) neutralises soil acidity as illustrated by the reaction:

$$2CaO + 2H_2O \leftrightarrow 2Ca(OH)_2 \qquad \text{Eq. 2.4}$$

Liming acid soils augments nature's supply of base forming cations. By raising soil pH, liming improves the ability of soils to supply nutrients to crops (Floate and Enright, 1991). Chemically this effect is reflected in the content of CaO and MgO (Finck, 1982). Several liming materials are available in Tanzania. They include lime produced from coral reef (fossil or fresh) and Jurassic deposits along the coast. Ash from cashew leaves and some of the phosphate rocks available in Tanzania e.g. Minjingu rock phosphate are also able to raise soil pH (Kaihura *et al.* 1988). Irrigation waters that contain salts of base forming cations (calcium, magnesium and sodium) can increase soil alkalinity. Conditions that permit the exchangeable base forming cations to remain in the soil will encourage high pH values. For example, recycling of cations by deep-rooted plants. This recycling accounts for the relatively high soil pH of the semi-arid regions, and prevents some soils in the humid tropics from becoming excessively acid (Brady, 1990).

3.12 Nutrient sulphur and factors affecting its availability in soils

Sulphur undergoes mineralisation before being absorbed by plant roots. The rate at which mineralisation occurs, depends on the same environmental factors that affect nitrogen mineralisation, including moisture, aeration, temperature, and pH. The mineralisation reaction is expressed as follows:

$$\text{Organic sulphur} \rightarrow \text{decay products} + O_2 \rightarrow SO_4^{2-} + H^+ \qquad \text{Eq. 2.5}$$

Thus, to meet their sulphur requirement, plants absorb S as SO_4^{2-} ions. There are many factors affecting the availability of S in the soil. Aulakh and Chhibba (1992) indicate that contents of clay, silt, organic carbon and calcium carbonate of the soil influence availability of sulphur. In a review of factors affecting sulphur availability, Takkar (1988) reported a positive relationship between soil temperature, content of organic matter and available sulphur.

The role of sulphur in plant growth has been extensively studied (Beaton *et al.*, 1971; Aulakh and Chhibba, 1992; Hilal *et al.*, 1992). Working on finger millet in Uganda, Zake (1970) reported that sulphur deficiency affects millet yield as well as protein quality. In a review of the effects of sulphur on crops, Randall and Wrigley (1992) indicated that sulphur deficiency can bring adverse effects on seed quality in addition to reducing plant growth and seed yield. In the rain forest and savannah zones of Nigeria, Kayonde (1990) observed that application of sulphur at 10-kg ha^{-1} significantly increased sulphur content and protein yield of cowpeas. Inherent content of sulphur in soils plays a significant role in influencing crop response to applied S. For example, Ngongi *et al.* (1977) recorded significant positive response of cassava on soil with 4.0-4.5 $cmol_c\ kg^{-1}$ S and none on soil containing 9.0 $cmol_c\ kg^{-1}$ S. Sulphur requirements of most cereals, grasses and legumes is between 10 and 30 kg ha^{-1} (Beaton *et al.*, 1971).

Studies of the effects of sulphur dust on the performance of trees in tropical environments are scanty. Most of the information on the effects of high doses of sulphur on plant growth is from temperate forest regions attributable to sulphur emission from processing plants. For example in Canada, Maynard *et al.* (1986) and Nyborg and Malhi (1991) indicate that deposition of elemental sulphur wind blown from natural gas processing plants on the vegetation resulted in elimination of the mosses and a reduction in the herbal cover.

Chapter 4

General methodological aspects

4.1 Selection of sites for the pH survey

Powdery mildew disease of cashew was first reported in South Eastern Tanzania in late 1970s (Castellani and Casulli, 1981; Casulli, 1981). By 1984, researchers at Naliendele Agricultural Research Institute (NARI) had already established that sulphur was effective in controlling the disease (Intini and Sijaona, 1983; Sijaona, 1984). However, adoption of sulphur dusting started in the mid 1980s mainly through the World Bank financed Cashew Improvement Pilot project (Hill, 1989) and the Italian-Tanzania government project (Partel, 1988). These pilot projects were implemented in selected districts in collaboration with the regional extension service and NARI. Through these projects a database consisting of location, cashew sale points, previous cashew sales and farmer's records has been established for about 300 cashew growing villages. Thus when the need to select villages for the pH survey came, the regional extension service and NARI were consulted and a provisional list of target 150 villages was prepared

Since the Makonde plateau and Inland plains account for 70 % of the cashew nut production in Tanzania (Martin *et al.*, 1997, Topper *et al.*, 1998c), it was decided that the survey be confined to these two major landscape units. The Makonde plateau comprises the Makonde Dissected plateau (also known as the Eastern Makonde plateau) and the Makonde High plateau (also called Western Makonde plateau). The Inland plains, located westwards of the Makonde plateau, consist of Lulindi plain, Southern Masasi plain, Nachingwea-Masasi plain and Mbangala plain and the Mnero-Ruangwa plain. In view of accessibility, time and efficiency, most villages sampled were located on or close to roads (Figure 4.1). In most cases, these were expected to have access to sulphur and therefore were able to use sulphur continuously after adoption of the practice.

During visits to the villages about 15-30 farmers were present at the village office on the appointed days. Choice of a farmer depended on fulfilling criteria which were explained prior to listing of farmers' names. The criteria were (a) adoption of sulphur dusting following the recommended rate of 90 kg of elemental sulphur dust per hectare (b) continuous sulphur dusting for the specified number of years the farmer had been dusting (c) ownership or presence of another nearby grove which had not been dusted before. A farmer was chosen at random from the list. Shortage of time and resources permitted coverage of only 70 cashew growing villages from the provisional list of 150 villages. Attempts were made to include in the pH survey groves with a history of dusting from 0 to 12 years. The procedure for soil sampling is detailed in Chapter 8. Considering that about 15-20 farmers were present at each of the selected village, around 1200-1700 farmers were involved in the survey. A detailed inventory of the 70 farmers and their groves is available for future reference at the Soils Department of Naliendele Agricultural Research Institute.

4.2 Selection of sites for the soil profiles

Thirty out of the 70 cashew groves involved in the pH survey were selected for detailed soil characterisation. Sixteen of these were located on the plateau and 14 in the Inland plains (Figure 4.1). Selection of these groves was based on the 1:250,000 scale soil map of Bennett *et al.* (1979) and on field experience acquired during the pH survey. This map is based on soil studies along 140 long traverses in South Eastern Tanzania where 158 soil profiles, 634 auger holes and numerous in situ profiles of exposed roadside cuttings and incised valleys were examined. The 16 groves from the Makonde plateau were located on areas where the map indicates occurrence of uniform and well-drained sandy soils classified as *Rhodic, Xanthic* or *Haplic Ferralsols* by Bennett *et al.* (1979). For the Inland plains, the study of Bennett *et al.* (1979) and others (Anderson, 1957; Charter, 1957; Aitken, 1961) found uniform soils only on elevated parts of the Inland plains. Much soil variability was found on sloping land and valleys. Five of the cashew groves in the Inland plains were located on elevated parts on the Nachingwea-Masasi plain and nine were located on sloping land or valleys.

At each selected grove. transect walks were made through the grove the purpose of which was to assess local variability of soils by augering. Farmers present not only gave their views and perception on the soil variability observed but also showed their knowledge on the performance of cashew and the intercrops of the grove. Eventually an observation plot (of 4 cashew trees) was selected on the most representative location of the cashew grove for locating a soil profile and detailed investigations on the trees.

Details of soil profile sampling and soil analytical procedures are given in Chapter 8.

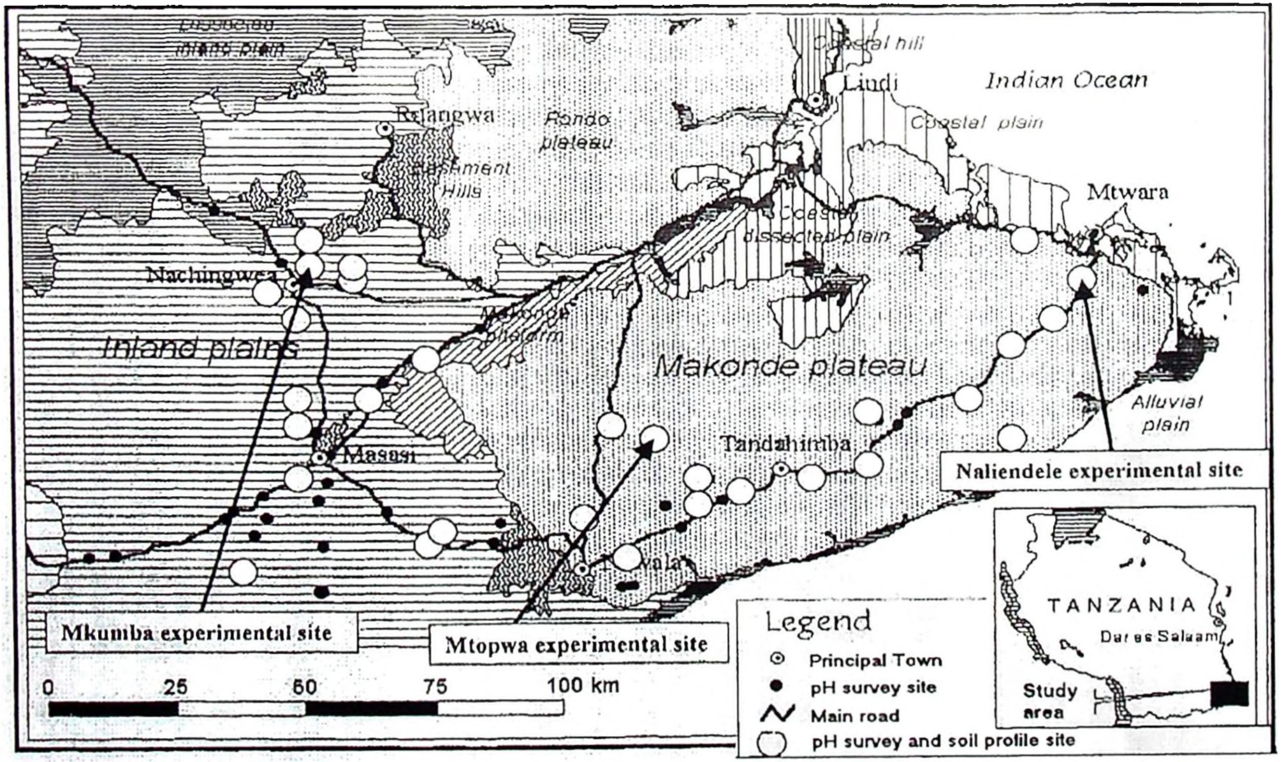


Figure 4.1 Location of pH survey and soil profile sites

4.3 Selection and background information on the experimental sites

4.3.1 Selection of sites

Cashew groves at Naliendele (latitude 10^0 21' S; longitude 40^0 11' E), Mtopwa (latitude 10^0 37' S; longitude 39^0 23' E) and Mkumba (latitude 10^0 19' S; longitude 38^0 46' E) were selected for investigating the effects of sulphur on annual crops. Naliendele and Mtopwa are located on the Makonde plateau and Mkumba is located in the Inland plains (Figure 4.1). These sites were selected in view of their ecological representativeness of major cashew growing areas in South Eastern Tanzania and for security considerations. They are accessible by all weather roads and the experiments could be monitored regularly by nearby agricultural experimental stations. The site at Naliendele is close to the main agricultural research institute in South Eastern Tanzania with laboratory facilities for evaluating effectiveness of soil amendments.

4.3.2 Soils of the experimental sites

Soils of Naliendele and Mtopwa are deep, highly weathered and dominated by low activity 1:1 clays consisting mainly of kaolinite. They are derived from sandstone and have a low pH, low total bases and cation exchange capacity. The dominant soil unit at Naliendele is *Haplic Acrisol* with dark brown loamy sand topsoil and dark reddish sandy loam subsoil. At Mtopwa the dominant soil unit is *Haplic Ferralsol* with brown loamy sand topsoil and bright brownish sandy clay loam subsoil. The soils at Mkumba are slightly less weathered than the soils at Mtopwa and have moderate pH (>5.2 throughout the profile) and total bases. The dominant soil unit is *Rhodic Ferralsol* with dark reddish brown loamy sand topsoil and brown clay subsoil. Soils are derived from basement rocks mainly gneiss. Table 4.1 summarises analytical properties of the soils at the three experimental sites.

4.3.3 Average annual rainfall and rainfall during the study period

The three experimental sites have a monomodal rainfall pattern and rains start falling in late November and end in April. Approximately 80% of the rains fall between December and April. Annual rainfall is higher at Naliendele (1132 mm) and Mtopwa (1245 mm) than at Mkumba (823 mm) in the Inland plains. This variation is attributed to the influence of the sea for Naliendele and altitude for Mtopwa. Monthly rainfall data during the study period is presented in Figure 4.2. Rainfall amount was highest during season II (1997/98) attributable to the effect of El-Niño which prevailed in the whole of Eastern Africa in 1998.

Table 4.1 Selected soil properties of the three experimental sites

Site	Soil depth (cm)	Sand (%)	Silt (%)	Clay (%)	Silt/clay	OC[1] (%)	pH-H_2O	CEC[2]	CEC clay	TEB[3]	BS[4] (%)
								<——cmol$_c$ kg^{-1}——>			
Naliendele											
	0-15	87	2	11	0.18	0.51	5.4	4.00	36.40	1.67	42
	15-47	85	1	14	0.07	0.24	5.5	2.20	15.70	1.42	65
	47-108	80	2	18	0.11	0.03	5.0	4.00	22.20	1.21	30
	108-200	71	3	26	0.12	0.20	4.9	7.00	26.9	1.62	23
Mtopwa											
	0-28	85	2	13	0.15	0.74	4.2	3.27	25.20	0.49	15
	28-58	76	2	22	0.09	0.39	4.3	2.00	9.10	0.07	15
	58-116	76	2	22	0.09	0.20	4.3	0.33	1.50	0.05	15
	116-200	73	2	25	0.08	013	4.3	0.44	1.80	0.08	18
Mkumba											
	0-16	85	5	10	0.50	0.56	5.6	4.81	48.10	2.07	43
	16-47	61	4	35	0.11	0.39	5.3	5.76	16.50	2.59	45
	47-92	37	4	59	0.07	0.21	5.2	6.79	11.50	2.85	42
	92-200	46	7	47	0.15	0.10	5.3	6.00	12.80	2.76	46

[1] Organic carbon [2] Cation exchange capacity [3] Total exchangeable bases [4] Base saturation

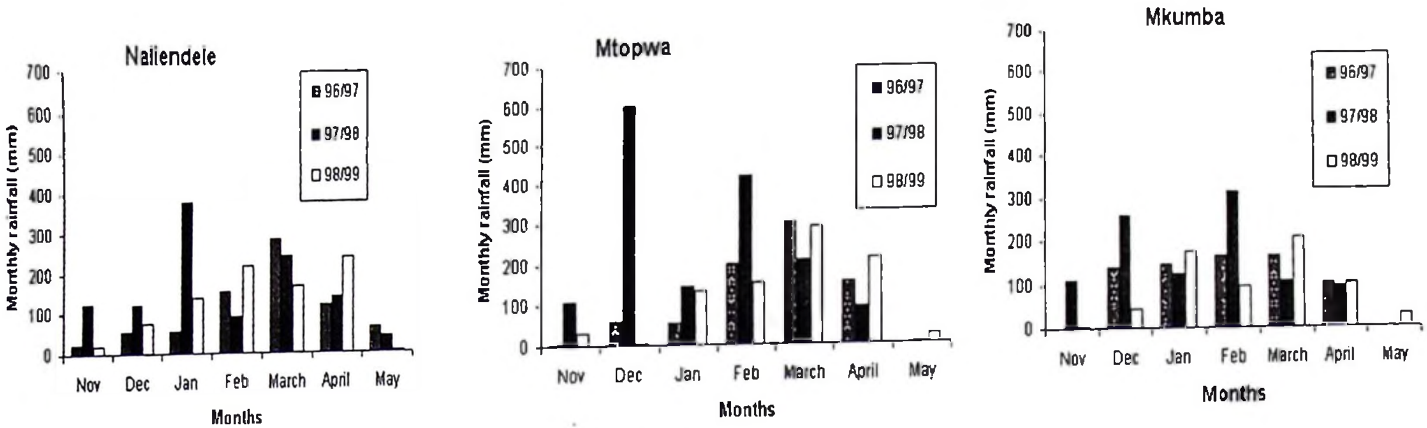


Figure 4.2 Monthly rainfall (mm) at the experimental sites during growing seasons

Chapter 5

Characterisation of soils in cashew growing areas of South Eastern Tanzania

5.1 Introduction

In South Eastern Tanzania cashew nuts are grown on the plateaux and in the Inland plains in Mtwara and Lindi regions and Tunduru district of Ruvuma region. The plateaux consist of the Makonde plateau in Mtwara region, Rondo plateau and Kilwa plateau in Lindi region and Tunduru plateau in Tunduru district in Ruvuma region. Inland plains are found west of the plateaux in both Mtwara and Lindi regions.

Although cashew is a major cash crop in these areas, the soils on which it is grown have not been thoroughly studied. Inadequate information exists on morphological and soil physico-chemical characteristics as well as soil groupings. When cashew was introduced in Southern Tanzania in the early 1930s there was little information available concerning its soil requirements.

Early soil studies in southern Tanzania were done in Nachingwea district in Lindi region in search for land to grow groundnuts. "Suitable" soils were found on elevated parts of the plains and were named as 'Nachingwea Red Loam' (Grantham, 1949) or 'Nachingwea Red Earth' (Anderson, 1957). These soils are equivalent to *Rhodic Ferralsols* in the FAO (1990a) soil classification system. Bennett *et al.* (1979) made the first reconnaissance survey of the physical resources of southern zone in Tanzania that also covered soils. Based mainly on textural and colour characteristics, soils on the plateau were named as *Rhodic*, *Xanthic* or *Orthic Ferralsols*. The study of Bennett *et al.* (1979) is complemented with the unpublished report of the Italo-Tanzania project (Italo-Tanzania, 1981) which sought to produce a soil map of the southern zone. Later, De Pauw (1984), working on the agroecological zonation of Tanzania, produced a map at the scale of 1:2,000,000 which included soils of the southern zone. As these soil studies were intended to provide baseline information for agricultural planning at the regional or zonal level, coverage was extensive and emphasis was on major soil groupings.

Other soils reports, albeit at project scale, are provided by Kips and Kimaro (1993), National Soil Service (1987) and Ngailo and Kips (1991). According to Kips and Kimaro (1993), *Vertisols* and *Vertic Cambisols* of the Kitere Basin in Mtwara region are suitable for rice production. The National Soil Service (NSS, 1987) study of Kikwetu sisal estate indicates that *Chromic Cambisols* and *Xanthic Ferralsols* are suitable for sisal production. At Mikindani estate in Mtwara district, Ngailo and Kips (1991) identified *Rhodic Ferralsols* and *Xanthic Ferralsols* as being suitable for sisal production. Further contribution towards the understanding of soils of southern Tanzania includes surveys conducted by Verwilghen (1996), Wijffels (1997), Cools (1998) and Dederen (1998). Verwilghen's study, which classified some of the cashew growing soils, was restricted to south-western part of the Makonde plateau.

This study aims at identifying morphological and physico-chemical characteristics of soils in the cashew growing areas in South Eastern Tanzania. This information will ultimately provide a basis for sustainable cashew production in the target regions.

5.2 Materials and Methods

This study was conducted in 30 cashew groves spread over the Makonde plateau and Inland plains of South Eastern Tanzania. Sixteen soil profiles were located on the Makonde plateau and 14 in the Inland plains (Figure 4.1). The locations of the profiles were geo-referenced by a global positioning system (GPS). The locations of these groves are shown in Figure 4.1 (Chapter 4). The selection of the 30 cashew groves is described in Chapter 4. At each cashew grove, a soil profile was dug and described according to FAO (1990b) guidelines. Soil samples from respective horizons were collected, dried and sieved through a 2-mm sieve for laboratory analyses.

Particle size distribution was analysed by the pipette method (Day, 1965). pH was measured potentiometrically in water and KCl in a 1:2.5 soil:liquid suspension using a pH meter. Organic carbon was estimated by the wet combustion method of Black and Wakley method (Nelson and Sommers, 1982). Total nitrogen was determined following the method by Bremner and Mulvaney (1982). Available phosphorus was determined by the Bray-Kurtz 1 method (Bray and Kurtz, 1945). Electrical conductivity was determined by a conductivity bridge. Cation exchange capacity (CEC) and exchangeable bases (Ca^{2+}, Mg^{2+}, K^+ and Na^+) were extracted using neutral 1M NH_4OAc at pH 7 (Thomas, 1982) and the absorbed NH_4^+ displaced by K^+ using 1M KCl and CEC was then determined by Kjeldahl distillation method and exchangeable cations by Atomic absorption spectrophotometer.

Field and laboratory data were used in classifying soils according to the FAO (1990a) legend of the Soil Map of the World. However, correlation with the recently adopted World Reference Base (WRB) for Soil Resources (FAO-ISRIC-ISSS, 1998) and USDA (Soil Survey

Staff, 1996) is shown in Annex 1 Soil groupings were categorised as dominant, associated and inclusions as based on frequency (%) of occurrence. Detailed physico-chemical and morphological characteristics of four profiles on the Makonde plateau and four in the Inland plains are elaborated upon in this chapter and the occurrence of common soil groupings are illustrated by schematic cross sections.

5.3 Results and Discussion

5.3.1 Soil groupings in cashew growing areas on the Makonde plateau

Soil groupings found in cashew groves sampled on the plateau are *Ferralsols*, *Alisols*, *Acrisols* and *Luvisols* (Table 5.1). With over 60 % frequency of occurrence, *Ferralsols* are the most dominant soil grouping in cashew groves on the Plateau. *Alisols* (19 %) is the associated soil grouping. The other two groupings, categorised as soil inclusions, have a low frequency of occurrence. According to Kent *et al.* (1971) and Bennett *et al.* (1979), the common soil parent material of soils on the plateau are sandy sedimentary deposits of Neogene age.

The major characteristic of *Ferralsols* is the occurrence of a ferralic horizon (i.e. a horizon with a depth of at least 30-cm deep with sandy loam or of finer particle size and cation exchange capacity (CEC) by 1 M NH_4OAc of 16 $cmol_c\ kg^{-1}$ or less). *Ferralsols* have deep profiles with highly weathered soils (presence of resistant primary minerals, dominance of kaolinitic clays and iron and aluminium oxides and hydroxides). Presence of these oxides impart on *Ferralsols* a stable microstructure and the yellowish (goethite) or reddish (hematite) colours. *Alisols* on the other hand have an argic horizon which has a cation exchange capacity of 24 $cmol_c\ kg^{-1}$ clay or more and a base saturation (by 1M NH_4OAc at pH 7.0) of less than 50 % in at least part of the B-horizon within 125 cm of soil depth.

Acrisols are characterised by having an argic horizon as in *Alisols* but with a CEC of 24 $cmol_c$ kg^{-1} clay or less and a base saturation (by 1M NH_4OAc at pH 7.0) of less than 50 % in at least part of the B-horizon within 125 cm of soil depth. As with *Ferralsols*, soils are strongly weathered soils with a dominance of stable low activity clays and base saturation.

Table 5.1 Frequency of occurrence of soil groupings on the Makonde plateau

Landscape	Categorisation	Soil grouping	Occurrence	%
Makonde Plateau	Dominant	*Ferralsols*	11	69
	Associated	*Alisols*	3	19
	Inclusion	*Acrisols*	1	6
	Inclusion	*Luvisols*	1	6
Total			16	100

Luvisols are also characterised by the presence of an argic horizon but with a cation exchange capacity (by 1M NH_4OAc) of 24 $cmol_c\ kg^{-1}$ clay or more and a base saturation of more than 50 % within 125 cm of the surface soil. The argic horizon is formed by translocation of clay from the surface to the depth of illuviation. These soils have higher soil fertility than *Ferralsols*, *Alisols* and *Acrisols* since they are moderately weathered and have high base saturation.

Subsequent sections provide a brief description of the main morphological characteristics of one or two dominant soil units for each of the four major soil groupings elaborated upon above. Dominant soil units on the Makonde plateau are *Xanthic Ferralsols* and *Haplic Ferralsols*. Morphological characteristics of a *Xanthic Ferralsol* are shown in Table 5.2 for the profile located at Namkuku on the Makonde dissected plateau. The topsoil is loose and soils are non-sticky and non-plastic while the subsoil is slightly sticky and slightly plastic. Soils are well drained as indicated by absence of mottles. The profile is free from gravel and hardpan within 200 cm of soil depth. The topsoil is dull yellowish brown (10 YR 5/4) and the subsoil is brown (10YR 4/6).

The dominant soil unit of *Alisols* on the Makonde plateau is *Haplic Alisol* whose morphological characteristics are presented in Table 5.2. The profile is located at Kitangari on land sloping towards the Mambi river valley. The topsoil is brownish grey (7.5 YR 4/1) and the subsoil is yellowish brown (10 YR 5/6). The surface soil is non-sticky and non-plastic with a fine granular structure and the subsurface soil is slightly sticky and slightly plastic. The profile is free draining and is without gravel and concretions within 2 m of soil depth.

Haplic Acrisol is the dominant soil unit at Naliendele whose morphological characteristics shown in Table 5.2. The profile is deep and well drained. There are no gravel and hardpans within 200 cm of soil surface. The topsoil is loamy sand with dark reddish brown colour (7.5 YR 3/4) and the subsoil is reddish brown (2.5 YR 3/6) sandy clay loam. Soils are friable when moist, slightly sticky and slightly plastic to 43 cm of soil depth beyond which it becomes sticky and plastic. Morphological characteristics of the *Haplic Luvisol* at Nanguruwe are presented in Table 5.2. The topsoil is greyish yellow brown (10 YR 4/2) colour and the subsoil is dull yellowish brown (10 YR 4/3) to bright brown (7.5 YR 5/6) colour. The topsoil structure is weak fine to medium sub-angular blocky which changes to moderate medium sub-angular blocky in the subsoil. Consistence of the soft when dry and moist, non-sticky and non-plastic. The profile is well drained and is free from concretions, gravel, mottles and hardpans within 2 m of soil depth.

Physico-chemical properties

Physico-chemical properties of the four soil groupings found on the Makonde plateau are summarised in Table 5.3. Clay content of topsoil (0-50 cm) is low varying between 8-14 %. In the subsoil clay content ranges from 17-30 % indicating that clay increases with soil depth. Soil pH values, which range from 4.2 – 5.8 (pH-H_2O), show clearly that cashew growing soils on the Makonde plateau have acidic reaction. The levels of base cations, organic carbon, available P, and BS are generally low and decrease rapidly with depth. These properties show that soils on the Makonde plateau have a low level of chemical fertility.

Soil textural data show clearly that soils on the Makonde plateau have loamy sand or sandy loam topsoil and sandy clay loam subsoil. The high sandy content of the upper 30-50 cm of most soil units on the Makonde plateau appear to have misled several past soil surveyors who classified them as *Arenosols*.

Table 5.2 Soil morphological characteristics of representative profiles on the Makonde plateau

Site	Horizon	Depth (cm)	Diagnostic Horizon	Colour notation	Colour	Consistence	Mottles/ hardpan	Roots	Cutans
Haplic Acrisols (Nahendele)									
	Ap	0-15	Ochric A	7.5YR 3/4	Dark brown	F, non-s/p	None	Common	Patchy
	AB	15-47		7.5YR 4/6	brown	F, sl-s/non p	None	Common	Patchy
	BA	47-108	Ferralic B	2.5YR 4/6	Reddish brown	F, sl-s/p	None	Common	Patchy
	B	108-200	Ferralic B	2.5YR 3/6	Dark reddish brown	F, sl-s/p	None	Common	Patchy
Haplic Luvisols (Nanguruwe)									
	Ap	0-39	Ochric A	10YR 4/2	Greyish yellow brown	L, non-s/p	None	Common	Patchy
	AB	39-65	Argic B	10YR 4/3	Dull yellowish brown	L, non-s/p	None	Common	Patchy
	BA	65-143	Argic B	10YR 4/3	Dull yellowish brown	F, sl-s/p	None	Few	Patchy
	Bt	143-200	Argic B	7.5 YR 5/6	Bright brown	F, sl-s/p	None	Few	Patchy
Xanthic Ferralsols (Namkuku)									
	Ap	0-8	Ochric A	10YR 5/4	Dull yellow brown	L, non-s/p	None	Common	Patchy
	AB	8-31	-	10YR 5/6	Brown	F, sl-s/p	None	Common	Patchy
	BA	31-87	Ferralic B	10YR 4/6	Brown	F, sl-s/p	None	Few	Patchy
	B	87-200	Ferralic B	10YR 4/6	Brown	F, sl-s/p	None	Few	None
Haplic Alisols (Kitangari)									
	Ah	0-5	Ochric A	7.5YR 4/1	Brownish grey	L, non-s/p	None	Common	None
	AE	5-30	-	7.5YR 5/3	Dull brown	L, sl-s/p	None	Common	None
	Bt_1	30-72	Argic B	10YR 6/6	Bright yellowish brown	F, sl-s/p	None	Few	None
	Bt_2	72-200	Argic B	10YR 5/6	Yellowish brown	F, sl-s/p	None	Few	None

Key F—Friable, non-s/p –non sticky non plastic, sl—slightly plastic, L—loose, sl s/p—slightly sticky and slightly plasti

Table 5.3 Soil physico-chemical characteristics of representative profiles on the Makonde plateau

Horizon.	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	pH (H_2O)	pH (KCl)	OC (%)	Av. P (mg kg^{-1})	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	CEC	CEC clay	BS (%)
									< ------------		cmol$_c$ kg^{-1}			------------ >		
(a) Nahendele (*Haplic Acrisols*)																
Ap	0-15	87	2	11	5.4	4.6	0.51	1.53	0.94	0.17	0.44	0.12	1.668	4.0	36.4	42
AB	15-47	85	1	14	5.5	4.5	0.24	0.53	0.71	0.33	0.29	0.09	1.416	2.2	15.7	64
BA	47-108	80	2	18	5.0	4.2	0.03	0.70	0.60	0.16	0.37	0.08	1.214	4.0	22.2	30
B	108-200+	71	3	26	4.9	4.3	0.20	0.73	0.51	0.57	0.37	0.17	1.607	7.0	26.9	23
(b) Nanguruwe (*Haplic Luvisols*)																
Ap	0-39	87	5	8	5.6	4.5	0.42	3.27	0.81	0.94	0.33	2.08	4.159	1.8	22.5	100
AB	39-65	83	2	15	5.4	4.15	0.20	2.10	0.65	0.31	0.17	2.49	3.622	3.2	21.3	100
BA	65-143	76	3	21	5.3	4.0	0.18	0.83	1.68	0.45	0.27	2.52	4.917	4.8	22.9	100
Bt	143-200+	71	3	26	5.2	4.0	0.22	0.80	0.71	0.34	0.25	2.66	3.959	5.6	21.5	71
(c) Namkuku (*Xanthic Ferralsols*)																
Ap	0-8	89	1	10	4.4	3.2	0.53	5.53	0.09	0.06	0.09	0.01	0.25	1.56	15.6	16
AB	8-31	86	1	13	4.2	3.8	0.68	1.64	0.06	0.03	0.05	0.05	0.19	1.27	9.8	15
BA	31-87	82	1	17	4.4	3.9	0.26	1.61	0.07	0.04	0.03	0.03	0.17	1.11	6.5	18
B	87-200+	73	3	24	4.6	4.0	0.10	2.16	0.03	0.02	0.02	0.05	0.12	0.55	2.3	22
(b) Kitangari (*Haplic Alisols*)																
Ah	0 - 5	91	1	8	5.3	4.1	1.04	16.68	0.60	0.30	0.08	0.08	1.06	2.30	28.8	47
AE	5-30	91	0	9	5.3	4.1	1.02	15.46	0.60	0.30	0.08	0.08	1.06	2.30	25.6	45
Bt_1	30-72	85	1	14	4.9	4.0	0.56	5.60	0.60	0.20	0.03	0.03	0.86	2.97	21.2	29
Bt_2	72-200+	83	1	16	4.8	4.0	0.35	14.16	0.40	0.20	0.01	0.03	0.64	4.27	26.7	15

Note: details of soil units and physico-chemical properties are shown in Annex IV

Approximate locations of the soil units on a topographic sequence along the Makonde plateau are indicated in Figure 5.1. Soil pattern on the plateau can be explained by differences in elevation, age of the weathering surface and in soil moisture dynamics (and therefore redox conditions). Considered over long periods, these differences have greatly influenced soil development and soil types. For example on elevated parts of the plateau (e.g. Newala), *Haplic Ferralsols* dominate the landscape (oldest landforms) while on long linear slopes between Newala and Kitangari *Haplic Alisols* have formed. In the Makonde dissected plateau (parts of Tandahimba and Nanyamba divisions) *Xanthic Ferralsols* is the dominant soil unit.

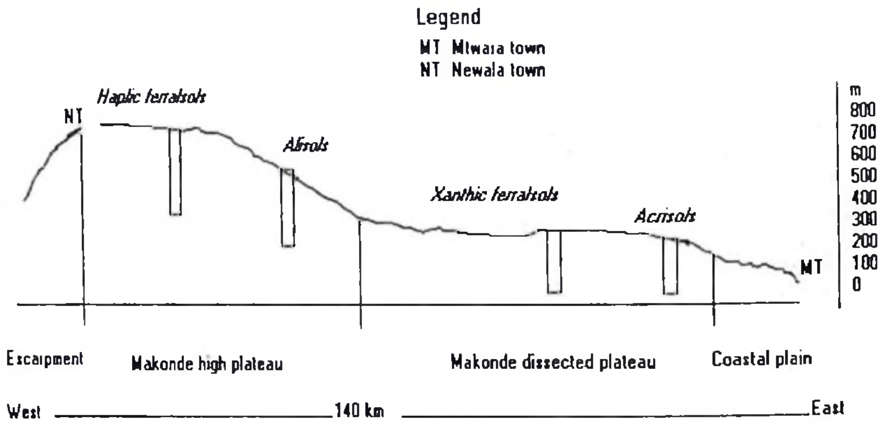


Figure 5.1 Schematic cross section of the Makonde plateau showing approximate locations of soil groupings

5.3.2 Soil groupings in cashew growing areas in the Inland plains

Seven soil groupings (FAO, 1990a) were identified in cashew groves sampled in the Inland plains (Table 5.4). These soil groupings are *Ferralsols*, *Alisols*, *Cambisols*, *Acrisols*, *Plinthosols*, *Phaeozems* and *Luvisols*. Except for *Ferralsols* which have a frequency of 36 %, other soil groupings occur in low frequencies and were treated as soil inclusions. The soil parent material for soils in the Inland plains is basement rocks mostly gneiss.

Table 5.4 Frequency of occurrence of soil groupings in the Inland plains

Landscape	Categorisation	Soil grouping	Occurrence	%
Inland Plains	Associated	*Ferralsols*	5	37
	Inclusions	*Alisols*	2	14
	"	*Cambisols*	2	14
	"	*Acrisols*	2	14
	"	*Plinthosols*	1	7
	"	*Phaeozems*	1	7
	"	*Luvisols*	1	7
Total			14	100

Ferralsols in the Inland plains have the same basic characteristics as those on the Makonde plateau i.e. having a ferralic B-horizon. A few differences, however, exist between *Ferralsols* on the plateau and in the Inland plains. *Ferralsols* are more reddish in the plains than on the plateau due to higher content of hydrated gibbsite and hematite (Bennett *et al.*, 1979, Majule, 1999). In the plains, *Ferralsols* are clayey, sticky and plastic. Soil structure is moderate medium sub-angular blocky to angular blocky while the consistence is often friable to firm. The topsoil compacts easily making soils prone to surface capping and susceptible to erosion. Another feature of the *Ferralsols* in the plains is the increase in friability with depth attributed to increased free iron (Bennett *et al.*, 1979; Driessen and Dudal, 1991).

The dominant soil unit of *Ferralsols* in the Inland plains is *Rhodic Ferralsol* represented by the profile at Mkumba. Morphological characteristics of this unit are shown in Table 5.5. The topsoil is dark reddish brown (2.5 YR 3/3) while the subsoil is brown (10 YR 4/6). Like the *Ferralsols* on the plateau, the soils are deep, highly weathered and free from mottles, gravel and hardpan.

In the Inland plains, *Alisols* are clayey and more reddish in colour (Table 5.5) than those on the Makonde plateau. The dominant soil unit is *Haplic Alisol* whose morphological characteristics are shown in Table 5.5 for the profile at Nampemba. The topsoil is dark reddish brown (2.5 YR 4/6) sandy loam and the subsoil is reddish brown (2.5 YR 4/8) sandy clay. Soils are friable when moist, slightly sticky and slightly plastic to 40 cm after which the soil is sticky and plastic. The profile is well drained and has no mottles and hardpan within 2 m of soil depth.

The cashew grove at Mwenge village is located on a *Cambisol*. This soil grouping is characterised by having a Cambic horizon. This an altered horizon (transition horizon) lacking typical propertiess that meet the requirement of an argic horizon, natric or spodic horizons. The characteristics of *Cambisols* reflect a transitional stage of profile development from a young soil to a mature (Driessen and Dudal, 1991). The dominant soil unit is *Humic Cambisol* and its morphological properties are indicated in (Table 5.5). The topsoil is brownish black (5 YR 2/2) and overlie dark reddish brown (5YR 4/6) and bright reddish brown (5YR 5/6) subsoil. The topsoil is non-sticky and non-plastic but the subsoil is slightly sticky and slightly plastic. The profile is free draining to 75 cm beyond which mottles are common and a hardened layer of manganese concretion is located at 130 cm of soil depth.

Plinthosols is a soil grouping characterised by having 25 % or more plinthite by volume within 50 cm of the surface or within the depth of 125 cm when underlying an albic horizon. A plinthite is an iron-rich and humus poor-mixture of clay and quartz that hardens as a brick when exposed to the open air. The soil unit is *Albic Plinthosol* located at Temeke Chini village. Morphological characteristics of the profile are shown in Table 5.5. The topsoil is loamy sand and has dark reddish brown colour (5 YR 3/2) and the subsoil is sandy clay loam and greyish brown (5 YR 6/2). Soils are very friable when moist, non-sticky and non-plastic with a fine to medium sub-angular structure to 40 cm. The profile is well drained only to 40 cm of the surface soil after which prominent mottles typical of soft plinthite are common. Beyond this soil depth, soils are sticky and plastic. Typical hydromorphic characteristics were observed below 140 cm.

Soil profiles of other soil groupings in the Inland plains such as *Acrisols*, *Luvisols* and *Phaeozems* are detailed in Annex IV.

Table 5.5 Soil morphological characteristics of representative profiles in the Inland Plains

Site	Horizon	Depth	Diagnostic Horizon	Colour notation	Colour	Consistence	Mottles/ hardpan	Roots	Cutans
Mkumba -(*Rhodic Ferralsols*)									
	Ap	0-16	Ochric A	2.5YR 3/3	Dark reddish brown	F, sl-s/p	None	Common	Patchy
	AB	16-47	-	2.5YR 3/6	Dark reddish brown	F, sl-s/p	None	Common	Patchy
	Bs1	47-92	Ferralic B	2.5YR 3/6	Dark reddish brown	F, sl-s/p	None	Common	Patchy
	Bs2	92-200	Ferralic B	10YR 4/6	Brown	F, sl-s/p	None	Few	Patchy
Nampemba-(*Haplic Alisols*)									
	Ap	0-18	Ochric A	7.5YR 4/6	Dark reddish brown	F, sl-s/p	None	Common	Patchy
	AB	18-43		2.5YR 4/6	Reddish brown	F, sl-s/p	None	Common	Patchy
	BA	43-77	Argic B	2.5YR 4/8	Reddish brown	F, s/p	None	Common	Patchy
	Bt1	77-143	Argic B	2.5YR 4/8	Reddish brown	F, s/p	None	Common	Patchy
	Bt2	143-200+	Argic B	2.5YR 4/8	Reddish brown	F, s/p	None	Common	Patchy
Mwenge-(*Humic Cambisols*)									
	Ap	0-20	Mollic A	5YR 2/2	Brownish black	F, non s/p	None	Many	None
	AB	20-48	Cambic B	5YR 3/4	Dark reddish brown	F, sl-s/p	None	Common	Patchy
	Bt_1	48-75	-	5YR 4/6	Reddish brown	F, sl-s/p	None	Common	Patchy
	Bt_2	75-130	-	5YR 5/6	Bright reddish brown	F, sl-s/p	Yes	Few	None
	R	>130							
Temeke Chini-(*Albic Plinthosols*)									
	Ap	0-14	Ochric A	5YR 3/2	Dark reddish brown	F, non-s/p	None	Many	Nonne
	E	14-40	Albic E	5YR 4/3	Dull reddish brown	F, non-s/p	None	Common	None
	Bv1	40-91	Argic B	5YR 5/3	Dull reddish brown	F, s/non-p	Yes	Few	None
	Bv2	91-140	Argic B	5YR6/2	Greyish brown	F, s/p	Yes	Few	None

Key Sl-s/p—slightly sticky slightly plastic, non-s/p—non sticky non plastic, F–friable

Physico-chemical characteristics of soil units in the plains are summarised in Table 5.6. Soil pH-H_2O ranges from 4.8 – 6.6 indicating that cashew growing soils in the Inland plains have higher pH than those on the plateau. The levels of OC and available phosphorus are comparable to levels of soils on the plateau. However, contents of TEB, CEC and BS are slightly higher in soils of the plains than those on the plateau indicating that soils are chemically better than on those the plateau.

Table 5.6 Physico-chemical properties of four soil profiles in the Inland plains

Horizon	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	pH (H_2O)	pH (KCl)	OC (%)	N (%)	Av. P (mg kg^{-1})	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	CEC	CEC clay	BS (%)
										<------------- cmol$_c$ kg^{-1}						------------->	
(a) Mkumba (*Rhodic Ferralsols*)																	
Ap	0-16	85	5	10	5.2	4.3	0.56	0.05	5.03	1.20	0.64	0.18	0.05	2.07	4.81	48.1	43
AB	16-47	61	4	35	5.3	4.3	0.39	0.04	1.13	1.55	0.93	0.09	0.02	2.59	5.76	16.5	45
Bs_1	47-92	37	4	59	5.2	4.6	0.21	0.02	0.56	2.25	0.52	0.03	0.05	2.85	6.79	11.5	42
Bs_2	92-200+	46	7	47	5.3	4.2	0.10	0.01	1.55	2.11	0.62	0.02	0.01	2.76	6.00	12.8	46
(b). Mwenge (*Humic Cambisols*)																	
Ap	0-20	81	12	7	6.3	5.4	0.75	0.06	4.12	0.70	0.30	0.28	0.02	1.30	1.71	24.4	76
AB	20-48	77	12	11	6.4	5.3	0.25	0.03	2.41	1.70	0.40	0.15	0.02	2.27	2.73	24.8	83
Bt_1	48-75	76	11	13	6.5	5.0	0.16	0.02	2.26	2.00	0.60	0.11	0.04	2.75	3.27	25.2	84
Bt_2	75-130	79	10	11	6.6	5.0	0.12	0.01	3.03	1.70	0.60	0.11	0.02	2.43	2.83	25.7	86
(c) Nampemba (*Haplic Alisols*)																	
Ap	0-18	77	4	19	5.2	4.0	0.65	0.05	7.51	0.80	0.80	0.15	0.02	1.77	4.43	23.3	40
AB	18-43	45	3	32	4.8	3.8	0.34	0.04	4.88	1.70	0.50	0.04	0.04	2.28	8.14	25.4	28
BA	43-77	59	2	39	4.8	3.8	0.45	0.04	10.28	1.60	0.80	0.04	0.02	2.46	9.92	25.4	25
Bt_1	77-143	59	3	38	5.0	3.9	0.76	0.50	1.86	2.00	1.20	0.08	0.02	3.30	9.43	33.7	35
Bt_3	143-200+	56	5	39	4.8	3.9	0.57	0.03	1.89	1.60	0.70	0.01	0.02	2.33	9.71	24.9	24
(d) Temeke Chini (*Albic Plinthosols*)																	
Ap	0-14	85			5.6	4.6	0.35	0.04	4.66	0.70	0.40	0.13	0.02	1.25	2.31	25.7	54
I	14-40	79	7	14	5.4	3.9	0.26	0.04	2.09	1.00	0.60	0.09	0.02	1.71	3.49	24.9	49
Bv_1	40-91	53	6	42	5.5	3.7	0.44	0.03	1.89	3.60	1.70	0.05	0.07	5.42	10.4	24.8	52
Bv_2	91-140	51	6	43	5.8	3.8	0.28	0.03	1.85	2.00	1.10	0.05	0.21	3.36	5.42	12.6	62

Note: details of soil units and physico-chemical properties are shown in Annex IV

Soils are derived from Basement rocks, mostly gneiss (Bennett *et al.*, 1979). The distribution of soil groupings in the Inland plains is complex. Figure 5.2 shows approximate locations of the soil groupings. According to Bennett *et al.* (1979), changes of soil groupings seem to reflect variation in lithology, drainage and erosional history of the area and require ground checking to predict. *Ferralsols* occur on elevated parts of the landscape where influence of erosion is low. *Plinthosols* are usually found on slopes near river valleys.

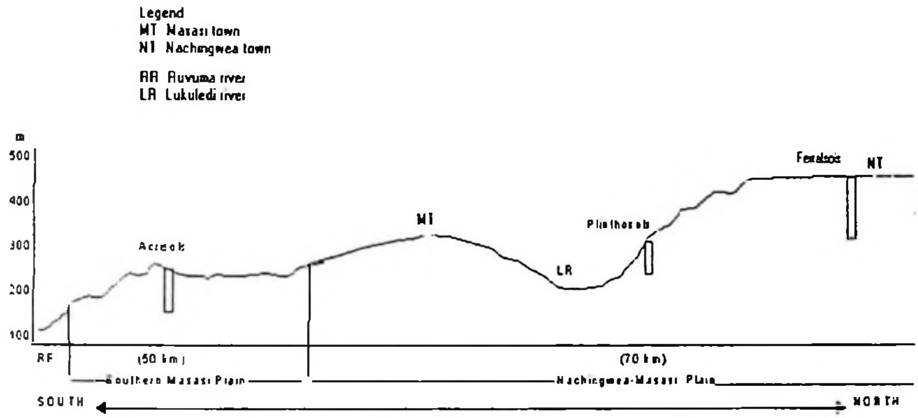


Figure 5.2 Schematic cross section of the Inland plains showing approximate locations of soil groupings

5.4 Summary and conclusions

Soil morphological and physico-chemical characteristics of 30 geo-referenced cashew groves located on the Makonde plateau and in the Inland plains were investigated. On the Makonde plateau, cashew is grown mainly on *Ferralsols* (over 60 %). Other soil groupings with low frequencies of occurrence in cashew groves are *Alisols, Acrisols* and *Luvisols*. Soils are highly weathered, deep, loamy sand or sandy loam overlying sandy clay loam soils. Soils are derived from sedimentary sandstone and are free from mottles, gravel and hardpan. Following the FAO revised Legend (FAO. 1990a) *Xanthic Ferralsols* and *Haplic Ferralsols* are the dominant soil units on the Makonde plateau.

In the Inland plains cashew trees grow on several soil groupings. Occurrence of soil groupings is complex, however, their distribution reflects variation in lithology, drainage and erosional history of the locality. On elevated parts least affected by erosion, deep, reddish sandy clay *Ferralsols* mostly *Rhodic Ferralsols* are predominant. On slopes and valleys, shallow soils often with impeded drainage are found. Common soil units are *Humic Cambisols*, *Eutric Cambisols* and *Albic Plinthosols*.

Chapter 6

Soils and landscape suitability for cashew nut production in South Eastern Tanzania[1]

6.1 Introduction

Cashew nut is one of Tanzania's major cash crops. In 1998, cashew nuts ranked second as the most important foreign exchange earning crop being exceeded only by coffee (Bank of Tanzania. 1999). The crop is mostly grown by smallholder farmers and around 70% of the national production comes from South Eastern Tanzania (Martin *et al.*, 1997; Topper *et al.*, 1998c). When cashew nut production was introduced to the area in the early 1930s, little was known about the influence of soils and climate on its growth and production. As a result, farmers planted cashew trees indiscriminately. Sixty years later, Martin and Kasuga (1995) observed that trees of the same age widely differ in form and productivity. However, no plausible explanation was provided.

According to Ohler (1979) the cashew tree prefers loose, deep, aerated and well-drained soils. The plant's rooting system, particularly the young taproot, is sensitive to physical soil limitations. Heavy, compact soils, with hard surface, or with concretions at shallow depth, prevent the roots from penetrating downwards or sideways. FAO (1994) indicates that optimum pH for cashew growth is between 4.5 and 6.5, with the lower limit as low as 3.8. A warm climate and an average annual rainfall of 600 to 1600 mm spread over 5-7 months are necessary (Ohler, 1979).

To produce cashew nuts in sufficient quantities requires availability of land, suitable soils, and rainfall and temperature. Poulton *et al.* (1997) complemented recently by reports from the agricultural establishment in the zone (Cashew Research Report, 1998/99, 1999/00; Cashewnut Board of Tanzania. 1999) have shown that since 1990 planting of cashew trees has increased and possibilities for expansion exists.

[1] Based on the papers (a) Ngatunga EL, Dondeyne S, Cools N, Majule A.E, Mugogo S and Deckers JA (2001) "Soils and landscapes of the Southern Zone: their suitability for cashew production" accepted for publication in a handbook titled "A case history of the Tanzania Integrated Cashew Management Programme for Southern Tanzania" (b) Ngatunga EL, Cools N, Dondeyne D and Deckers JA (2001) "Soil suitability for cashew production in South Eastern Tanzania" accepted for publication in the journal "The Land".

In this chapter relationship between soil properties and growth and yield of cashew trees of 30 farmers' cashew groves in the study area is examined. The study also assesses the suitability of various landscapes for cashew nut production.

6.2 Materials and Methods

6.2.1 Location of soil profiles

The soil suitability study was confined to 16 selected cashew groves on the Makonde plateau and 14 others in the Inland plains. The locations of these groves are shown in Figure 4.1 (Chapter 4). The selection of the 30 cashew groves is described in Chapter 4 and the description of soils is given Chapter 5.

6.2.2 Determination of soil properties

At each grove, a soil profile was described following the FAO guidelines (FAO, 1990b) and classified according to FAO (1990a). Soil samples consisted of bulked sub-samples taken evenly from each horizon. Soil samples were air-dried, crushed and passed through a 2-mm sieve. Analysis of fractions less than 2 mm was carried out at the National Soil Service of Tanzania according to the methods presented in Table 6.1. As roots did occur over the total length of each profile, the profile depth can be taken as a measure for the rooting depth. Details on the soil profiles are attached in Annex IV.

Table 6.1 Soil analysis methods used

Property	Method
pH(H_2O) and pH(KCl)	1:2.5 soil solution ratio of distilled water and 1 M KCl
Organic carbon	Wet oxidation method after Walkley and Black
Available phosphorus	Bray 1 method
Particle size	Pipette method after Hydrogen peroxide treatment
Electrical conductivity	1:2.5 soil:distilled water suspension with a conductivity bridge
Cation exchange capacity	Percolation with 1 M ammonium acetate at pH 7
Exchangeable bases (Ca. Mg. K. Na)	Percolation with 1 M ammonium acetate at pH 7 followed by Atomic absorption spectrophotometry (Ca, Mg), flame spectrophotometry (K, Na)

6.2.3 Determination of cashew tree parameters

Cashew tree canopy diameters along N-S and W-E directions, tree height, crown height and girth at one metre above ground were measured on four trees nearby each soil profile. Farmers were provided with bags for storing and weighing the nuts of each individual tree. Tree age was estimated based on farmers' knowledge that made it possible to adhere on trees aged between 30 and 40 years. A one metre square wooden frame was used to count potential inflorescence at the four cardinal directions of each tree canopy. A potential inflorescence is a terminal bud, which can develop either into a vegetative or a reproductive branch. Cashew breeders at Naliendele Agricultural Research Institute in South Eastern Tanzania associate number of potential inflorescences with yield potential of the tree. Marking of potential inflorescences with red ink was done during the first season in April 1997 and during the month of April 1998 and 1999 annual growth were recorded. In August to September of each year, nuts were counted on 40 labelled branches from all the four trees per grove. As time for fruiting is variable counting of nuts was extended till time of harvesting. This was possible since the point of nut detachment to the inflorescence remains visible for several weeks after nut fall.

6.2.4 Processing of soil and tree data

For each profile, a single value of the soil chemical properties and texture was obtained by taking the weighed average measured per horizon over the profile depth, as a function of the horizon thickness. The soil depth, observed to a maximum of 2 m, was an additional variable. To take care of the high variability within cashew groves (Martin and Kasuga, 1995; Martin and Kasuga, 1998), the median value of the four trees at each site was used in the analysis.

6.2.5 Multivariate analysis of soils and tree data

Factor analysis and Pearson correlation coefficients were used to investigate relationships between the soil properties and tree parameters. Factor analysis is a multivariate statistical technique which weighs the available variables to provide the maximum discrimination between individuals (Dytham, 1999). It does this by reducing the variables to a smaller number of un-correlated compound axes called factors. The 19 soil properties and the 20 tree parameters were each in turn subjected to factor analysis. Factor scores of the first two principal factors were used to study, separately, the variability in the population of soils and trees in the study. Finally, the correlation coefficients between the soil factors and tree factors were calculated.

6.2.6 Soils of various landscapes in South Eastern Tanzania

Soils data of more than 140 profiles were retrieved from the geographical information system (GIS) centre at the Agricultural Research Institute Naliendele in Mtwara. Dominant soils of each landscape unit were classified according to the revised Legend of the Soil Map of the World (FAO, 1990a).

6.2.7 Climatic data

Long-term rainfall and temperature records were retrieved from the GIS centre at Naliendele. These were used to compute yearly and average monthly rainfall as well as the 20% and 80% dependable rainfall for Naliendele (Mtwara), Newala, Masasi, Nachingwea, Liwale and Tunduru. Additionally reference evapotranspiration (ETo) for Naliendele was calculated by using the *FAO Penman-Monteith* equation (Allen *et al.*, 1999).

6.3 Results and Discussion

6.3.1 Soil suitability for cashew nut production

6.3.1.4 Factor analysis of the soil properties

The 19 soil parameters were reduced to three factors explaining 68% of the original variance of the soil population to which a physical interpretation could easily be given (Table 6.2). Factor 1 which has high positive loadings for the base saturation, pH, silt/clay ratio, potassium content, cation exchange capacity, silt content can be interpreted as the weathering status. Decrease of these parameters indicates increase in weathering status of the corresponding soils. Factor 1 has a negative loading for profile depth. Factor 2 has high positive loadings for the total exchangeable bases, magnesium, calcium and clay content. This is linked to the soil fertility and reflects the nature of the soil parent material. Factor 3 reflects organic matter as it has high loadings for nitrogen, organic carbon content and C/N ratio.

Table 6.2 Factor loadings of the soil properties on first three factors after varimax rotation

Property	Factor 1	Factor 2	Factor 3
Base saturation	0.90	-	-
pH(H_2O)	0.90	-	-
pH(KCl)	0.89	-	-
Silt/Clay	0.89	-	-
K	0.69	-	-
Depth	-0.68	-	-
CEC	0.56	-	-
Silt	0.51	-	-
TEB	-*	0.94	-
Mg	-	0.92	-
Ca	-	0.93	-
Clay	-	0.76	-
Sand	-	-0.77	-
N	-	-	0.83
OC	-	-	0.82
C/N	-	-	0.68
P	-	-	-
EC	-	-	-
Na	-	-	-
Subtotal**	33	56	68

* absolute value < 0.5

** cumulative percentage explained variance

In Figure 6.1 the study sites and the soil properties are plotted on the first two factor axes representing 56% of the variance. The sites are labelled with the soil classification names following the revised Legend (FAO, 1990a). Group 1, which scores high on the first axis, represents the shallower or less weathered soils as a *Eutric Plinthosols*, *Haplic Phaeozems*, *Chromic Luvisols* and *Humic Cambisols*. Group 2 assembles highly weathered and nutrient-poor soils of the Makonde plateau (mostly sandy *Ferralsols*). Group 3 (*Ferralsols*, *Alisols*, *Plinthosols*) and Group 4 (*Ferralsols*, *Luvisols*, *Acrisols*) represent soils of the Inland plains. These soils have moderate pH-values but a relatively high Mg^{2+}, Ca^{2+}, TEB and clay content. Group 5 contains relatively young and sandy soils.

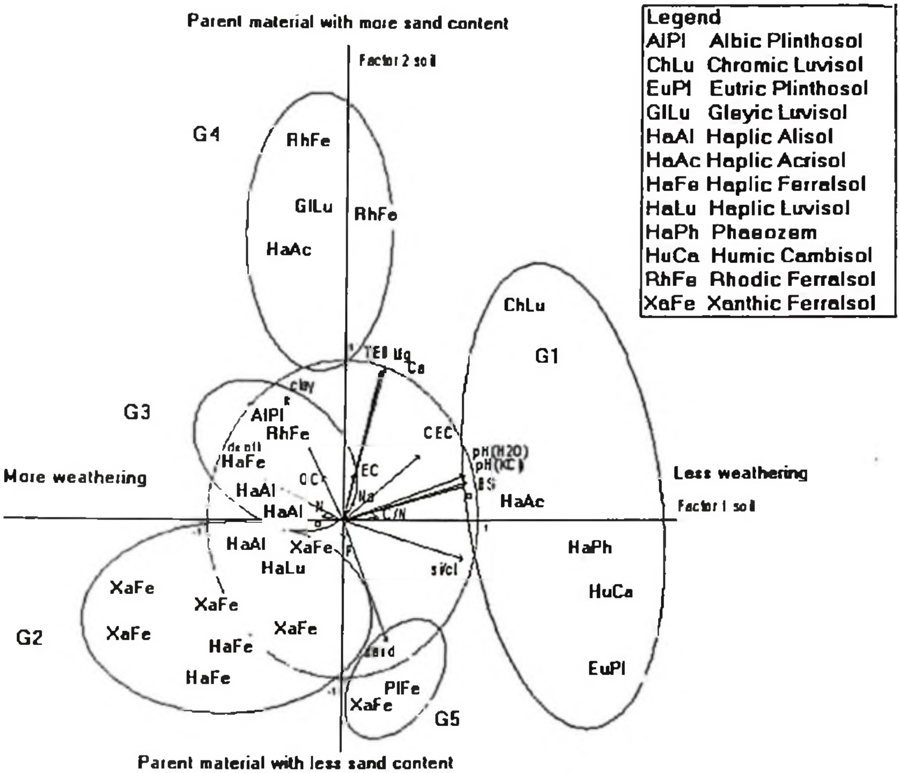


Figure 6.1 Ordination of cashew groves based on soil factors 1 and 2

6.3.1.2 Factor analysis of the tree parameters

The 20 tree parameters were reduced to three factors explaining 70% of the variance (Table 6.3). Factor 1 has high loadings for tree size and yield, confirming the high correlation between tree dimensions and yield reported by Tsakiris and Northwood (1967), Nayar *et al.* (1981) and Falade (1984). Factor 2 represents the number of nuts per unit area canopy and is thus not correlated to the total yield. This was an unexpected result as one would assume the yield per tree to be a function of the number of nuts per square meter times the total canopy area. This finding has implications for future on-farm experimentation, as the method was originally developed to estimate yield of cashew trees (Cashew Research Report, 1992/93). High number of nuts may also cause strong competition between the nuts resulting in shedding. Early fruit fall is indeed known to occur in cashew (Purseglove, 1968). It is also possible that there exists a high variability in the weights of nuts, whereby many small nuts may give a lower yield than few large nuts.

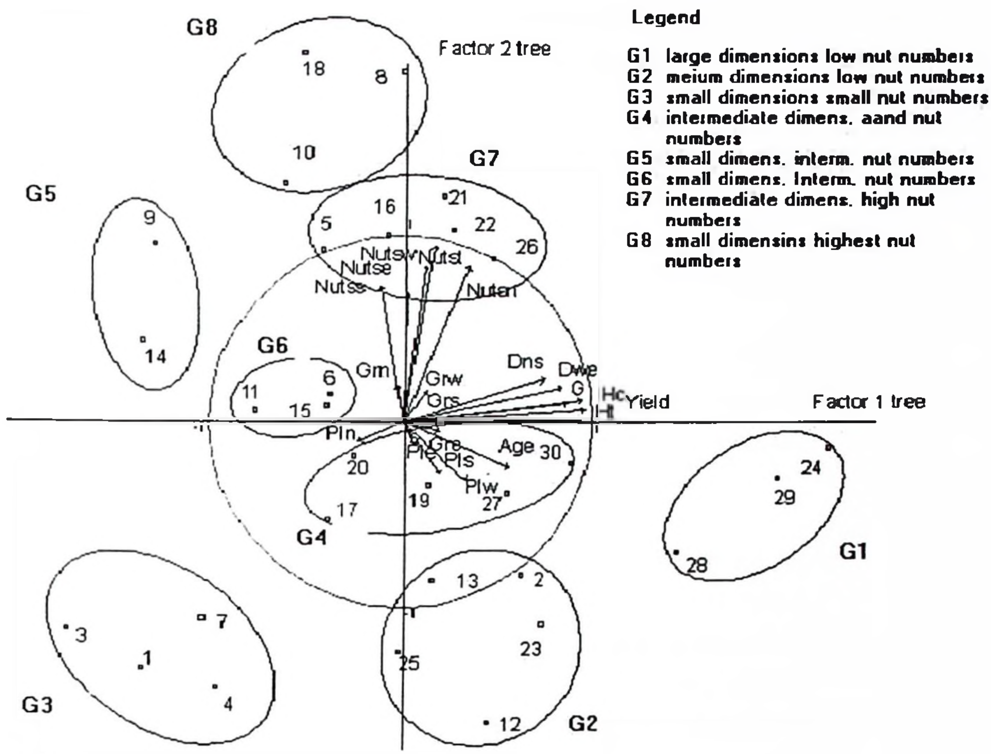
Table 6.3 Factor loadings of the tree parameters on first three factors after varimax rotation

Parameters	Factor 1	Factor 2	Factor 3
Branch growth N	-*	-	0.89
Branch growth E	-	-	0.90
Branch growth S	-	-	0.80
Branch growth W	-	-	0.80
Nuts/m^2 N	-	0.84	-
Nuts/m^2 S	-	0.73	-
Nuts/m^2 W	-	0.84	-
Nuts/m^2 E	-	0.70	-
Total nuts/4 m^2	-	0.95	-
Crown diameter NS	0.75	-	-
Crown diameter WE	0.84	-	-
Height tree	0.96	-	-
Height crown	0.95	-	-
Girth	0.86	-	-
No of Potential inflorescence N	-	-	-
No of Potential inflorescence S	-	-	-
No of Potential inflorescence E	-	-	-
No of Potential inflorescence W	-	-	-
Age	0.56	-	-
Yield/tree	0.96	-	-
Subtotal**	32	55	70

* absolute value < 0.5

** cummulative percentage explained variance

In Figure 6.2 the sites and the tree parameters are plotted on the first two factor axes representing 55% of the total variability. The many groupings indicate existence of heterogeneity in the cashew tree populations. Group 1 are cashew groves on the plateau with large trees and high yields, although the number of nuts counted during the growing season was rather low. Trees of Group 2 have medium dimensions and a low number of nuts. These stands are found on the plateau, except for one location. In two of the cashew groves of Group 3 some of the nuts were stolen. Trees of Group 4 and 6 have medium yield, dimensions and number of nuts. Group 5 has two cashew groves on the plateau where dimensions are small and yields are low. Groups 7 and 8 have a higher number of nuts per unit area of the canopy although they produce a poor yield. This heterogeneity could be due to variability in seed (as farmers had different sources of seed), tree age, environment (soils and rainfall), management of the groves, which were beyond the control of the study.



Legend

Pln, Ple, Pls, Plw	Potential inflorescence on respectively northern, eastern, southern and western side of the tree
Grn, Gre, Grs, Grw	Annual growth of branches on respectively northern, eastern, southern and western side of the tree
Nutsn, Nutse, Nutss, Nutsw	Nut counts on respectively northern, eastern, southern and western side of the tree
Nutst	Sum of nuts on 4 sides of tree
Ht	Height of tree
Hc	Height of crown
Dns, Dwe	Diameter of crown in respectively north-south and east-west direction
G	Girth of tree stem
Age	Age of tree
Yield	Total yield per tree in weight

No.	Location	No.	Location
1	Chikukase	16	Nangurukwe
2	Chikundi	17	Chemchem
3	Mundelunde 1	18	Libea
4	Mundelunde 2	19	Mandai
5	Mnanje	20	Mkumba
6	Mraushi	21	Namatuli
7	Mwenga	22	Nampemba
8	Temeke	23	Chikwaya
9	Kiromba	24	Kitangari
10	Maranje	25	Makonga
11	Mbawala	26	Mkopura
12	Msijute	27	Kitama
13	Mtiniko	28	Madaba
14	Naliendele	29	Mkule
15	Namkuku	30	Nanyanga

Figure 6.2 Ordination of cashew groves based on tree factors 1 and 2

Result of ordination of tree factors 2 and 3 is shown on Figure 6.3. Growth of branches varied between 15 and 40 cm while nut counts between 0 and 90. Group 1 includes two groves (one from the plateau and the plain) with highest nut counts of 75-90. Group 2 comprises mainly groves from the plateau with between 45-60 counts. Group 3 which has trees with nut counts varying between 0-30 has more groves from the plain than from the plateau but groves have the same growth rate. Trees in Group 4 have a slightly higher growth rate but low nut counts. It is apparent from this groupings that much of the variation is from nut counts rather than from growth rate of branches. It seems that there are other factors which influence nut counts per square unit of a cashew canopy which calls for further research.

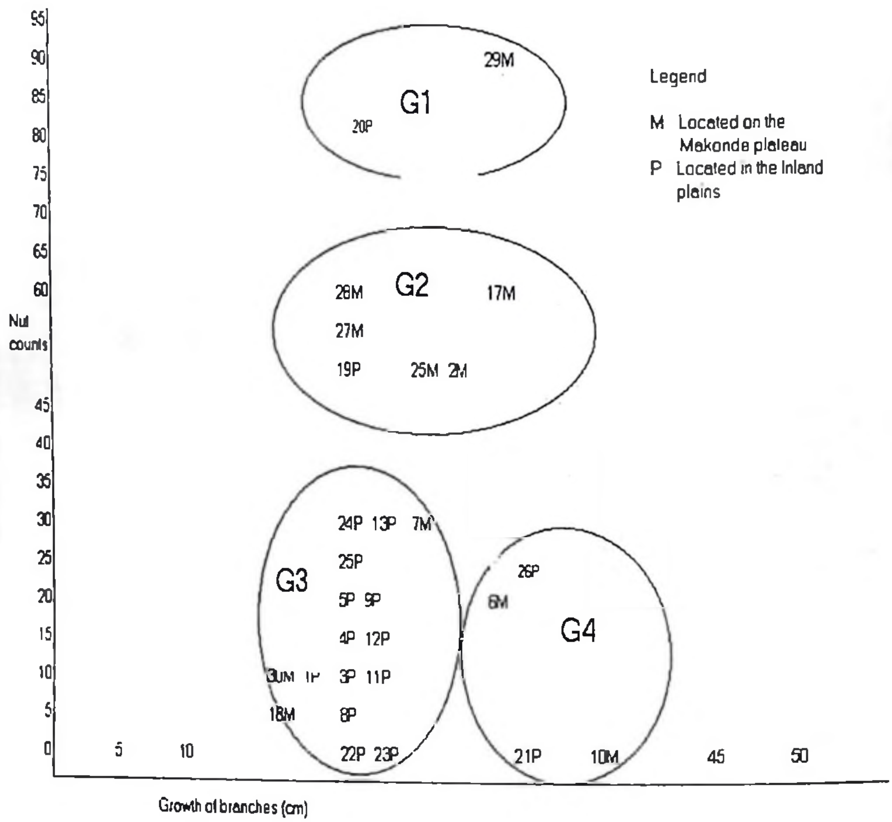


Figure 6.3 Ordination of cashew groves based on tree factors 2 and 3

6.3.1.3 Correlation analysis

The Pearson correlation coefficients in Table 6.4 give an indication of the degree of linear association between the soil and tree factors. There is a significant correlation between the weathering status and soil depth (soil factor 1) and tree dimensions and yield (tree factor 1). A weaker correlation is found between the number of nuts per unit area canopy (tree factor 2) and the weathering status and soil depth (soil factor 1), the exchangeable base content and texture (soil factor 2) and the organic matter content (soil factor 3). This suggests that these soil properties influence number of nuts. The number of cashew nuts per unit area canopy seems to be higher on clayey soils with high exchangeable bases. Since nut quality was not checked. it is not possible to establish a relationship between these properties and nut quality. This finding may be of interest in future investigations on the physiology of the cashew tree.

Table 6.4 Pearson correlation coefficients between soil and tree factors

Soil factors	Tree factors		
	Tree size and yield	**Nuts/m² canopy**	**Branch growth**
Weathering and soil depth	-0.54***	-0.36**	-0.26
Exchangeable base content and texture	0.06	0.34*	-0.16
Organic matter content	0.17	0.34*	-0.26

two tailed levels of significance: *** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$

The relationship between cashew tree dimensions and yield in relation to soil weathering and landscape units is depicted in Figure 6.4. Cashew groves with large, high yielding trees were on highly weathered, deep, well drained, acid soils and are most common on the Makonde plateau (Quadrant IV). Groves with small trees and low yield were mostly on shallow or less weathered soils found in the inland plains (Quadrant II). Since the plateaux have more rainfall than the plains (Martin *et al.*, 1997), it could be argued that differences in tree dimensions between these two landscape units arise from rainfall differences. However, trees with medium dimensions and yield in Quadrants III and IV are from both the plateaux and the plains. Thus differences in dimensions and yield on the plateau and in the plains cannot be attributed to rainfall alone. Weathering status and soil depth are the main physical factors determining size and yield of cashew trees. These properties can easily be checked in the field and this seems especially worth doing in the inland plains.

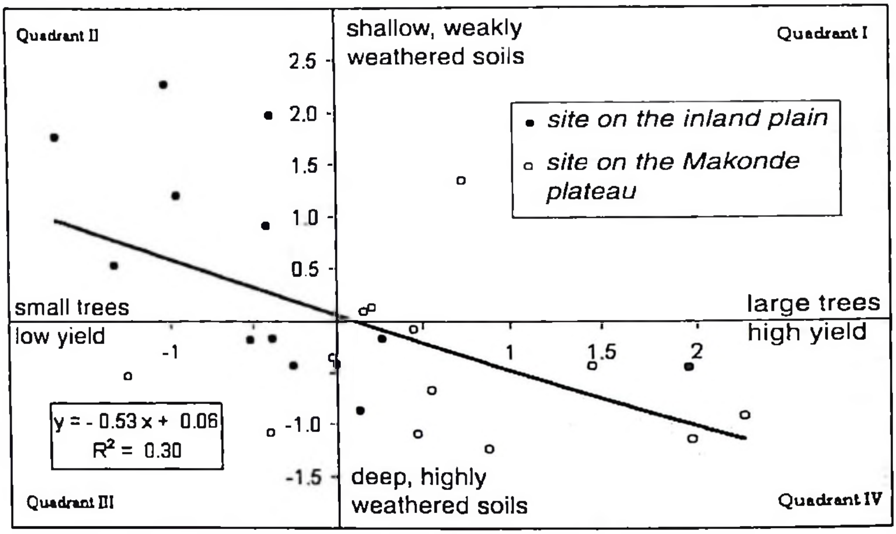


Figure 6.4 Cashew tree dimensions and yield in relation to soil weathering and landscape units

6.3.2 Landscape suitability for cashew nut production

6.3.2.1 Climatic requirements

For proper vegetative development and regular fruit setting cashew requires an average annual rainfall of 600 to 1600 mm. spread over 5-7 months (Ohler, 1979). Higher rainfall leads to excessive vegetative development, accompanied by a scarcity of flowers and fruits (Behrens, 1996) Insufficient rain leads to irregular flowering and fruit setting (Behrens, 1996). Cashew has a preference for high but above all constant temperatures, such as that of the coastal belt of the tropical regions in which it grows best. The most favourable mean annual temperature for cashew lies between the 24° and 27°C.

Mean annual rainfall in South Eastern Tanzania ranges between 820 and 1245 mm (Table 6.5). Rainfall pattern is uni-modal, but very erratic as can be seen from the ranges of the monthly dependable rainfall (Figure 6.5). A dry spell of one to two weeks often occurs at the end of January or at the beginning of February. This is reflected in a decrease of the rainfall with 20% changes of exceedance in Tunduru, Naliendele and Newala. In Nachingwea, Liwale and Masasi, it gets reflected in the rainfall with 80% changes of exceedance.

Table 6.5 Annual rainfall (mm) for a dry and wet year (10 year return period)

Station	Dry year	Wet year (mm)	Average
Nachingwea	605	1025	823
Liwale	503	1220	868
Masasi	538	1550	873
Tunduru	656	1379	1016
Naliendele (Mtwara)	649	1505	1132
Newala	688	1912	1245

Both the annual (Table 6.5) and the monthly rainfall data (Figure 6.5) show that rainfall is higher on the plateaux (Newala, Naliendele and Tunduru). Due to its proximity to the ocean, rains at Naliendele persist longer; the contrary is true for Tunduru, which is about 350-km inland. Nachingwea, Liwale and Masasi have a distinct drier climate. The growing season starts in December when the rainfall is half the reference evapotranspiration (ETo), and ends in April when the rainfall is less than half the ETo (Figure 6.5).

Temperatures vary little: the mean temperature is 24.3°C in July and 27.5°C in December. Cashew is thus well adapted to the climate of Tanzania's Southern Zone. However, at 850 m mean annual temperature is between 19°C in July and 22°C in December (Bennett *et al.*, 1979). Thus, while low rainfall may be a limitation in the driest parts of the inland plains, low temperatures will be unfavourable in the highest parts, i.e. on the Rondo plateau, the north-western part of the Makonde plateau and the highest parts of the Tunduru plateau where altitude exceeds 800 m.

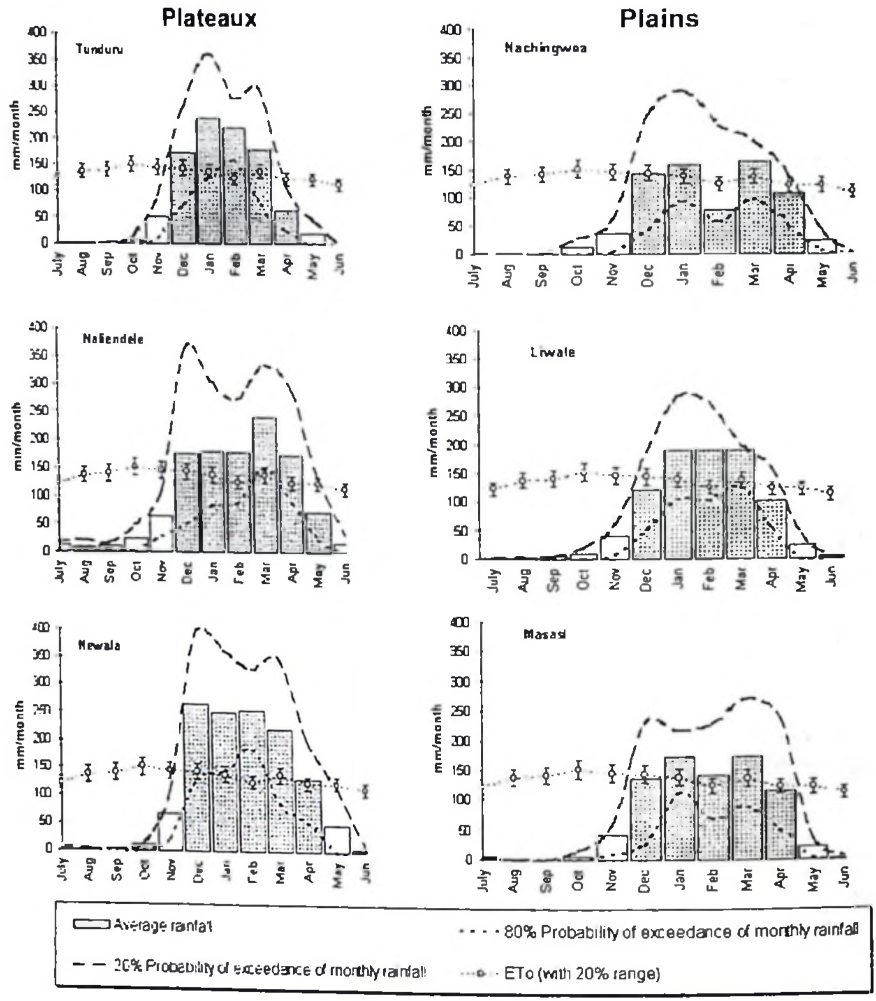


Figure 6.5 Average monthly rainfall, 20% and 80% dependable monthly rainfall and reference evapotranspiration (The dark shaded bars are from the wet months)

6.3.2.2 Soil requirements

The cashew tree prefers loose, deep, aerated soils that are above all well drained (Ohler, 1979). Heavy clayey, compact soils, or those with hard surface setting or with concretions at shallow depth, even when naturally fertile, retard the plant's growth preventing the roots from penetrating downwards and more generally sideways. The tree requires soils with little calcium. Too high levels of free lime will result in chlorosis. Optimum pH is between 4.5 and 6.5 and the minimum pH required for growth is 3.8 (FAO, 1994).

Detailed account of landscapes of South Eastern Tanzania has been reported in Chapter 1 and soils in Chapters 1 and 5.

6.3.2.3 Suitability of various landscapes

Coastal areas

In the coastal plains, it is the deep, sandy and highly weathered soils developed on coral lime which are suitable for cashew. Major parts of the coastal plains are marginally suitable due to shallow soils or too high soil pH. The coastal dissected plains and coastal hills in Lindi and Kilwa districts have dark cracking clay soils not suitable for cashew.

Makonde, Rondo and Kilwa Plateaux

The highly weathered sandy soils of the plateaux are very suitable for cashew. The Makonde plateau indeed is the major cashew producing area within the Zone. Cashew production could possibly be expanded on the Rondo and Kilwa plateaux. Soils of the plateaux are however more sensitive to acidification when sulphur is applied for controlling powdery mildew (Ngatunga *et al.*, 1998).

Floodplains and valleys

The alluvial floodplains are not suitable due to their poorly drained and heavy clayey soils. Cashew growth is limited in valleys and swampy areas due to poor drainage. Stony, clayey and cracking *vertic* soils do not permit an extensive root system commonly required by the plant.

Central plain area

As the soil pattern of this area is complex, so is its suitability. The deep and highly weathered soils on interfluves are very suitable. Moreover, soils in the Inland plains have the advantage of being less sensitive to soil acidification. Marginally suitable are the soils on slopes that tend to be shallow or the poorly drained soils in the valley bottoms. In this area, however, low rainfall can be a major limitation to cashew production.

Western plateau and upland area

Tunduru plateau and the sandy dissected uplands in Tunduru and Liwale districts are very suitable but areas above 800 m on plateaux, are marginally suitable as lower temperatures are unfavourable for cashew production.

6.4 Summary and conclusions

Multivariate analysis was used to investigate relationships between soil properties and the growth and yield of cashew trees in South Eastern Tanzania. Cashew trees are larger and yield more in deep, strongly weathered soils, mostly *Ferralsols*. These soils are most common on the Makonde plateau, where they are sandy, but also occur on the Inland plains, where they are more clayey. Cashew trees are smaller in dimensions and have lower yields on shallow (e.g. *Eutric Plinthosols*) or poorly weathered soils (e.g. *Humic Cambisols* and *Gleyic Luvisols*) commonly found on the Inland plains. Numbers of nuts per unit area canopy are higher on deep, clayey soils with high exchangeable base content, but this is not correlated with the total yield per tree. Future planting of cashew trees should be done on deep and highly weathered soils free from hardpans. Although the relationship between soils and yield of cashew nuts have been established, this study did not explore the influence of soil properties on quality of cashew nuts.

High temperatures, a long dry season, and deep and highly weathered soils explain why South Eastern Tanzania is the major cashew producing area of Tanzania. Landscapes with deep and highly weathered soils such as the plateaux and uplands are suitable for cashew nut production. Shallow and less weathered soils are marginally suitable. Clayey, poorly drained soils of the coastal areas, valleys and floodplains are not suitable for cashew nut production. Low rainfall is a limiting factor for cashew production particularly in the inland plains. Areas above 800 m on the plateaux are marginally suitable due to low temperature.

Chapter 7

Buffering capacity of cashew growing soils in South Eastern Tanzania[1]

7.1 Introduction

In 1998, cashew nuts ranked second as the most important foreign exchange earning crop in Tanzania being exceeded only by coffee (Bank of Tanzania, 1999). Tanzania's production is about 9% of the world total (FAO, 2000). The crop is mostly grown by smallholder farmers and around 70% of the national production comes from South Eastern Tanzania (Topper *et al.* 1998c). The first reported export of nuts occurred in 1938 when 210 ton of raw nuts were shipped to India (Northwood and Kayumbo, 1970). Widespread planting took place after 1945 and a peak production of 145,000 ton was reached in the 1973/74 marketing season. A catastrophic decline followed, and a record low production of 17,060 ton was reached in 1990 (FAO, 2000). The production decline has been attributed to socio-economic factors linked to the resettlement programme in the 1970s and to the outbreak of powdery mildew disease, caused by *Oidium anacardii* Noack (Martin *et al.*, *1997*; Topper *et al.*, 1998b). Recent market liberalisation and high nut prices have encouraged farmers to increase production and during the 1999/2000 season 106,500 ton of nuts were marketed (FAO, 2000).

In the early 1980s, research at the Naliendele Agricultural Research Institute in Tanzania led to the identification of sulphur as a suitable chemical for controlling powdery mildew disease (Sijaona, 1984; Partel, 1988). Sulphur has been widely adopted by farmers and during the last three years (1997-1999) sulphur imports to South Eastern Tanzania (regions of Lindi, Mtwara and Tunduru district) went up from 2500 to 7000 ton (Cashewnut Board of Tanzania, 1999). The standard recommendation is to dust 1.25 kg of sulphur per tree per season. For the recommended spacing of 12 × 12 m per tree, this is approximately 90 kg ha^{-1} of S. When trees are not dusted flower buds, flowers, young leaves and young shoots are attacked by the mildew resulting in poor harvest and inferior nut quality. Despite its effectiveness, it was quickly realised that sulphur could have serious environmental consequences. Field surveys indicated that sulphur acidifies soils on which cashew is grown (Majule *et al.*, 1997;

[1] Based on the paper Ngatunga EL, Cools N, Dondeyne S, Deckers JA and Merckx R (2001b) "The buffering capacity of cashew growing soils of South Eastern Tanzania", Soil Use and Management, 17(3):155-162

Ngatunga *et al.*, 1998). The sustainable production of cashew and intercropped food crops is of major concern.

7.1.1 Soil acidification

Adverse changes in soil pH can affect plant growth due to a variety of reasons. As soil acidity increases, exchangeable calcium decreases and calcium deficiencies may ensue. More important may be the indirect effects as the reduction of available phosphate following fixation with soluble iron and aluminium (Shen *et al.*, 1998). There are also effects on trace elements particularly the increased solubility of manganese may prove toxic to plants (Robarge and Johnson, 1992). Both fungal and bacterial activity may be curtailed in adverse pH environments, leading to poorer nutrient recycling (Hassett and Banwaart, 1992).

Under moist aerobic conditions sulphur is oxidised to sulphuric acid by autotrophic bacteria, including five species of the genus *Thiobacillus* (Brady, 1990). For every sulphur atom oxidised, two hydrogen ions are formed which may lower soil pH. Nortcliff and Wong (1995) concluded that the rate of sulphur oxidation depends on the size of the microbial population and factors affecting soil microbial activity such as soil water potential, organic matter content, pH and temperature. For example, *Thiobacillus thiooxidans* oxidises elemental sulphur to sulphate and operates optimally between pH 3 and 3.5. *Thiobacillus ferrooxidans* may also be involved in the transformation of S into SO_4^{2-} and operates optimally between pH 2 and 3.5 (Rowell, 1981). The size of the sulphur particles is important (Weir *et al.*, 1963; Fox *et al.*, 1964). Sulphur powder has a large specific surface area facilitating oxidation. The oxidation rate can be expressed in terms of the surface area exposed and, under optimal conditions, rates of 48 - 76 μg S cm^{-2} day^{-1} have been reported (Watkinson, 1989). The powdered sulphur applied in Tanzania has particle sizes smaller than 50-μm diameter. If the lower rate reported by Watkinson (1989) is applicable to sulphur used in Tanzania, about 3.2 kg S ha^{-1} day^{-1} is oxidised. Hence, it can be assumed that within a year 90 kg ha^{-1} will be completely oxidised.

7.1.2 Buffering capacity

The buffering capacity of a soil is defined as its resistance to changes in pH when an acid or a base is added. It can be expressed as the quantity of protons required for changing the soil pH by one unit (mmol H^{+} kg^{-1} pH^{-1}) (Rowell, 1994). The buffering capacity of a soil depends among other factors on base status (Magdoff and Bartlett 1985; Brady, 1990), cation exchange capacity (McFee, 1983) and presence of weatherable minerals. Soil components that constitute buffering mechanisms also include clay and humic fractions. Buffering at intermediate pH levels (5.0 to 7.5) is mainly governed by exchange reactions whereby functional groups of organic matter and clay act as sinks for H^+ and OH^- (Nielsen *et al.*, 1995; Curtin *et al.*, 1996). If active acidity is neutralised, residual acidity releases H^+ ions and no change in soil pH occurs until the reserve of H^+ is exhausted. Residual acidity is often greater than active acidity, but is less in sandy soils than in clayey soils (Brady, 1990). Laboratory methods for evaluating buffering capacity involve potentiometric titration with either an acid or a base (Magdoff and Bartlett, 1985). Field methods involve application of lime and monitoring changes of soil pH and base saturation.

Predicting the long-term effect of sulphur applications in Tanzania is difficult, as the buffering capacity of the cashew soils has never been investigated. In this study, the buffering capacity of soils from 35 cashew groves in six landscape units of South Eastern Tanzania was assessed. The objective was to elucidate the role of physico-chemical soil properties in the buffering capacity of the soils and to assess the implications for soil management of current sulphur use in South Eastern Tanzania.

7.2 Materials and Methods

Soil samples were taken from 35 profiles in farmers' cashew groves in major cashew growing areas of South Eastern Tanzania. Results of detailed physical and chemical analysis of the soil profiles were reported by Cools (1998) and are summarised in Table 7.1. Soil profiles were classified according to the 'revised legend of the Soil Map of the World' (FAO, 1990a).

7.2.1 Soils and landscapes

Bennett *et al.* (1979) mapped soils and landscapes of South Eastern Tanzania at a reconnaissance scale of 1:250,000. Separated from the Indian Ocean by a narrow coastal plain, plateaux dominate the eastern part of the study area. Of these, the Makonde plateau is the most populated and it produces about 50% of the cashew nuts from South Eastern Tanzania. Geologically, the plateau consists of sandy sedimentary deposits of Neogene age on which deep soils are formed, with a sandy topsoil and sandy loam or sandy clay loam subsoil. Following the FAO Legend (1990a), the dominant soils of the Makonde plateau are *Xanthic Ferralsols*. Most common associated soils are *Haplic Ferralsols* and *Haplic Alisols*. Based on relief characteristics, the plateau has been subdivided into the Makonde high plateau and the Makonde dissected plateau.

Table 7.1 Summary statistics (mean and standard deviation for $n > 1$) per landscape unit and soil groupings of physico-chemical soil properties

Landscape unit /Soil grouping	Horizon	pH(H_2O)	pH(KCl)	OC (%)	P (g kg^{-1})	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	CEC	CECclay	BS** (%)	Clay (%)	Sand (%)	Silt (%)	Silt/Clay
						< ----------	cmol$_c$ kg^{-1}					---------- >					
Makonde plateau																	
Acrisol	top**	5.6	4.5	0.42	3.27	0.8	0.9	0.3	0.2	2.3	1.8	22.5	100	8	87	5	0.63
	sub	5.4	4.2	0.20	2.10	0.7	0.3	0.2	0.2	1.3	3.2	21.3	42	15	83	2	0.13
Alisols (n=3)	top	5.4 ± 0.06	4.1 ± 0.15	0.7 ± 0.43	10.1 ± 5.99	0.8 ± 0.21	0.3 ± <0.01	0.1 ± 0.08	0.04 ± 0.03	1.2 ± 0.15	2.6 ± 0.27	26.6 ± 1.9	48 ± 0.6	10 ± 1.5	88 ± 2.3	2 ± 1.0	0.20 ± 0.09
	sub	5.1 ± 0.20	4.1 ± 0.17	0.3 ± 0.22	6.0 ± 1.87	0.9 ± 0.35	0.4 ± 0.25	0.1 ± 0.06	0.02 ± 0.01	1.4 ± 0.59	3.8 ± 0.82	34.5 ± 20.1	37 ± 7.6	12 ± 3.8	83 ± 2.1	5 ± 5.3	0.60 ± 0.72
Ferralsols (n=13)	top	5.2 ± 0.66	4.4 ± 0.73	0.7 ± 0.4	9.6 ± 10.25	1.0 ± 1.15	0.4 ± 0.59	0.2 ± 0.17	0.25 ± 0.72	2.0 ± 1.93	3.7 ± 2.03	30.8 ± 27.2	47 ± 25.9	14 ± 4.2	83 ± 4.5	3 ± 1.5	0.30 ± 0.16
	sub	5.0 ± 0.52	4.1 ± 0.34	0.3 ± 0.17	1.9 ± 2.06	0.7 ± 1.31	0.3 ± 0.58	0.2 ± 0.14	0.09 ± 0.20	1.2 ± 1.93	3.0 ± 2.68	11.6 ± 7.9	34 ± 16.4	23 ± 6.9	74 ± 7.2	2 ± 1.5	0.11 ± 0.07
Piedmont																	
Acrisol	top	5.9	4.9	0.84	7.15	2.7	1.3	0.3	0.02	4.3	6.5	58.9	66	11	80	9	0.82
	sub	4.9	3.8	0.43	0.35	2.0	1.2	0.1	0.02	3.3	9.3	16.3	35	57	41	2	0.04
Arenosol	top	5.8	5.1	0.91	2.30	2.1	0.4	0.3	0.57	3.4	10.0	125.0	34	8	89	3	0.09
	sub	6.2	5.0	0.20	0.73	1.0	0.2	0.3	0.14	1.5	4.0	40.0	39	10	87	3	0.30
Ferralsol	top	5.9	5.2	0.33	2.54	0.7	0.3	0.1	0.08	1.1	1.8	43.8	65	4	93	3	0.75
	sun	6.3	4.8	0.10	1.38	0.4	0.2	0.1	0.02	0.7	0.9	11.5	76	8	90	2	0.25
Luvisol	top	5.8	4.8	0.96	0.70	4.9	1.5	0.9	0.13	7.4	10.6	32.1	70	33	59	8	0.56
	sub	6	4.8	0.59	0.43	4.0	1.6	0.8	0.12	6.6	10.4	27.4	63	38	53	9	0.24
Inland plain																	
Acrisol	top	5.8	5.1	0.7	2.30	0.8	0.6	0.2	0.03	1.6	2.5	36	62	7	84	9	1.29
	sub	6.2	4.8	0.29	3.48	1.2	0.8	0.3	0.02	2.4	3.1	13.4	76	23	72	5	0.22
Alisols (n=3)	top	5.8 ± 0.78	4.9 ± 1.07	0.5 ± 0.18	7.8 ± 7.58	2.1 ± 1.21	0.8 ± 0.19	0.2 ± 0.1	0.04 ± 0.03	3.1 ± 1.29	5.2 ± 1.18	67.0 ± 47.6	61 ± 27.5	11 ± 7.5	85 ± 7.5	4 ± <0.01	0.45 ± 0.48
	sub	5.5 ± 0.51	3.8 ± 0.58	1.1 ± 0.38	2.0 ± 5.38	5.0 ± 1.72	1.6 ± 0.43	0.02 ± 0.11	0.03 ± 0.02	6.7 ± 2.12	13.6 ± 3.60	31.7 ± 3.2	49 ± 19.7	43 ± 10.6	53 ± 9.7	4 ± 1.5	0.09 ± 0.09
Cambisols (n=2)	top	6.4 ± 0.07	5.4 ± <0.01	0.6 ± 0.23	4.4 ± 0.42	1.3 ± 0.78	0.4 ± 0.14	0.2 ± 0.11	0.05 ± 0.04	1.9 ± 0.86	2.7 ± 1.46	49.9 ± 36.1	79 ± 4.2	6 ± 1.4	87 ± 7.8	8 ± 6.4	1.16 ± 0.78
	sub	6.5 ± 0.07	4.7 ± 0.49	0.2 ± 0.06	1.6 ± 0.92	1.4 ± 0.92	0.5 ± 0.14	0.2 ± 0.06	0.04 ± 0.01	2.0 ± 1.00	2.4 ± 1.21	23.8 ± 2.1	85 ± 0.7	10 ± 4.2	82 ± 8.5	8 ± 4.2	0.78 ± 0.09
Ferralsols (n=5)	top	5.6 ± 0.56	4.6 ± 0.39	0.6 ± 0.42	2.4 ± 1.64	2.1 ± 0.95	1.0 ± 0.33	0.3 ± 0.12	0.07 ± 0.04	3.4 ± 1.27	6.4 ± 2.52	36.7 ± 14.9	56 ± 18.2	20 ± 9.4	75 ± 10.3	5 ± 1.9	0.23 ± 0.16
	sub	5.4 ± 0.45	4.3 ± 0.39	0.3 ± 0.21	0.6 ± 0.59	2.2 ± 1.38	1.0 ± 0.59	0.2 ± 0.22	0.08 ± 0.09	3.5 ± 1.63	7.8 ± 1.82	16.5 ± 7.1	43 ± 12.5	51 ± 14.1	45 ± 14.9	4 ± 2.3	0.09 ± 0.04
Luvisol	top	6.9	6.0	0.33	1.54	1.7	0.5	0.2	0.02	2.4	2.46	24.6	98	10	82	8	0.80
	sub	7.4	5.8	0.25	2.59	4.4	2.4	0.3	0.02	7.1	6.28	25.1	100	25	69	6	0.24
Phaeozem	top	6.2	5.2	1.08	2.91	0.8	0.5	0.3	0.02	1.6	2.19	24.3	74	9	83	8	0.89
	sub	6.7	5.2	0.22	2.59	1.2	1.0	0.2	0.02	2.4	2.71	24.6	90	11	83	6	0.55
Plinthosol	top	5.6	4.6	0.35	4.66	0.7	0.4	0.1	0.02	1.3	2.31	25.7	54	9	85	6	0.67
	sub	5.5	3.7	0.44	1.89	3.6	1.7	0.1	0.07	5.4	10.42	24.8	52	42	53	5	0.12

* top = surface horizon (between 0-20 cm); sub. = subsurface horizon (around 50 cm), ** BS, base saturation = Σ(Ca,Mg,K,Na)x100/CEC

Westwards of the plateaux are the Inland plains which, within the study area, Bennett *et al.* (1979) mapped as the Lulindi plain, the Nachingwea-Masasi plain and the Southern Masasi plain. These are gently undulating plains with broad flat-topped interfluves, wide shallow valleys, formed on Precambrian Basement rocks, mostly gneiss. Soil changes reflect variations in lithology, drainage and erosional history. On the interfluvial crest, least affected by erosion, typically highly weathered, deep, red, sandy clay loam or sandy clay soils occur. They are *Rhodic Ferralsols* and *Haplic Acrisols* according to the FAO Legend (FAO, 1990a). On the slopes, a variety of less weathered, often shallow soils occur. Most common soil units are *Rhodic Luvisols*, *Chromic Cambisols*, *Gleyic Alisols* and *Albic Plinthosols* occur in the valleys, while *Ferralic* and *Luvic Arenosols* are common on the Piedmont of the Makonde plateau.

7.2.2 Determination of buffering capacity

Buffering capacity was examined for the surface horizon (0-20 cm) and the subsurface horizon at around 50 cm. Twenty grams of fine earth (less than 2 mm) of each sample was placed in 100 ml glass bottles to which 50 ml of distilled water was added as for standard soil pH measurements. Sulphuric acid was added to these bottles as 0 (reference), 0.5, 1 and 2 ml of 0.015M H_2SO_4. These additions represented 0, 0.75, 1.5 and 3 mmol H^+ kg^{-1} soil. The bottles were shaken for 30 minutes after which a first pH measurement was made; a second measurement was made after 24 hours.

The concentrations of added acid were based on the rationale that for every sulphur atom, two hydrogen ions are formed. If sulphur is applied according to the recommendation of 90-kg ha^{-1}, the amount of H^+ added to the soil can be calculated as shown below:

1 mol S = 32 g, therefore 90 kg ha^{-1} of S = 2.8 kmol/ha of S---------------------------[1]

For the upper 20 cm of 1 ha, with a bulk density of 1400 kg/m^3 this is

2,800,000 kg ha^{-1} ------------------------[2]

Dividing [1] by [2], 90 kg of S correspond to 1 mmol S kg^{-1} soil which produces 2 mmol H^+kg^{-1} soil.

7.2.3 Statistical analysis

Pearson correlation coefficients, with two tailed levels of significance, were calculated to identify relationships between buffering capacity and physico-chemical soil properties. The buffering capacity is calculated as the quantity of protons added (3 mmol H^+ kg^{-1} soil) divided by ΔpH, with

$$\Delta pH = pH\ (0\ mmol\ H^+\ kg^{-1}\ soil) - pH\ (3\ mmol\ H^+\ kg^{-1}\ soil).$$

The effect on the pH of the quantity 'H^+ added' (random factor with four levels), sampling depth (fixed factor with two levels 0-20 and 50 cm), time (random factor with two levels 0.5 h and 24 h). landscape unit (fixed factor with six levels) and soil groupings (fixed factor with nine levels) was analysed with a variance analysis of repeated measures. The procedure adopted was the PROC MIXED programme of the statistical package SAS (Littell *et al.*, 1996). The PROC MIX programme is able to verify whether "populations" are statistically significant differences; similar to a pair-wise t-test for two populations. The populations in this case are "landscape units" and "soil groupings". The pair wise t-test can not be used because there are more than two populations (e.g. *Ferralsols, Acrisols, Cambisols*, etc.) and six landscape units (Makonde dissected plateau, Makonde high plateau, Nachingwea-Masasi plains, etc). The PROC MIXED programme makes a multiple pairwise comparisons by using least square means as criteria to compare the populations. The results enabled to rank landscape units and soil units in terms of their risk for soil acidification.

7. 3 Results and Discussion

7.3.1 Titration curves

The titration curves in Figure 7.1 illustrate two examples from the Makonde plateau and two from the inland plains. The samples from the plateau had a more acidic initial soil pH than those of the inland plains. The pH measured after 24 h was higher than after 30 minutes, but the increase was more pronounced for the soils of the plains. The buffering capacities derived from the titration are presented in Table 7.2. The buffering capacity of these tropical soils is about 10 times lower than those of a range of British soils reported by Rowell (1994). There seems to be no differences between the buffering capacity of the various landscape units nor of the various soil units.

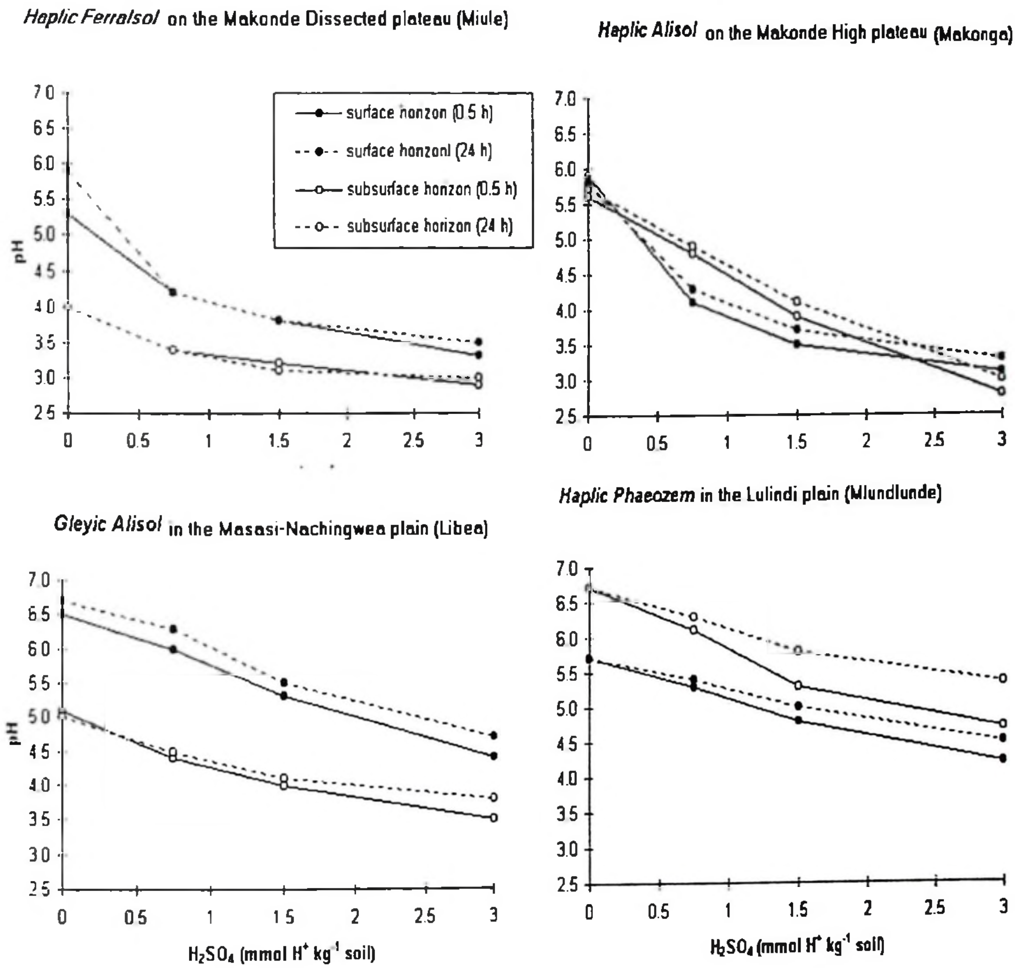


Figure 7.1 Titration curves of profiles on the Makonde plateau and in the Inland plains

Table 7.2 Buffering capacities (mmol H^{+} kg^{-1} pH^{-1}) of 35 soil profiles measured 30 min and 24 h after addition of sulphuric acid

Soil unit*		Surface horizon (0-20 cm)		Subsurface horizon (around 50 cm)	
Landscape unit	Profile	$BC_{30\,min}$	$BC_{24\,h}$	$BC_{30\,min}$	$BC_{24\,h}$
Makonde Dissected plateau					
Haplic Acrisols	Nanguruwe	1.3	1.3	1.8	1.7
Haplic Alisols	Madaba	1.2	1.3	1.4	1.3
Haplic Ferralsols	Miule	1.5	1.3	2.7	3.0
"	Mtmiko	1.9	1.9	1.3	1.4
"	Msijute	2.7	2.7	1.3	1.4
Rhodic Ferralsols	Nahendele	1.6	1.5	2.0	2.3
Xanthic Ferralsols	Kiromba	1.6	1.7	2.1	2.3
"	Maranje	2.0	2.0	2.1	2.0
"	Mbawala	2.0	2.1	1.5	2.5
"	Namkuku	2.0	2.0	3.0	2.7
"	Kitama	2.3	3.0	1.6	2.0
"	Nanyanga	2.3	2.5	2.5	2.5
Makonde High plateau					
Haplic Alisols	Makonga	1.1	1.2	1.1	1.1
"	Kitangari	1.6	1.8	2.0	2.5
Haplic Ferralsols	Mtopwa	2.5	2.3	2.5	3.3
Rhodic Ferralsols	Chikwaya	3.8	10.0	0.9	1.3
Xanthic Ferralsols	Chiwambo5	2.0	2.0	2.3	2.7
Piedmont					
Haplic Acrisols	Chikundi	2.5	3.3	4.3	5.0
Ferralic Arenosol	Chiwambo3	1.4	1.6	1.1	1.1
Plinthic Ferralsol	Chikukwe	0.9	1.0	1.0	1.3
Chromic Luvisol	Chiwambo2	2.0	2.3	2.0	2.1
Nachingwea Masasi plain					
Albic Plinthosol	Temeke	1.4	2.0	2.5	2.7
Eutric Cambisol	Chemchem	1.3	1.4	1.2	1.3
Gleyic Alisol	Libea	1.4	1.5	1.9	2.5
Haplic Alisol	Nampemba	1.6	1.9	2.7	3.8
Humic Cambisol	Mwenge	1.8	1.9	1.0	1.3
Rhodic Ferralsol	Mkumba	1.3	1.8	3.8	5.0
"	Namatula	1.9	2.3	1.4	2.1
"	Mandai	2.7	4.3	2.7	4.3
"	Mraushi	2.7	2.7	3.3	3.8
Southern Masasi plain					
Haplic Acrisol	Mnanje	1.4	1.9	1.3	1.8
Lulindi plain					
Chromic Luvisol	Mlundelunde2	1.4	1.8	1.1	1.8
Gleyic Alisol	Chiwambo1	1.3	1.4	1.4	1.4
Haplic Phaeozem	Mlundelunde1	2.0	2.5	1.5	2.2
Rhodic Ferralsol	Chiwambo4	1.4	1.8	2.0	2.1

*classification following FAO Legend (FAO, 1990a)

7.3.2 Buffering capacity in relation to soil properties

The correlation coefficients (with $p < 0.1$) are presented in Table 7.3. The buffering capacity of the surface horizon measured after 30 minutes showed a significant positive linear relationship with the clay content and, reciprocally, a negative relationship with the sand content. In the subsurface horizon the silt content and especially the silt/clay ratio is negatively related to the buffering capacity, but this is difficult to interpret as absolute silt contents were very low (Table 7.3). Higher organic carbon contents are positively correlated with higher buffering capacity. These observations support earlier findings by Rowell (1981) and Van Breemen *et al.* (1984), which showed that the buffering capacity lies in the exchange capacity of the clay and the organic matter content of the soil. Although the relationship is weaker, this also explains the correlation found with the CEC of the soil.

For the divalent exchangeable bases (Ca^{2+} and Mg^{2+}) and the available P only a weak correlation was found for the surface horizon. As the pH of the soils were in the acidic range, exchangeable bases are bound to the exchange complex provided by the organic matter, the clay fraction or sesquioxides. As the buffering capacity seems only to relate with these elements in the surface horizon, this could indicate an exchange reaction of H^+ with these elements bound to humic substance of the Ah horizon.

Table 7.3 Pearson correlation coefficients between buffering capacity (BC) and physico-chemical properties of 35 soil profiles in cashew groves

Soil	Surface horizon (0-20 cm)		Subsurface horizon (around 50 cm)	
Property	BC30 min	BC24 h	BC30 min	BC24 h
Sand	-0.47***	-0.36**	-0.56****	-0.65****
Clay	0.47***	0.34**	0.63****	0.71****
Silt	-	-	-0.36**	-
Silt/Clay	-	-	-0.47***	-0.46***
OC	0.36**	-	0.31*	0.30*
P	0.47***	0.49***	-	-
Ca	0.31*	-	-	-
Mg	0.39**	0.3*	-	-
K	-	-	-	-
Na	-	-	-	-
TEB	0.31*	-	-	-
CEC	0.36**	-	-	0.32*
CECclay	-	-	-0.33*	-0.33*
BS	-	-	-0.54***	-0.47***
pH-H_2O	-	-	-0.62****	-0.51***
pH-KCl	-	-	-0.55***	-0.43**

Two tailed levels of significance: - $p \geq 0.1$; * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$; **** $p < 0.001$

The high correlation between the buffering capacity and the initial pH of the subsurface horizon confirms the fact that more acidic soils are better buffered than the less acidic ones. Magdoff and Bartlett (1985) and Godefroy and Dormoy (1990) have reported similar findings, namely that soils are poorly buffered between pH 4.5 and 6.5 and well buffered below pH 4. They further stated that soils are well buffered above pH 7. Since there are no profiles in this study with pH values exceeding this range, this could not be verified.

7.3.3 Risk for soil acidification in relation to landscape units and soil groupings

Results of the variance analysis of factors contributing to the changes in pH are presented Table 7.4. The factor 'Landscape unit', horizon 'Depth', quantity 'H^+ added', 'Time' and 'Soil groupings' contributed significantly to the model. However, as significant interactions were found between the factors 'Landscape unit', 'Depth' and 'H^+ added' on one hand and 'Soil groupings' on the other hand, the model was split into two new models containing four non-interacting factors each. Model 1 contained the factors 'Landscape unit', 'Depth', 'H^+ added' and 'Time' and Model 2 contained the factors 'Soil groupings', 'Depth', 'H^+ added' and 'Time'. In these models the factor 'Time' is less significant.

Table 7.4 Variance analysis of factors contributing to the changes in pH upon addition of H_2SO_4

Factor	F-value	Probability
Overall model		
Landscape unit	16.11	< 0.001
Depth	50.09	< 0.001
H^+ added	721.44	< 0.001
Time	8.61	< 0.01
Soil grouping	12.66	< 0.001
Landscape unit × Soil grouping	18.02	< 0.001
Depth × Soil grouping	8.85	< 0.001
H^+ added × Soil grouping	2.08	< 0.05
Time × Soil grouping	0.35	0.944
Model 1		
Landscape unit	35.14	< 0.001
Depth	44.09	< 0.001
H^+ added	250.00	< 0.001
Time	5.67	< 0.05
Model 2		
Soil grouping	48.42	< 0.001
Depth	64.76	< 0.001
H^+ added	822.03	< 0.001
Time	8.30	< 0.01

The results of the family of pairwise tests of the landscape units (Model 1) and of the soil groupings (Model 2) are presented in a line plot in Figure 7.2. On the left hand side, landscape units with least square means that do not differ ($p < 0.05$) are grouped together. Similarly, on the right hand side groups of 'Soil groupings' are presented. This analysis results in a ranking of landscape units (Model 1) and soil groupings (Model 2) in terms of their risk for soil acidification

After the addition of H_2SO_4, the Least Mean Square of the pH is the lowest for soil of the Makonde plateau (Group L_1, Figure 7.2) and highest for soils of the Inland plains (groups L_4 and L_5) Soils of the Piedmont are placed in both groups L_2 and L_3, which reflects the heterogeneity of the soils of this unit; soils are partly derived from sandy colluvium from the Makonde Plateau, partly from Precambrium Basement material. The Least Mean Square of the pH takes into account the initial pH as well as the intermediate and final values. The pH of a soil with either a low initial pH or a low buffering capacity has a higher risk of falling to a critical level, and in this analysis, this gets reflected by a low Least Square Mean of the pH. The higher risk for getting to critical pH levels on the Makonde plateau can be explained by the lower initial pH of these soils (Table 7.1, see also Table 8.1.

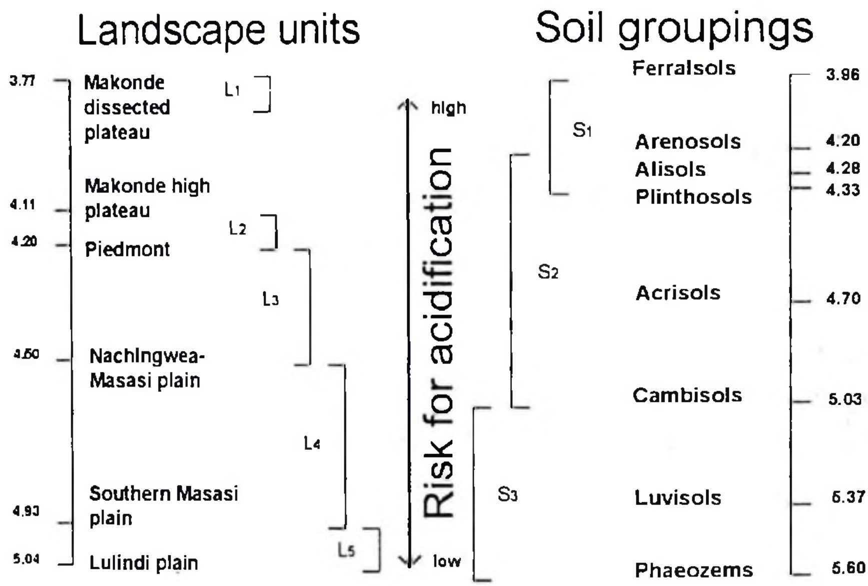


Figure 7.2 Ranking of landscape units and soil groupings based on significant differences ($p \leq 0.05$) between the least square means of the pH after addition of H_2SO_4 solution

A similar analysis applied to the soil groupings (Model 2) resulted in three groups (Figure 7.2), and reveals the complexity of the inland plains. Soils with the highest risk for soil acidification are *Ferralsols*, *Arenosols* (Group S_1) and *Alisols* and *Plinthosols* (Group S_1/S_2 in Figure 7.2). Light textured *Ferralsols* and *Arenosols* are typical for the Makonde plateau and its piedmont. But *Ferralsols*, *Alisols* and *Plinthosols* are also common in the plains. The soils with lowest risk for soil acidification, *Cambisols*, *Luvisols* and *Phaeozems* (Group S_3) which are typically found in the plains and had a higher initial soil pH (Table 7.1).

In both models there was a significant contribution of the factor 'Depth'. Buffering capacity of the subsurface horizon is usually better than that of the surface horizon, which has to be attributed to the greater clay content and a lower initial pH in most cases. In the surface horizon organic matter plays a relatively greater role as a sink for H^+.

7.3.4 Implications for soil management

Assuming that all sulphur dusted enters the soil, four years of dusting is likely to cause a pH decline between 0.3 and 3.1 pH units in the surface horizon and between 0.6 and 2.7 pH units in the subsurface horizon on the Makonde plateau (Figure 7.1). These pH changes are slightly higher than the field observations made by Majule *et al.* (1997) and Ngatunga *et al.* (1998) on cashew groves under S dusting for a period of 12 years. This is explained by the fact that direct acid application as was the case for the titrations has a much faster effect on soil pH. This is why the effect of a single dose of 90 kg S/ha is not expected to bring much effect on soil pH. However, the accumulative effect over several seasons of continuous S application on soils with low clay and organic matter contents and low initial soil pH, is likely to disturb growth and nutrition of annual food crops.

The negative effect of soil acidification depends on the tolerance to acidity of the crops being grown. The minimum, maximum and optimal pH values for the different crops are shown in Table 8.2 (Chapter 8). Crops like sorghum and millet with low tolerance are likely to suffer early. Cashew trees develop deep rooting systems and tolerate low pH levels; concerns for their long-term productivity seem justified when sulphur dusting has to proceed for many years.

As soils of the Makonde plateau have the highest risk for reaching critical soil pH levels, alternative approaches for controlling the powdery mildew disease are most pressing here. As long as resistant varieties are not widely available, the basic options are reducing the incidence of the disease by crop sanitary measures such as pruning and removal of diseased plant parts, or by using organic fungicides. Alternatively, the acidification effect of sulphur could be mitigated by liming. To neutralise 90 kg ha^{-1} of S, one would need about 200 kg ha^{-1} of $Ca(OH)_2$. Although this is locally available as burned coral lime, such quantities would be financially prohibitive for smallholder farmers and its widespread use would be detrimental to the marine environment. Fossil coral lime, available in the coastal plain and not exploited yet, would be a possible alternative.

Less sulphur would be needed and less lime would be required, if crop sanitary techniques as demonstrated by Kasuga *et al.* (1998) and Nathaniels (1998), would be widely adopted. This would require a large involvement of extension staff as these techniques imply farmers to understand aspects of the epidemiology of the disease. Water based organic fungicides have been proven effective for controlling powdery mildew disease (Smith *et al.*,1998) but these have the disadvantage of costing more than sulphur and of being more toxic to humans and animals (Tomlin, 1994). Moreover, they are applied in water which is scarce on the Makonde plateau.

7.4 Summary and conclusions

Buffering capacity of soils of 35 cashew groves was determined and the role of physio-chemical soil properties and implications of current sulphur use in cashew groves assessed. Clay content, organic carbon content and weathering status determine the buffering capacity of soils on which cashew trees grow. Buffering capacity was strongly and positively correlated with clay content and weakly with organic carbon content. The risk for severe acidification and for a decline in productivity of annual crops is highest on the Makonde plateau — where about 50 % of the cashew nuts from South Eastern Tanzania are produced. In the long run, acidification due to sulphur is likely to reduce the productivity of both cashew trees and annual crops. Further development and dissemination of techniques that can reduce the use of sulphur are therefore highly needed.

Chapter 8

Assessment of soil acidification from sulphur dusting in farmers' cashew groves in South Eastern Tanzania[1]

8.1 Introduction

In Tanzania, cashew nuts (*Anacardium occidentale* L.) are mostly grown by smallholder farmers. In 1998, cashew nut ranked second as the most important foreign exchange earning crop being exceeded only by coffee (Bank of Tanzania, 1999). Around 70% of the national production comes from the south-eastern part of the country (Martin *et al.*, 1997; Topper *et al.*, 1998c), where the Makonde plateau and the inland plains are the major cashew growing areas.

Powdery mildew disease (*Oidium anacardii*, Noack) is the main biological constraint to cashew nut production in Tanzania (Castellani and Casulli, 1981; Martin *et al.*, 1997). A large share of the yield decline from 145,000 ton in 1974, when Tanzania was the second world producer, to 16,500 ton in 1987 has been attributed to this disease (Shomari, 1996; Martin *et al.*, 1997). Low producer prices, poor marketing and abandonment of cashew groves due to the resettlement policy in mid 1970s also contributed to the decline (Poulton *et al.*, 1997).

In the early 1980s, sulphur was identified as an effective agent against the powdery mildew disease and its widespread use contributed to the recovery of the cashew nut industry (Topper *et al.*, 1998b). The standard recommendation is to dust 1.25 kg of sulphur per tree per season. It is applied with motorised blowers in four to five applications, the first application coinciding with the initiation of flower buds. If trees are not treated, flower buds, flowers, young leaves and young shoots are attacked by the mildew resulting in poor harvest and inferior nut quality (Shomari, 1996). Smith *et al.* (1998) reported, however, that up to 78% of the sulphur drifts away from the tree. When sulphur gets to the soil, under moist aerobic conditions it gets oxidised into sulphuric acid by autotrophic bacteria (Brady, 1990). For every sulphur atom, two hydrogen ions

[1] Based on the paper Ngatunga EL, Dondeyne S and Deckers JA (2001) "Is sulphur acidifying Cashew soils of South Eastern Tanzania?" submitted to Agriculture, Ecosystems and Environment in the Netherlands in March 2001.

are fonned which may result in a lowering of the soil pH. This raises the concern that prolonged use of sulphur may affect the production of cashew nuts as well as of intercrops such as cassava, maize, sorghum, cowpea and finger millet. These crops are very important for the food security of the people in cashew growing areas.

In a case study of five cashew groves, Majule *et al.* (1997) reported that the use of sulphur in South Eastern Tanzania indeed acidifies the soils and argued that its use is not sustainable. To date sulphur dusting has been adopted by about 60 % (Kasuga, personal communication) of cashew nut farmers. However, little is known on the extent and magnitude of the problem. The objective of this study was to assess the geographical extent and severity of the acidification in farmers' cashew groves.

8.2 Materials and methods

8.2.1 Location and selection of sites for the pH survey

This study was confined to the Makonde plateau and Inland plains. These landscape units are the major cashew growing areas of South Eastern Tanzania. Details of selection of the villages for the pH survey are given in Chapter 4. Locations of the 70 cashew growing villages where the pH survey where conducted are shown in Figure 4.1.

8.2.2 Field survey and analysis of soil samples

The pH survey was conducted from October 1996 to December 1997 in 31 cashew growing villages on the Makonde plateau and 39 villages in the Inland plains. In each village a cashew nut grove was sampled where farmers had applied sulphur following the standard recommendations. Samples of the topsoil (0-20 cm) and subsoil (20-40 cm) of each grove consisted of bulked sub-samples taken under four trees and at a one-meter interval from the tree trunk towards the end of the canopy. For comparison, a nearby, similar cashew grove was sampled where sulphur had never been used. The samples were air-dried, crushed and passed through a 2-mm sieve, after which the pH was measured in a 1:2.5 soil distilled water suspension with a Glass Calomel electrode pH meter. The number of years farmers had used sulphur on the concerned grove was obtained through informal interviews.

8.2.3 Data analysis

As the data was not normally distributed, Wilcoxon signed ranks tests were used to verify whether sulphur had acidified the soils. This is the non-parametric equivalent of the paired t-test

(Dytham, 1999). Regression analysis and the boundary line technique (Walworth *et al.* 1986; Sumner, 1987) were used to investigate and interpret the effect of the duration of sulphur use.

8.3 Results and Discussion

Summary statistics and results of the Wilcoxon signed ranks test are presented in Table 8.1. Overall the soil pH of the topsoil and subsoil of dusted cashew groves is lower than of the undusted groves. Separating the data according to landscape units, showed that this is however only valid for soils of the Makonde plateau and not for those of the inland plains. As could be expected, the effect is stronger for the topsoil than for the subsoil. Moreover, soil pH on the Makonde plateau, of both dusted and undusted groves, is lower than of those from the inland plains. As demonstrated in Chapter 7, the risk for soil acidification of cashew growing soils of the Makonde plateau is higher than of those of the Inland plains. The high risk is due to low initial soil pH, high sand content and low organic matter of soils on the Makonde plateau. Soils of the Inland plains seem thus to have neutralised the acidity released by the sulphur.

Table 8.1 Summary statistics of soil pH from 70 sulphur dusted and 70 undusted farmers' cashew groves of South Eastern Tanzania

		Sulphur dusted groves			Non sulphur dusted groves			P-value*
		Mean pH	Sd	n	Mean pH	sd	n	
Overall	topsoil	5.50	0.71	70	5.62	0.73	70	< 0.01
	subsoil	5.46	0.73	70	5.53	0.72	70	0.08
Plateau	topsoil	4.88	0.40	31	5.10	0.50	31	< 0.01
	subsoil	4.83	0.46	31	4.96	0.51	31	0.03
Plain	topsoil	5.98	0.40	39	6.03	0.45	39	0.38
	subsoil	5.96	0.46	39	5.99	0.50	39	0.71

sd standard deviation n number of groves

*Wicoxon signed ranks test

The effect of duration over which sulphur has been used is apparent from Figure 8.1. On the Makonde plateau, pH seems to decline over time, while this is not the case for soils of the inland plains. Although the regression lines, for the case of the Makonde plateau, seem to be significant, the R-squares are very low. It seems that there are other factors that facilitate the process of soil acidification from sulphur use, which are not accounted for by the regression model. Removal of biomass is one of the factors as demonstrated by Van Breemen *et al.* (1984) and Majule (1999).

This can be through harvesting of nuts and apples but also through weeding, done to ease the harvesting of cashew nuts. Sakala (1998) and Majule (1999) also showed that addition of organic matter has a neutralising effect.

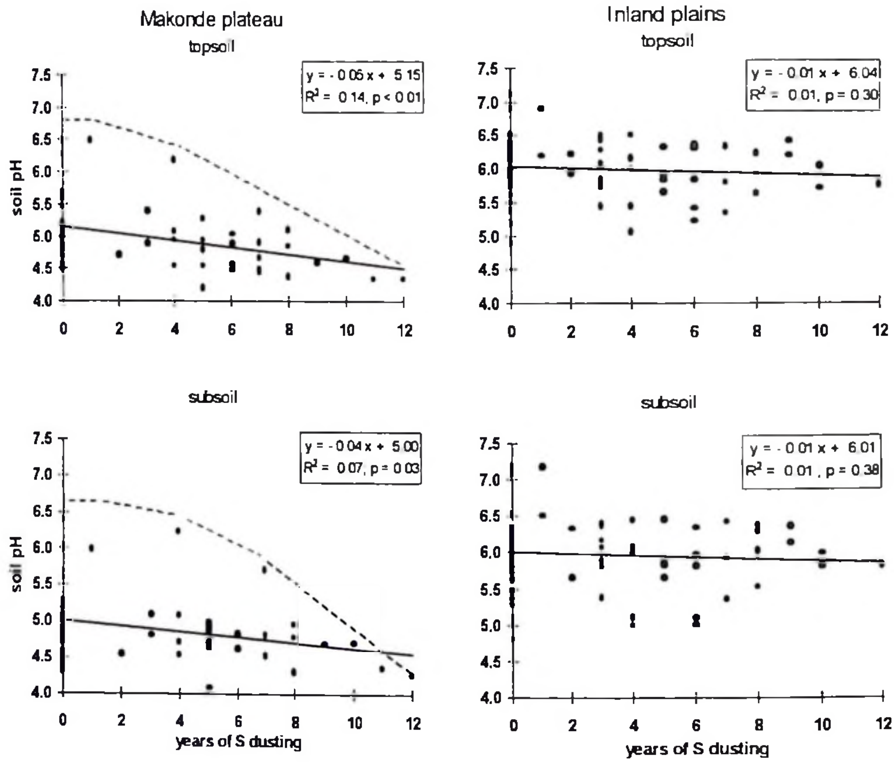


Figure 8.1 Relationship between years of sulphur use and soil pH of 140 cashew groves

Regression analysis, however, is not well suited to these data, as it requires the independent variables to be measured without error. As the duration of sulphur use was based on farmers' reports, this assumption cannot be guaranteed. Furthermore, the pH values are not normally distributed. This is linked to the fact that the measurements were made in farmers' groves, hence where other acidifying factors were out of the researchers' control. The boundary line (Figure 8.1) is therefore used to interpret the results. It defines a cloud of points representing all possible field situations. Combinations beyond the boundary line are deemed impossible. The variability of the pH is clearly large when sulphur has only been used for a small number of years, or not at all. but with increasing years of sulphur use the variability decreases sharply. This indicates that with time the acidifying effect of sulphur dominates processes that could neutralise the acidification On the Makonde plateau, 12 years of sulphur use resulted in a soil pH of around 4.5 As the optimum pH range for the cashew tree is between 4.5 and 6.5 (FAO, 1994), effects on the cashew nut production may not yet be noticeable, but effects on more sensitive intercrops such as sorghum, maize and finger millet can be expected So far, on the inland plains pH seems to have remained stable around 6, which is perfectly suitable for the growth of most crops.

The negative effect of soil acidification depends on the tolerance to acidity of cashew and the annual crops intercropped with it. The minimum, maximum and optimal pH values for the different crops are shown on Table 8.2. Cashew and pineapples are relatively tolerant to low pH values. Damage caused by soil acidification should first be felt by crops like millet and sorghum. The relation between the critical pH values (Table 8.2) and pH values measured in the laboratory needs some care as field pH can be very variable. Long-term pH measurements are needed to establish reliable relationships.

Table 8.2 Minimum, maximum and optimal pH values for cashew and its intercrops

Crop	Minimum pH	Optimal minimum pH	Optimal pH	Optimal maximum pH
Cashew	3.8	4.5	6.5	8.7
Cassava	4.0	6.0	6.5	8.2
Cowpea	4.3	5.5	7.5	8.8
Maize	4.5	5.0	7.0	8.5
Millet:Sorghum	5.2	6.0	6.5	8.2
Pigeon pea	4.5	5.0	7.0	8.4
Pineapple	3.5	4.5	6.5	8.0
Pumpkin	4.5	5.5	7.5	8.3

Source: FAO. 1994)

As shown in Chapter 7. the soil pH of the Makonde plateau might only level out at around 4.0. Continuing the use of sulphur according to the standard recommendations will likely affect the cashew nut production. Alternative approaches for controlling powdery mildew disease are therefore required. Liming, use of organic fungicides and crop husbandry techniques which reduce the incidence of the disease are the basic options as long as resistant varieties are not widely available.

Soil acidification can be neutralised by importing into the acidified cashew groves an equivalent amount of bases and organic matter. This needs research to determine the amount of lime required for the different soil types and acidification levels of the groves. Although this is locally available as burnt coral lime collected along the seashore within the study area, such quantities would be financially prohibitive for smallholder farmers and its widespread use would be detrimental to the marine environment. Fossil lime, also available in the coastal plain and not exploited yet, would be a better alternative.

As indicated in Chapter 7, amount of sulphur used could greatly be reduced if cultural practices were used to suppress incidences of powdery mildew. The water based organic fungicides proven effective for controlling powdery mildew disease (Smith *et al.*, 1998) can also be used but have the disadvantage of costing more than sulphur and of being more toxic to humans and animals (Tomlin, 1994). Moreover, they are applied in water which is scarce on the Makonde plateau. A systems approach involving breeding for resistant clones, cultural practices to reduce disease innoculum, use of non-pollutant and less toxic fungicides and adoption of soil amendments is required.

8.4 Summary and conclusions

Soil pH of topsoil (0-20 cm) and subsoil (20-40 cm) of 70 farmers' cashew groves, where farmers had applied sulphur for up to 12 years, was compared to similar undusted groves. The soil pH of sulphur dusted groves on the Makonde plateau was significantly lower than undusted groves. For cashew groves of the Inland plains, no significant effect could be established. Soil pH on the Makonde plateau decreased with increasing years of sulphur use while it remained stable in the Inland plains. This is explained by the higher risk for acidification of soils on the Makonde plateau compared to soils of the Inland plains. While the acidification has not yet affected cashew nut production on the Makonde plateau, critical pH levels for some of annual crops intercropped with cashew such as sorghum and maize have been reached. Measures to mitigate the effect of sulphur, such as liming, reducing the incidence of powdery mildew by cultural practises or by using organic fungicides are most pressing on the Makonde plateau.

Chapter 9

Effect of sulphur application on seed germination and grain yield of maize, sorghum and cowpeas in South Eastern Tanzania[1]

9.1 Introduction

Cashew groves in South Eastern Tanzania are often intercropped with a complex mixture of annual crops (Bennett *et al.*, 1979; Martin and Kasuga, 1998). The number of crops and the pattern of cropping depend on the type of soil or food security requirement (Martin *et al.*, 1997). Intercropping is usually practised in young cashew groves, however, old cashew trees can also be intercropped in areas with a shortage of land for annual crops (as in parts of Newala district) or where tree size is small (as in Masasi and Tunduru districts). The most common crops, in order of preference, are cassava, maize, cowpea, sorghum, pigeon pea, bambaranut, upland rice and groundnuts. Annual food crops make an important contribution to the income and food security of many households in cashew growing areas. Cassava, sorghum and maize are the staple crops while cowpeas, pigeon peas and bambaranuts are used as a source of proteins and for relish. Intercropping annual crops with cashew is an important practice as it assures good field sanitation to the cashew trees due to regular weeding of the annual crops (Bennett *et al.*, 1979).

Since mid 1970's, cashew groves have been seriously attacked by powdery mildew disease (*Oidium Anacardii* Noak) (Sijaona, 1997). In order to sustain yield of cashew nuts, the disease is being controlled by dusting cashew trees with elemental sulphur dust at the rate of 1.25 kg S/tree per year equivalent to 90 kg S/ha/year. With this chemical control, large increases in nut yield in farmers' cashew groves are being realised (Martin *et al.*, 1997). While powdery mildew is being controlled and cashew yields are improving, soil acidification is taking place (Majule *et al.*, 1997; Ngatunga *et al.*, 1998). However, less attention is paid to the risk sulphur dusting can bring to growth and production of annual crops. Not adequately investigated are the long-term effects on soils and less acid tolerant annual crops.

[1] Based on the paper Ngatunga EL, Dondeyne S and Deckers JA (2001) "Effect of sulphur application on seed germination and yield of maize, sorghum and cowpeas in South Eastern Tanzania" submitted to the African Crop Science Journal in June 2001.

Once applied into soils, sulphur is oxidised by bacteria of the genus *Thiobacillus* to sulphuric acid (H_2SO_4) (Tisdale and Nelson, 1975; Blair, 1988). The acid affects plant growth directly through release of toxic aluminium ions which severely restrict plant growth (Brenes and Pearson, 1973; Alva *et al.*, 1986; Cameron *et al.*, 1986; Martinez and Estrella., 1996). In acidic soils, aluminium and hydrogen ions replace exchangeable bases from the exchange sites rendering them liable for leaching prompting deficiencies of bases. There are also the indirect effects of phosphate fixation as soluble iron and aluminium phosphate (Shen *et al.*, 1998). Solubility of divalent cations like manganese and molybdenum induced under acidic conditions may prove toxic to some plant species.

Smith *et al* (1995) have shown that 80 % of the 90 kg S ha^{-1} dusted on cashew trees drifts away from the trees. In absence of wind and sheet erosion, this amount ultimately falls on soils. Although sulphur is an essential nutrient for plant growth, studies of its agronomic requirements indicate that most annual crops require less than 50 kg ha^{-1} per season (Eriksen, 1997). There are, however, exceptional crops such as cabbage and rapeseed that require over 50 kg S ha^{-1} per season (Kemmler and Hobt, 1987).

The objective of this study is to assess the effect of sulphur on the germination and grain yield of maize, sorghum and cowpeas in major cashew growing areas in South Eastern Tanzania.

9.2 Materials and Methods

9.2.1 Location of experimental sites

Field trials for investigating the effects of sulphur on annual crops were conducted at Naliendele (latitude 10^0 21' S; longitude 40^0 11' E, 120 m asl) and Mtopwa (latitude 10^0 37' S; longitude 39^0 23' E, 585 m asl) on the Makonde plateau and Mkumba (latitude 10^0 19' S; longitude 38^0 46' E, 383 m asl) in the Inland plains (Figure 4.1). These locations were selected in view of their ecological representativeness of cashew growing areas in South Eastern Tanzania and on security considerations, as they are accessible through and monitored by agricultural experimental stations. Description of the soils and climate of the experimental sites are given in Chapter 4.

9.2.2 Experimental design

Three separate randomised block experiments were conducted at the three sites for maize, sorghum and cowpeas during growing seasons of 1996/97 (season I), 1997/98 (season II) and 1998/99 (season III). Prior to land preparation, fallow vegetation (shrubs and grass) was cut down and burnt The experimental blocks were hand-hoed (to approximately 5-10 cm). Each plot measured 5.4 m × 4 5 m and was separated from each other by a 2-m path to avoid contamination of sulphur from one plot to the other during heavy rainstorms.

9.2.3 Sulphur treatments

Sulphur was applied at the rate of 0, 60, 90, 120, 180 and 240 kg ha^{-1}. Each treatment was replicated four times. The rate of 90 kg S ha^{-1} simulated the amount of sulphur used by farmers for dusting cashew trees to protect them against powdery mildew disease. Rates of sulphur of 90-kg ha^{-1} and above were included for checking long-term effects on production of the test crops within the duration of the study. Sulphur was applied very early in the morning in order to escape wind drift as farmers do during sulphur dusting of the cashew trees. Soon after application, plots were raked to incorporate sulphur into the top 5 cm of the soil.

Maize (variety Staha) was planted at a spacing of 75 cm x 30 cm while sorghum (variety Tegemeo) was sown at 15 cm × 60 cm and cowpeas (variety Tumaini) at the spacing of 60 × 15 cm. Choice of variety and spacing was based on recommendations of the agricultural authorities in Tanzania for low to medium altitude (0-1000 m) areas. For basal fertiliser dressing maize plots received 40 kg N ha^{-1} (urea) and 30 kg P_2O_5 ha^{-1} (Triple Super Phosphate), sorghum 30 kg N ha^{-1} and 30 kg P_2O_5 ha^{-1} and cowpeas 30 kg P_2O_5 ha^{-1}. Crop yield was expressed in kilograms per hectare after adjusting for 12 % moisture content. Germination counts (number of planting hills without germination) were recorded one week after seeding during the second and third seasons.

9.2.4 Determination of soil pH, exchangeable bases and aluminium

Soils were sampled (0-20 cm) annually before planting and at harvest from plots of replicate 2 of the maize experiment. Samples were analysed for soil pH and contents of calcium, magnesium and aluminium. Soil pH was measured potentiometrically using a Glass Calomel electrode in a 1:2.5 suspension of water (H_2O) and in potassium chloride (1M KCl). Calcium and Magnesium were first extracted with 1M NH_4OAc followed by analysis with Atomic Absorption Spectrophotometer (AAS). To determine exchangeable acidity, 10 g of soil sample was shaken with KCl and filtered and then titrated with 0.1M NaOH. A blank titre was carried out with NaOH alone. Exchangeable acidity is calculated from the relation: - ml NaOH sample - ml NaOH blank. H^+ was separately determined and Al^{3+} obtained by subtraction.

9.2.5 Crop data analysis

Analysis of variance (ANOVA) was performed on grain yield using the General Linear Model (GLM) procedure of SAS (PC-SAS, 1988). Least significant differences (Duncan) were used for comparing treatment effects on the parameters studied. Since the purpose of the experiment was to find the effect of sulphur on the crops per site, ANOVA was done per site and crop for the three seasons.

9.3 Results

9.3.1 Effect of sulphur on maize grain yield

Summary of ANOVA for maize grain yield is presented in Table 9.1. Results show there were no significant effects due to sulphur application at all the sites during the first growing season. There were, however, grain yield differences due to site and season (Figure 9.1). Highest yield was obtained at the Mkumba site (1700-2000 kg ha^{-1}) and lowest at Naliendele (700 - 900 kg ha^{-1}). Site differences in yield are due to variation in soils and rainfall (Table 4.1 Chapter 4). Naliendele (located near the coast) and Mtopwa (on the Makonde plateau) have higher long-term rainfall amounts than the Mkumba site located in the Inland plains. However, the former two sites have sandy and chemically poor soils prone to drought. Rainfall distribution rather than amount is therefore very important at Naliendele and Mtopwa.

Table 9.1 Summary of statistical analysis of maize grain yield

Crop	Location	Season			CV (%)
		I	II	III	
Maize	Naliendele	Ns	**	***	28.4
	Mtopwa	Ns	*	**	28.1
	Mkumba	Ns	*	Ns	30.6

ns not significant * significant at $P \leq 0.05$; ** significant at $P \leq 0.01$;

*** significant at $p \leq 0.001$, CV coefficient of variation

There was a big decline in maize yield as of season II (1997/98) which was attributed to above average rainfall from the effect of El-Niño in that season (Figure 4.1 Chapter 4) and partly to the build up of sulphur effects. Maize yields in season II declined from 500 kg ha^{-1} in the no sulphur plots to 100 kg ha^{-1} in the 240 kg S ha^{-1} at Naliendele and Mtopwa and 150 kg ha^{-1} at Mkumba. The decline was more pronounced at Mkumba. Soil erosion at the Mkumba experimental site (with 8-10 % slope) enhanced the differences. Despite the heavy rains experienced during the season, application of sulphur resulted in differences in maize grain yield at all sites. Negative effect of sulphur levels became prominent in seasons II for Naliendele and Mtopwa for sulphur rates 180 and 240 kg ha^{-1}. During the third season there were significant grain yield differences only at Naliendele and Mtopwa. Maize grain yield from sulphur treatments 180 and 240 kg ha^{-1} declined by 40 and 70 % respectively from the control (without sulphur) treatment. Although there was a negative trend, sulphur application had no significant effect on yield at Mkumba.

The general trend in decreasing crop yield with season at all the experimental sites is attributable to deterioration of chemical and physical soil fertility since these areas were formerly under fallow. When fallow land is brought into cultivation, structural stability declines fast and therefore the ability to retain soil moisture and nutrients is also reduced (Van Reuler, 1996).

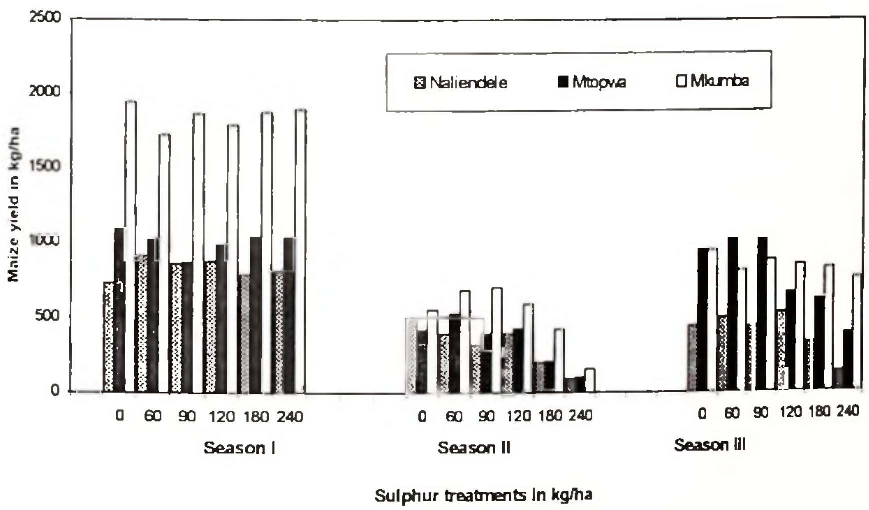


Figure 9.1 Maize grain yield (kg ha^{-1}) during the study period

9.3.2 Effect of sulphur on sorghum grain yield

Table 9.2 presents the summary of ANOVA for sorghum for the three sites. Results indicate that during season 1, there were no significant effects due to sulphur application at all the sites. As for maize grain yield, there were big differences in sorghum yield among the sites. Highest yield was obtained at the Mkumba site (2300-2500 kg ha^{-1}) and lowest at Naliendele (500 - 600 kg ha^{-1}). In season II sorghum grain yield declined drastically (Figure 9.2). As explained above for maize, South Eastern Tanzania experienced above average rainfall that interfered with the normal growth and production of the crops. This decline could also be due to the general decline of soil fertility (leaching and loss through drainage of nutrients). Negative effect of sulphur occurred at Naliendele and Mtopwa with rates of 120 kg ha^{-1} and above while for Mkumba as of 180 kg S ha^{-1} and above. During the third season there were significant grain yield differences effects at all sites. Sorghum grain yield from sulphur treatments 180 and 240 kg ha^{-1} declined to less than 10 % of the control (without sulphur) treatment.

Table 9.2 Summary of statistical analysis of sorghum grain yield

Crop	Location	Season			CV (%)
		I	II	III	
Sorghum	Naliendele	ns	**	***	30.5
	Mtopwa	ns	**	***	31.5
	Mkumba	ns	*	*	35.7

ns not significant * significant at P ≤ 0.05; ** significant at P ≤ 0.01, *** significant at P ≤ 0.001
CV coefficient of variation

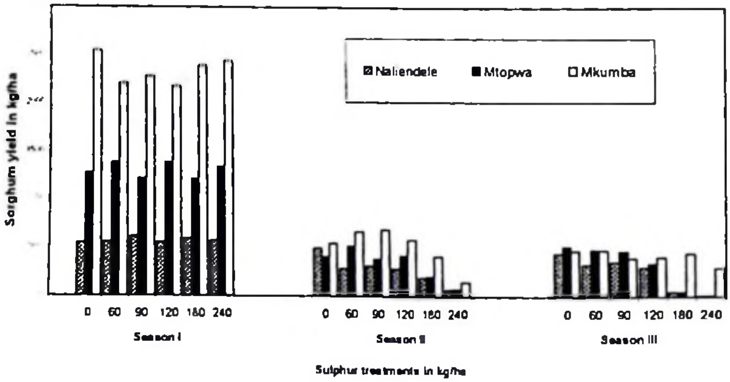


Figure 9.2 Sorghum grain yield (kg ha^{-1}) during the study period

9.3.3 Effect of sulphur on cowpea grain yield

The summary of the ANOVA for cowpea grain yield during the study period is presented in Table 9.3. Results for season I indicate that there were no significant effects due to sulphur application at all the sites. Data shows that there were large differences in cowpeas yield among the sites attributed mainly due to variation in soils and rainfall. Highest yield was obtained at the Mkumba site (100-1800 kg ha^{-1}) and lowest at Naliendele (600 - 700 kg ha^{-1}) (Figure 9.4).

Table 9.3 Summary of statistical analysis of cowpeas grain yield

Crop	Location	Season			
		I	II	III	CV (%)
Cowpeas	Naliendele	ns	ns	*	35.2
	Mtopwa	ns	ns	Ns	30.1
	Mkumba	ns	ns	Ns	28.7

ns not significant * significant at $P \leq 0.05$;

CV coefficient of variation

In season II cowpea grain yield declined at all the sites due to above average rainfall that season. There were no treatment differences (Figure 9.3). During the third year, significant treatment differences were obtained only at Naliendele. Cowpea grain yields from treatments 180 and 240 kg S ha^{-1} treatments were reduced by 30 % and 40 %, respectively. Large across site variation in cowpea grain yield was attributed to differences in soil properties and rainfall. Despite higher rainfall amont at Naliendele and Mtopwa, these sites have soils with low moisture retention capacity due high sand content compared to soils at Mkumba with soils containing high clay content.

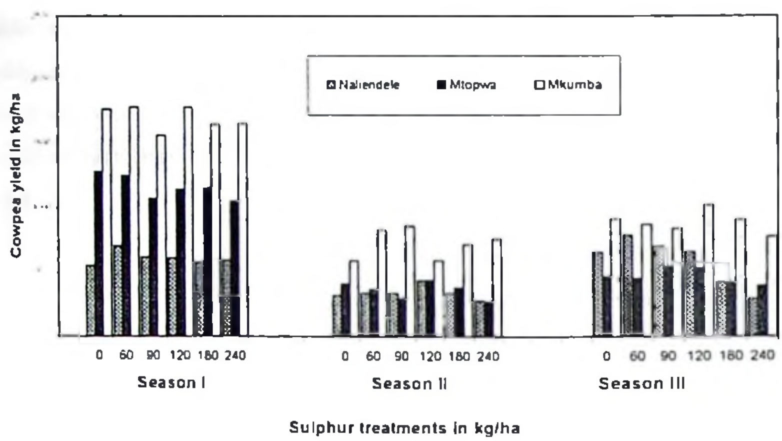


Figure 9.3 Cowpea grain yield (kg ha^{-1}) during the study period

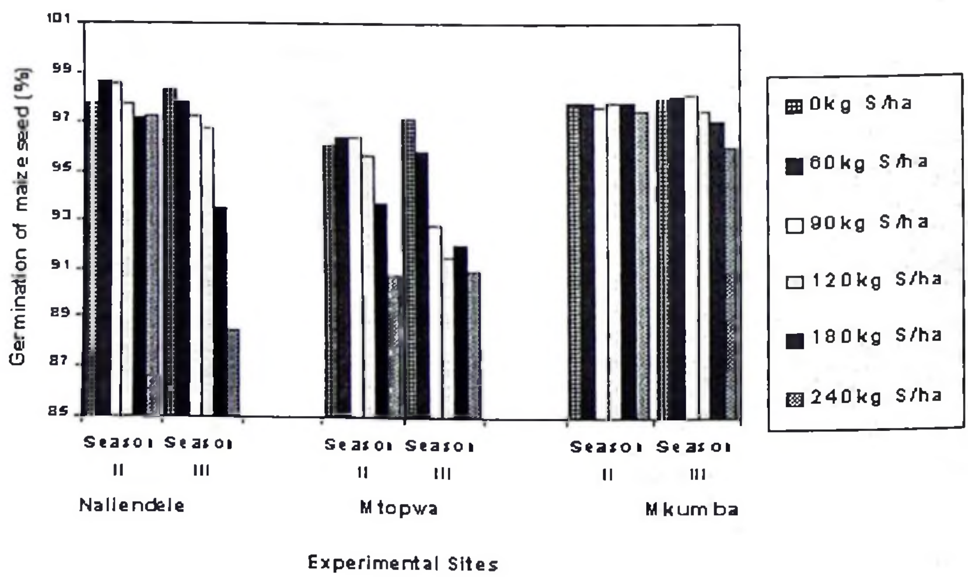


Figure 9.4 Effect of sulphur application on the germination of maize

9.3.4 Effect of sulphur on seed germination

Summary of ANOVA for percentage germination for years 1998 and 1999 for maize, sorghum and cowpea seeds is presented in Table 9.4. There was a significant reduction in percent germination of maize seed for the 1999 season at Naliendele and for both seasons at Mtopwa. Sulphur had no effect on maize germination at Mkumba. Reduction in percent germination for sorghum was significant for all the seasons and sites. The effect of S on cowpea seed germination was more pronounced at Naliendele than at Mtopwa. There was a trend in reduction of percent germination of cowpea at Mkumba but it was not significant.

Table 9.4 Summary of statistical analysis of germination of maize, sorghum and cowpea

Site	Year	Crops		
		Maize	Sorghum	Cowpea
Naliendele	1998	ns	**	*
	1999	**	**	**
Mtopwa	1998	**	**	*
	1999	**	**	*
Mkumba	1998	ns	**	ns
	1999	ns	**	ns

ns not significant * significant at $P \leq 0.05$; ** significant at $P \leq 0.01$;

Germination percentage (%) for maize, sorghum and cowpeas seed for seasons II and III are presented in Figure 9.4-9.6. Germination of maize seed was significantly lower than control for sulphur treatments 180 and 240 kg S ha^{-1} treatments at Naliendele and Mtopwa. Variation in seed germination was not significant at Mkumba. Sulphur application had a serious negative effect on sorghum seed germination beginning with sulphur treatment 120 kg ha^{-1}. The effect was more pronounced at Naliendele and Mtopwa than at Mkumba. While there was no reduction in cowpea seed germination at Mkumba, both Naliendele and Mtopwa recorded reductions in cowpea seed germination. These results show that application of sulphur to the soil causes serious reduction in the germination of sorghum and maize seed attributable to low soil pH.

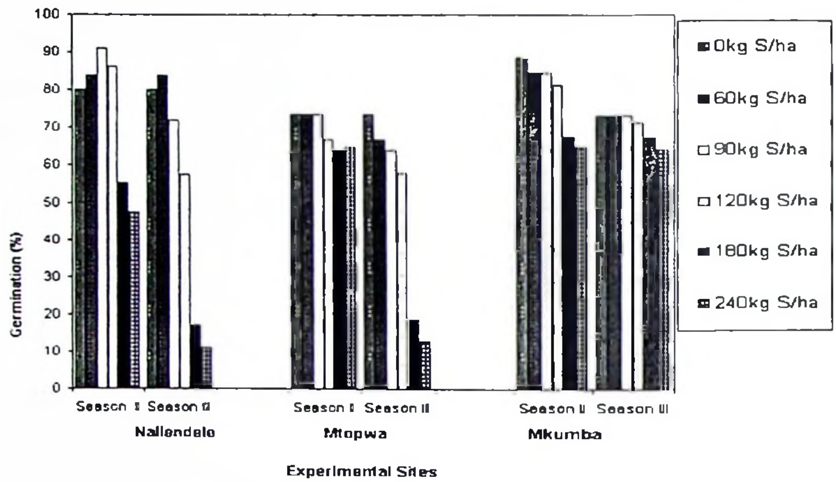


Figure 9.5 Effect of sulphur application on the germination of sorghum

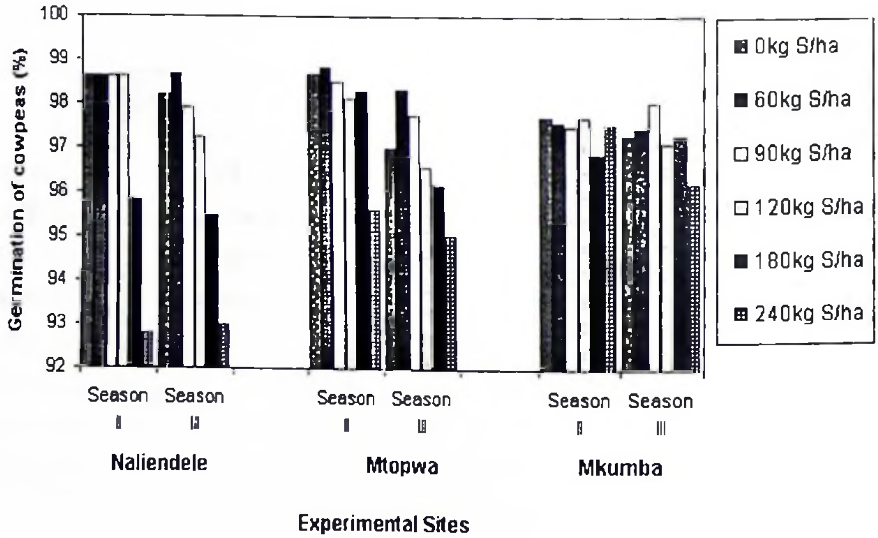


Figure 9.6 Effect of sulphur application on the germination of cowpeas

9.3.5 Effect of sulphur application on soil pH, exchangeable bases and aluminium

Soil analysis results are presented in Figure 9.7 - 9.10. Data in Figure 9.7 indicates that soil pH decreased with levels of sulphur, however, the decrease was very pronounced for Naliendele and Mtopwa. The lowest pH recorded at Naliendele was 4.2 while at Mtopwa it was around 4.4. The lowest soil pH at Mkumba was above 5.6.

The contents of calcium and magnesium, which decreased with increased application of sulphur, were lowest at Naliendele and Mtopwa and highest at Mkumba (Figure 9.8 – 9.9). This is due low level of these elements in the parent material of the soil at Naliendele and Mtopwa. Changes of aluminium with application of sulphur are shown in Figure 9.10. The content of Al increased as the rate of sulphur increased. Unlike calcium and magnesium, the content aluminium was higher at Naliendele and Mtopwa and than at Mkumba.

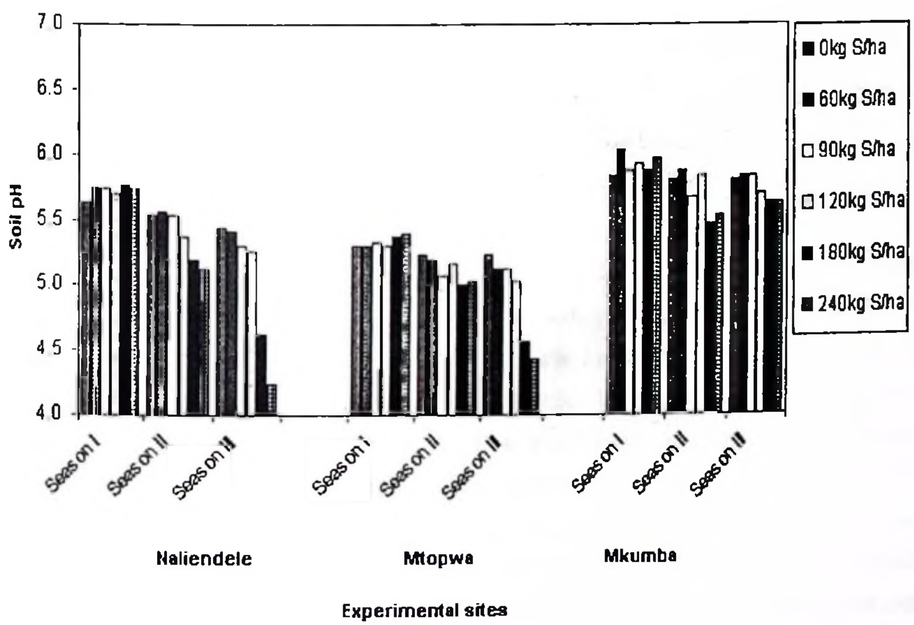


Figure 9.7 Effect of sulphur on soil pH during the study period

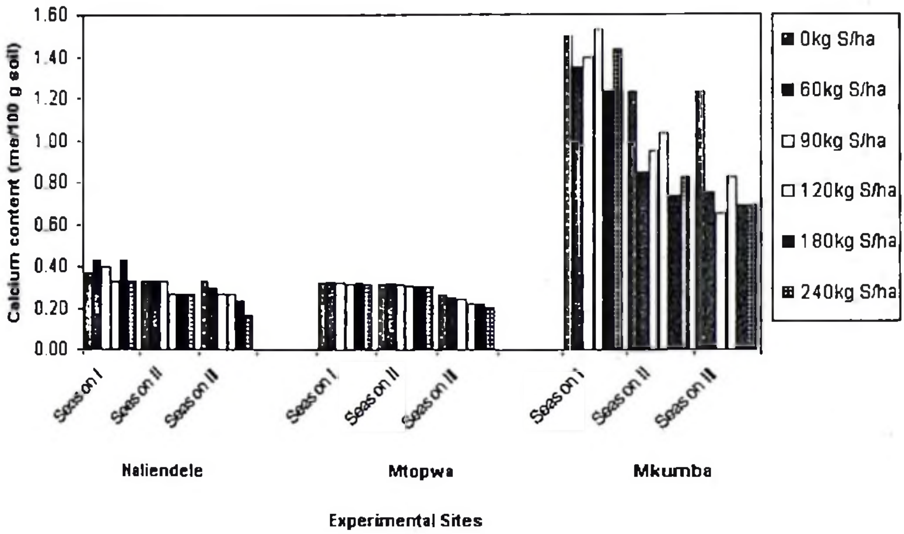


Figure 9.8 Effect of sulphur on calcium content during the study period

9.4 Discussion

The effect of sulphur on maize yield varied from site to site. The variation in yield was highest at Naliendele and lowest at Mkumba (Figure 9.1). The slight differences in S response between Naliendele and Mtopwa could be due to differences in clay content and buffering capacity (Table 7.1 and 7.2 Chapter 7). The clay content in subsoil at Mtopwa is higher than at Naliendele (Table 4.1 Chapter 4) and based on the studies of Beniamino (1991) , high clay content improves buffering capacity of soils. High clay content also ensures supply of moisture during times of dry spells typical in the study area. There was also a liming effect at Mtopwa originating from slash and burn of existing secondary vegetation (Van Reuler and Jansen, 1993; Van Reuler, 1996) at onset of the experiment. This effect of slash and burn was marginal at Naliendele since the quantity of vegetation was small. The absence of effect of sulphur application on maize at Mkumba contrasts with the other two sites. The reason is that soils at Mkumba have higher base status. moderate OM content, high clay content and soil pH is close to neutral (Table 4.1 Chapter 4), all properties which contribute to improved soil buffering capacity and good soil suitability for maize production The overall effect of sulphur use indicates negative effect on sorghum and maize for Naliendele and Mtopwa and none for Mkumba.

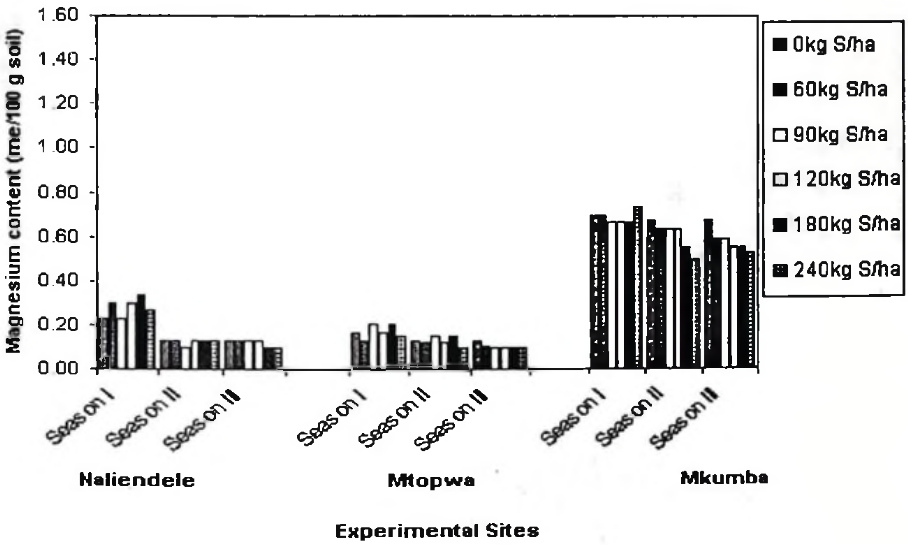


Figure 9.9 Effect of sulphur on magnesium content during the study period

The effect of sulphur on sorghum yield was more severe than that of maize particularly for Naliendele and Mtopwa (Figure 9.2). For example, while the negative effects of sulphur on maize at Naliendele and Mtopwa were prominent at sulphur rates of 180 kg S ha^{-1} and above, the effect for sorghum was prominent at 120 kg S ha^{-1} and above. During the third season, sorghum yield was below 50-kg ha^{-1} in the sulphur treatments at Naliendele and Mtopwa. The performance of Naliendele and Mtopwa which are representative of the Makonde plateau can be explained on the basis of soil properties as has been shown above for maize. The two sites have low soil pH values and other soil chemical properties (Table 4.1 Chapter 4). These results show clearly that with continued sulphur use, sorghum production may become impossible.

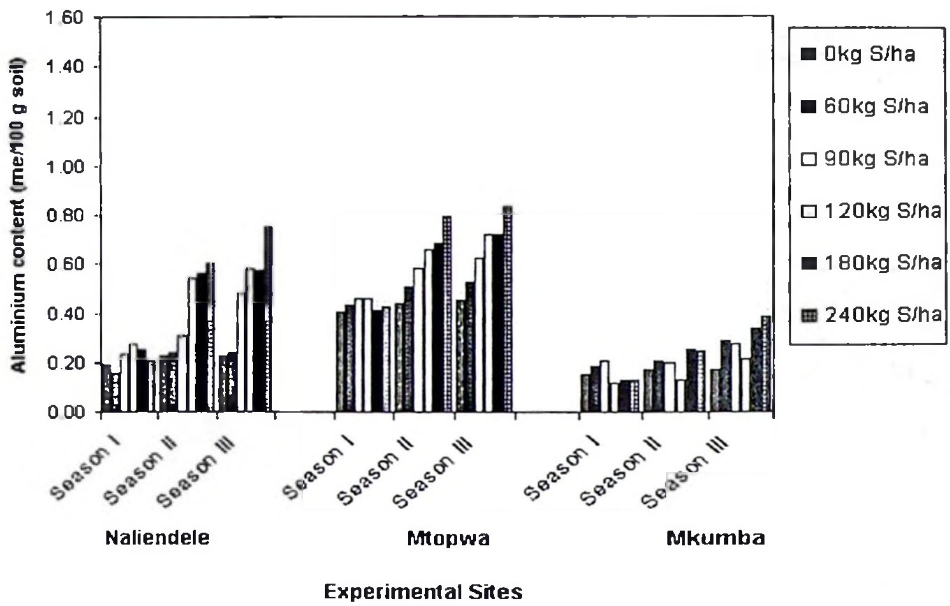


Figure 9.10 Effect of sulphur on aluminium content during the study period.

Cowpeas responded quite differently to sulphur application. Significant grain yield reduction was only observed at Naliendele during the third season (Table 9.3, Figure 9.3). Since the rates of sulphur application were the same for the three sites, this implies that cowpeas are either moderately acid tolerant or they have a high requirement for sulphur. Late response to S at Naliendele reflects high S requirement for cowpeas in comparison to sorghum and maize, confirming the findings of Pasricha and Fox (1993) and Fox *et al.* (1977) that cowpeas have a high S requirement. High S requirement for cowpea has also been demonstrated by Laurence *et al.* (1976) in Malawi where soil applied S not only produced kernels of better size but also of good quality than untreated samples. Unlike sorghum and maize, cowpea develops a taproot that facilitates escape from the effect of strongly acidified surface soils. Similarly, cowpea residues being rich in bases and organic matter may have accounted for better buffering than residues of sorghum and maize.

A significant reduction of seed germination particularly of maize and sorghum were observed in treatments with 120, 180 and 240 kg S/ha (Figures 9.4 - 9.5). The effect was more pronounced at Naliendele and Mtopwa than at Mkumba and was attributed to differences in pH and contents of base cations and aluminium (Table 4.1 Chapter 4; Figures 9.7 - 9.10). These results show that maize and sorghum seeds are sensitive to pH during germination. At both Naliendele and Mtopwa, soils appear to be poorer in buffering against sulphur compared to soils of Mkumba where soil pH is high and contents of base cations and clay are in moderate amounts (Table 4.1 Chapter 4). The high seed germination percentage at Mkumba is attributed to higher soil pH than the other two experimental sites.

The declining trend in soil pH as sulphur levels increase indicates that sulphur acidifies soils of the study area. This decline in pH is the main cause for the decreasing seed germination and crop yield for the test crops. Soil applied sulphur results in a fast reaction, however, in the field where sulphur is dusted onto canopies of trees reaction takes time. As observed in Chapter 8 (Figure 8.1) it has taken a decade for 90 kg sulphur dusted on trees to cause pH reduction in sandy and highly weathered soils on the Makonde plateau. As this has not been the case for the Inland plains, soil conditions play an important role in determining how long it takes to acidify soils.

9.5 Summary and conclusions

Effects of soil application of different levels of sulphur on germination and grain yield of maize, sorghum and cowpeas were assessed at three sites representing major cashew growing areas in South Eastern Tanzania. Sulphur acidified soils and the resulting acidity affected both germination and yield of the test crops. Negative effects on germination and yield of sorghum and maize occurred beginning the second growing season for rates above 120 kg S ha^{-1} for sorghum and 180 kg S ha^{-1} for maize indicating that sorghum was more sensitive than maize. Cowpeas showed higher tolerance than maize and sorghum. Decline of yield and percent germination was more severe on the plateau than in the plains attributed to better buffering against sulphur. Sulphur application decreased soil pH, calcium and magnesium contents and increased content of aluminium. As sulphur use is expected to continue in the near future, monitoring of soil pH and liming of acidified cashew groves needs to be instituted. A concerted effort is needed to find alternative practices to either reduce the amount of sulphur used or to replace it by other fungicides.

Chapter 10

Laboratory evaluation of locally available soil amendments for neutralising soil acidity from sulphur dusting

10.1 Introduction

To achieve high production of cashew nuts, cashew groves in South Eastern Tanzania are yearly dusted with 90 kg of sulphur per hectare in order to control powdery mildew disease. Without sulphur dusting there is considerable yield loss (Sijaona, 1984; Sijaona and Shomari, 1987; Martin and Kasuga, 1998; Martin *et al.*, 1997). Sulphur dusting, however, is known to acidify soils of cashew groves (Majule *et al.*, 1997; Majule, 1999). A suitable soil amendment is required to raise soil pH to levels conducive for the growth of annual intercrops.

Soil acidification affects crop production since it inhibits growth of plants due to Al^{3+} and H^{+} ion toxicity (Shen *et al.*, 1998; Xu *et al.*, 1991). Acidification causes loss of base cations through displacement by Al^{3+} and H^{+} resulting in a nutrient imbalance, aggravated by magnesium deficiency. Also important are the indirect effects like phosphate and micronutrients fixation by soluble iron and aluminium salts. There are also toxic effects to some plant species due to soluble divalent cations like manganese and molybdenum induced by acidity (Shen *et al.*, 1998).

In numerous instances where soil acidification has been a problem, liming is the strategy adopted to address it (Foster, 1970; Sanchez and Salinas, 1981; Gregan *et al.*, 1989; Floate and Enright, 1991). One procedure of determining how much lime to use is to incubate samples of acidified soils with known amounts of soil amendments for a specified length of time. The resulting soil pH is then plotted against amounts of the amendment. From the resulting curve it is possible to determine how much lime is necessary to achieve a desired soil pH. For tropical soils, where aluminium toxicity is a major problem, Sanchez and Salinas (1981) advise prior examination of soil properties of soils earmarked for liming. They argue that when liming tropical soils the aim should be to remove exchangeable aluminium and manganese ions and raise pH up to at least 5.5.

Limed acidic soils are known to make large contributions to increased crop yields (Robson, 1989; FAO, 1993). This is partly achieved through replacement of Ca^{2+} and Mg^{2+} lost through ionic displacement in the process of acidification (Gower *et al.*, 1995) and neutralisation of exchangeable aluminium (Kamprath, 1970). Neale *et al.* (1997) have shown that liming improves microbial activity and N transformations of acidic soils which are important for agricultural production. Liming causes precipitation of exchangeable aluminium resulting in the improvement of cementing agents which binds soil particles together that improves soil structure.

Soil amendments such as Mikindani lime, Minjingu rock phosphate and ash from dry cashew nut leaves are locally available in Tanzania. This study evaluated these soil amendments in order to select the most suitable one for managing acid affected soils in South Eastern Tanzania.

10.2 Materials and Methods

10.2.1 Location of experimental sites

The incubation tests were done at Naliendele Agricultural Research Institute in South Eastern Tanzania located at latitude 10^0 21' S and longitude 40^0 11' E (Figure 4.1). Description of soils and rainfall at the experimental site is given in Chapter 4.

Soil amendments evaluated in the study were Mikindani lime (MKL), Minjingu rock phosphate (MRP) and ash from cashew tree leaves (CLA). Mikindani lime is prepared by burning coral lime collected from the coastline of the Indian Ocean within the study area. It is a powdery material essentially consisting of $Ca(OH)_2$ and is locally used for painting walls and as an amendment in cement for building purposes. Minjingu rock phosphate is mined in Arusha region in northern Tanzania about 1200 km from the study area. The principal components of the Minjingu phosphates yield francolite (carbonate-fluorapatite [$Ca5(PO_4,CO_3)_3/F$]), calcite and quartz (Schlüter, *in press*). The rock, in powdery form, is used as raw material for the manufacture of TSP, for direct P fertilisation and as an amendment for cement. Ash was prepared by burning dry cashew leaves collected under the canopies of cashew trees. Samples of the three soil amendments were analysed at Tanzania national soil laboratory at Mlingano. Selected chemical properties of the soil amendments are shown in Table 10.1.

Table 10.1 Selected chemical properties of soil amendments used in the study

Amendment	P_2O_5 (%)	Calcium (cmol kg^{-1})	Magnesium (cmol kg^{-1})	pH-H_2O	pH-KCl	OM (%)
Mikindani lime	0.7	1159.2	741.6	12.1	11.0	0.14
Cashew leaf ash	2.6	269.2	225.7	8.6	7.9	2.29
Minjingu rock phosphate	25.6	891.0	408.8	9.4	9.3	0.24

Source: Analytical data from National Soil Service (Mlingano) and after Majule (1999)

10.2.2 Incubation tests

Soil samples were from the topsoil (0-10 cm) from plots the pH of which had acidified to pH 3.8 by sulphur applied on sorghum at the rate of 240 kg per hectare during a 3-year trial (Chapter 9). The original soil pH-H_2O was 5.4 (Table 4.1). In the laboratory the soil samples were mixed thoroughly and then divided into three lots. Soil pH of each lot was determined giving a mean pH value of 3.8 units. Each lot was then divided into 10 sub-samples and mixed thoroughly with soil amendments (MKL. CLA. MRP,) according to treatments which varied from 0 to 25 g. Soil samples were packed into plastic containers (measuring 19 cm in diameter and 18 cm in depth). Packing was done such as to replicate the field bulk density of 1.41 g cm^{-2}. The soil samples were incubated at room temperature (25^{0}C) for 4 months. Moisture was adjusted fortnightly to field capacity to account for water loss during incubation. After 4 months, soil pH was determined potentiometrically using a Glass Calomel electrode in a 1:2.5 suspension of water. "Response" curves relating the amount of soil amendment and resulting pH were established. The basis for pH 6 is that growth of most agricultural crops is optimum at this pH where problems of aluminium toxicity are less pronounced (Kennedy, 1992).

10.2.2 Rates of soil amendments used in the incubation

The weight of the soil sample in the plastic container was calculated based on the relation: $W1=\pi R^2 hB$ where W1 represents the weight of soil in the plastic container, R is the radius of the plastic container, h is the height of the container and B is the bulk density (1.41 g cm^{-3}) of the soil. The weight of the 10 cm soil in a ha was calculated based on the relation: W2=lpdB. W2 is the weight of 1 hectare soil at 10 cm, l and p are, respectively, the length and width of one hectare of land, d is the depth of soil considered and B is the bulk density of the soil. Weights of soil amendment (ton/ha) in the containers were converted to a hectare basis by a factor of W2/W1.

10.2.3 Cost of soil amendment needed to neutralise acidity in 1 ha

Three cost components were involved in evaluating the suitability of the soil amendments.

- The price of a 50 kg bag of the amendment
- The cost of transporting the amendment from its source to Naliendele (the study site)
- Labour cost for applying the material in the field

One 50 kg bag of Mikindani lime cost US$ 1.25 and to transport it from supplier to the study site costs US$ 0.30 while handling charges cost US$ 0.11. A bag of 50 kg of Minjingu rock phosphate costs US$ 6.25. It costs US$ 2.50 to transport it from supplier to the study site and US$ 0.50 for handling charges. Minjingu rock phosphate was ferried from Dar-Es-Salaam by boat and hence the high handling charges. Since no price was set for ash, its value was based on labour cost involved in collecting dry leaves and burning. The labour cost for preparing one bag of 50 kg of ash from cashew leaves was US$ 5.63. The total cost of soil amendment needed to raise pH to 6 is shown in Table 10.2.

Table 10.2 Costs of soil amendment in US$ per bag of 50 kg

Soil amendment	Buying	Transport	Labour	Cost per bag	Cost to raise pH*
Mikindani Lime	1.25	0.30	0.11	1.66	9.96
Cashew leaf ash	—	—	5.63	5.63	78.82
Minjingu rock phosphate	6.25	2.50	0.50	9.25	185.00

* To attain the target pH of 6, following amounts of amendments were required - 6 bags of MKL, 14 bags of CLA and 20 bags of MRP; na = not applicable; The price of a 50 kg bag of sulphur is US$ 12.5

10.3 Results

10.3.1 Response curves

The relation of soil pH and soil amendments is shown in Figure 10.1. At the beginning of the incubation test, when rates of amendments were low, neutralisation capacity was similar for the three soil amendments. This was attributed in part to the counter-effect of the inherent buffering capacity of the soil. As the rates increased inherent buffering capacity was exceeded. This was particularly evident for Mikindani lime. Higher rates of MRP and CLA were required to neutralise acidity as these amendments had low neutralising capacity.

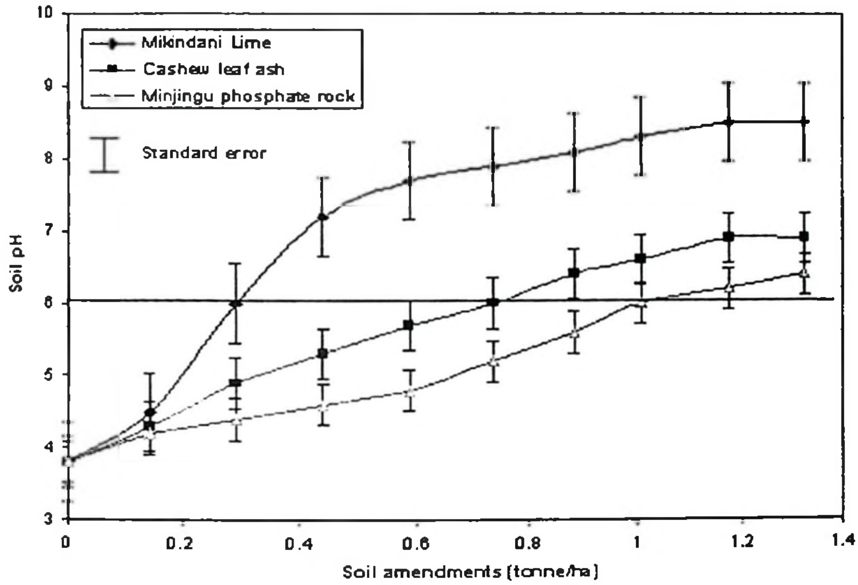


Figure 10.1 **Relation of amount of soil amendment applied and soil pH measured after incubation**

Response curves in Figure 10.1 show that to raise soil pH from 3.8 to 6 needed 0.3 ton of MKL while 0.7 ton was required for the ash from cashew leaves and 1.0 ton for Minjingu rock phosphate. Thus, MKL was superior in neutralising acidity than the other two soil amendments.

10.3.2 Comparison of the three soil amendments

Of the three soil amendments, the amount of Mikindani lime needed to raise pH to 6 was cheapest at US$ 10 (Table 10.3). Comparable figures for CLA and MRP were US$ 79 and 185, respectively, making MKL the cheapest soil amendment to manage the acidification problem. MRP is expensive due to high purchase price and transport costs. Due to the lack of field data of nut yield from the different amendments, the assessment of cost:benefit ratio could not be done. This warrants future research to refine the economic application rate of lime.

10.4 Discussion

Mikindani lime, proven in the study as the most suitable material to neutralise acidity, is Calcium hydroxide ($Ca(OH)_2$) produced locally by burning coral lime in Mtwara. The study shows that 0.3 ton ha^{-1} of MKL is suitable for farmers' cashew groves. At the rate of 0.7 ton ha^{-1} for CLA and 1 ton ha^{-1} for MRP, these soil amendments are too expensive for farmers. Additionally, when the amount of amendments becomes too high, restrictions on the availability of water from the soil solution may also limit plant growth. Assuming that labour to prepare and apply ash is not a major limitation, the P and organic matter in ash could make CLA an alternative to MKL. The advantage of CLA is that the P and organic matter can be available to supply part of the P and nitrogen demand of cereal crops. The role of ash in this respect has well been documented by Van Reuler and Jansen (1993).

Use of Mikindani lime for agricultural purposes may raise concern from environmentalists due to destruction of marine environment. The basis of the argument is that coral lime forms a suitable environment for fish and other aquatic species the destruction of which will deprive their natural habitat. However, in Tanzania supply of lime may not be much of a problem since the coastal areas of Tanzania are rich in fossil (coral) lime currently not exploited. What is needed is to mine these deposits. The other anticipated problem will be farmers' resistance to liming. Without assurance of additional advantages, liming may be considered a burden to the already high costs of using sulphur. Additional research may be required to find out if lime can have a beneficial effect on the growth and yield of cashew as well as annual crops when applied on reclaimed soils. Such effect would be an encouragement to farmers to engage in the use of lime and therefore save soils from acidification.

The amount of 0.3 ton/ha of Mikindani lime is specific for soils of Naliendele. Lime rate for other areas requires information about soil properties and the level of acidity. This is based on the fact that pH of the soil varies with the percentage exchangeable protons and the cation exchange capacity (Kennedy, 1992) and that soils with the same CEC and pH will have the same lime requirement. Assessment of suitability for a soil amendment has to consider the economic aspect prevailing at the site. As this was not done in this study, future research to refine the lime rate is warranted.

10.5 Summary and conclusions

This study intended to use laboratory incubation tests to find a suitable soil amendment for neutralising acidity due to sulphur use. Varying levels of Mikindani lime, Minjingu rock phosphate and ash from cashew leaves were evaluated. Mikindani lime attained the target pH 6 at the rate of 0.3 ton/ha at the total cost of procurement and application of 10 US$ per hectare. To achieve the same pH, ash from cashew leaves and Minjingu rock phosphate needed higher amounts valued at US$ 79 and 185 per hectare, respectively. Soil acidification from sulphur can be managed through use of Mikindani lime locally available in South Eastern Tanzania. As the lime rate depends on soil properties and level of acidity, amount of lime required for other sites has to be worked out depending on soil properties and level of acidity. Additional research is needed to refine lime requirement to take into account economic benefits of liming. To encourage farmers to adopt liming, research into economic and agronomic benefits of liming in cashew farming areas is warranted.

Chapter 11

Field evaluation of locally available soil amendments for neutralising soil acidity from sulphur dusting

11.1 Introduction

For the last fifteen years, cashew farmers in South Eastern Tanzania have used sulphur powder to protect cashew trees form powdery mildew disease (Cashew Research Report, 1998/99). In spite of its effectiveness as a chemical control agent (Sijaona, 1984), sulphur is found to accelerate acidification of soils on which cashew trees are grown (Majule *et al.*. 1997). This finding has led to testing of a range of organo-based fungicides to replace sulphur dusting (Topper *et al.*, 1998a; Topper *et al.*, 1998b). Additionally, different agronomic practices that lead to reducing disease infestation and therefore sulphur use are being tested (Cashew Research Report, 1998/99; Shomari, 1996; Shomari, 1999).

As sulphur use is expected to continue while alternatives to sulphur use are being developed, a strategy to address soil acidity arising from prolonged sulphur use is needed. This is important since soil acidity is a major limitation to the production of the annual cashew intercrops. Two fundamental factors limit the fertility of acid soils, namely (a) improvised nutrient status (e.g. deficiencies of P, Mo, S, K, Ca) and (b) the presence of phytotoxic substances (e.g. soluble Al and Mn) (Shadfan and Hussen, 1985). In particular, phosphates present special problems because of their strong fixation by acid soils (Sanchez and Uehara, 1980).

The practice of liming soils to reduce levels of phytotoxic elements (Al and Mn) and to improve soil conditions has long been recognised as a necessity for optimum production (FAO, 1993). This study was thus conducted to evaluate locally available lime resources such as Mikindani lime. Minjingu rock phosphate and ash from cashew leaves to neutralise soil pH.

11.2 Materials and Methods

The experiment was conducted at Naliendele Agricultural Research Institute (latitude 10° 21'S and longitude 40° 11'E, 120 m asl) on the Makonde plateau in South Eastern Tanzania. Description of soils and rainfall at the experimental site is given in Chapter 4.

11.2.1 Experimental design

A randomised plot experiment was superimposed on an existing block of AC4/200 clone trees. This grove was selected because its trees are in the bearing stage and is among five clones chosen as high yielding and showing some resistance towards PMD (Masawe *et al.*, 1999a). The spacing is of 6 × 12 m since originally the block was used as a breeding observation trial.

The treatments were Mikindani lime, ash from burnt cashew leaves, Minjingu rock phosphate and a control whose selected properties are shown in Table 10.1 (Chapter 10). As this was a pilot experiment, soil amendments were applied at the uniform rate of one ton per hectare. The soil amendments were applied two times i.e. in March 1997 and April 1998. Each plot, consisting of 4 trees, was replicated four times and separated from other plots by two rows of trees. In order to guard the experimental block against powdery mildew disease, elemental sulphur powder was dusted at the recommended rate of 250 g per tree five times in each season.

Mikindani lime (burnt coral reef lime) was obtained at Mikindani town about 20 km from the experimental site. Minjingu rock phosphate was ferried from Minjingu Phosphate mine in Arusha, northern Tanzania. Ash from burnt cashew leaves was prepared locally using dry leaves collected from cashew groves from the neighbourhood.

11.2.2 Measurement of annual growth of branches

In April of 1997, just before initiation of the new growth (elongation) of the terminal buds, twenty (ten in the north and ten in the south direction) buds were marked (with red ink) and labelled. These buds were among several buds within a one metre square quadrant placed on the outer surface of the canopy. New growth of these terminal branches was measured in June 1999.

11.2.3 Harvesting of cashew nuts

Cashew nuts were harvested from September to November of each year. Cashew nuts from each treatment were dried separately before weighing and bulking for storage.

11.2.4 Determination of soil pH

Soil samples for pH determination were taken in June 1997, 1998 and 1999 at 0-30 cm soil depths from two trees per treatment. Soil pH was analysed in water at the ratio of 1:2.5 soil-water suspension using a Glass Calomel electrode pH meter.

11.3 Results and Discussion

11.3.1 Effects of the soil amendments on soil pH

Figure 11.1 indicates trends in soil pH as monitored each October for three years beginning 1997. Mikindani lime, ash from cashew leaves and Minjingu rock phosphate raised soil pH but the increase was higher for Mikindani lime (0.2 pH units) than the other two soil amendments (at 0.1 pH units). Considering that the control plots (without soil amendments) had registered a decrease of soil pH (by 0.1 units), changes introduced by the amendments are pronounced. In view of the standard errors (Figure 11.1), this is a consistent trend that is expected to become significant in the future. The amendments had initially to neutralise sulphur added before raising the pH. This implies that the decrease in soil pH of the control plots is due to sulphur applied to control powdery mildew disease of cashew.

The results of this study suggest that soils at Naliendele respond to liming which provides an opportunity for neutralising soil acidity caused by sulphur dusting. This response could be attributed to low chemical status (low base cations) of the soils at the study site (Table 4.1 Chapter 4) which is typical of soils in the plateaux of southern Tanzania (Chapter 5). In previous studies in South Eastern Tanzania, Partel (1988) suggested that the acidification problem from sulphur dusting could be handled by mixing lime and sulphur before dusting. This may not be advisable since under optimal moisture conditions, lime can neutralise sulphur making it less effective in controlling PMD.

Results of this study show that the potential for a significant decline in pH exists if sulphur will be annually used. As the optimum pH range for cashew nut is between 4.5 and 6.5 (FAO, 1994), effects on the cashew nut production may not appear soon, but effects on more sensitive intercrops such as sorghum, maize and finger millet can be expected when critical pH levels are reached.

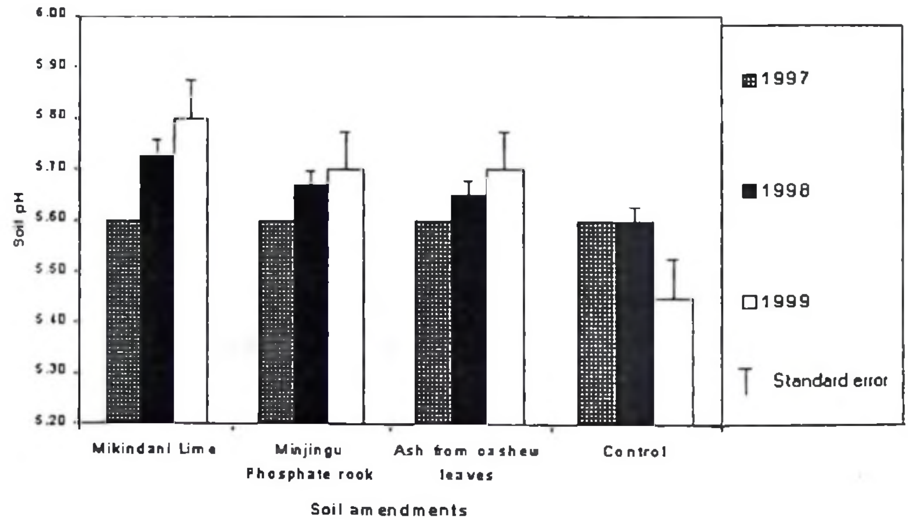


Figure 11.1 Effect of Mikindani lime, Minjingu rock phosphate and ash from cashew leaves on soil pH at Naliendele

11.3.2 Effect of soil amendments on cashew nut yield

Despite the fact that the population was from the same parent, mean yield of cashew nuts varied between 5.3 and 7.7 kg/tree (CV 13%). This yield is slightly higher than avearge farmers' yield and is attributed to high yielding clones as well as to the control of the powdery mildew disease. The results of analysis of variance of cashew nut yield are presented in Table 11.1. Data show that treatment effect was not significant at the 5% level of significance. Lack of significant treatment differences are attributed to short duration of the study period. Being a deep rooting perennial plant, cashew trees are not expected to respond rapidly to soil surface applied amendments. Coleman *et al.* (1958) indicate that reaction of lime with soils involves neutralisation and that movement of calcium and magnesium away from the point of reaction is relatively slow. The other viewpoint is that the optimum pH range for the cashew tree is between 4.5 and 6.5 (FAO, 1994), extreme effects on cashew nut yield are not expected as current pH is still within this range.

ANOVA results (Table 11.1) show that the seasonal effect is highly significant indicating clearly that yield of cashew trees had been influenced by climatic factors. The highest yield was obtained in season 3 (year 3) and the lowest was recorded in season 2 of the study. One of these seasonal effects could be variation in annual rainfall since in 1998 South Eastern Tanzania received above average rainfall (Figure 4.2). Influence of environmental factors on growth characteristics of cashew clones has also been demonstrated by Masawe *et al.* (1999b) in southern Tanzania.

Table 11.1 ANOVA of cashew nut yield at Naliendele

Source of Error	Sum of squares	Degree of freedom	Mean sum of squares	F-ratio	Probability value
Treatment	769274	3	256424	0.36	0.079
Season	4452060	2	222603	30.41	< 0.001
Treatment x Season	298288	6	49714	0.07	0.999
Error	26356170	36	732115	-	-

CV 13%

11.3.3 Effect of soil amendments on growth of cashew branches

Table 11.2 shows the results of ANOVA of growth of branches. There was no differences in growth of branches between the western and the eastern direction of the canopy. In an analogous study Ngatunga *et al., 2001*) observed higher nut number on the northern part of the cashew tree canopy than in the southern part. The exact explanation of this tendency is of particular interest of further research.

Table 11.2 ANOVA of growth of cashew branches at Naliendele

Source of Error	Sum of squares	Degree of freedom	Mean sum of squares	F-ratio	Probability value
Treatment	118.375	3	39.458	0.368	0.777
E-W direction	112.500	1	112.500	1.049	0.316
Treat × E-W irection	190.500	3	63.500	0.592	0.626
Error	2573.500	24	107.229	-	-

CV = 22.6% ns - not significant; E - stands for eastern direction and W - stands for western direction

Results of statistical analysis of the growth of branches are presented in Table 11.2. These results indicate that there were no significant (p=0.05) differences in growth of branches due to lime treatments. Considering that growth was confined to the period April 1997 to June 1999 and cashew being a perennial crop, lack of differences in growth of branches could be due to short duration of the study. Cashew being a deep rooting perennial plant, it is not strange to get non-significant differences in growth within a period of two years. Long observations are therefore a prerequisite for obtaining stable growth responses.

11.4 Summary and conclusion

A field experiment to evaluate Mikindani lime, ash from cashew leaves and Minjingu rock phosphate to neutralise soil pH was conducted at Naliendele and cashew nut yield, growth of branches and soil pH were recorded annually. Mikindani lime was superior in neutralising sulphur and raising soil pH than Minjingu rock phosphate and ash from cashew leaves confirming results of laboratory incubation tests. There were no significant differences on either growth of branches or nut yield due to soil amendments attributable mainly to the short duration of the study. The short-term outcome of this experiment shows that it is possible to ensure sustainable production of the cashew-intercrops by using low cost locally available liming resources in South Eastern Tanzania. As cashew is a deep rooting tree, absence of response was expected. Continued monitoring of the cashew trees under the same treatments may reveal the effects.

Chapter 12

Conclusions and Recommendations

This study examined the effects of sulphur dusting on soils and selected crops in South Eastern Tanzania. The overall objective of the study was to propose sustainable approaches for management of the cashew–intercrop based farming systems in the study area.

Soil profile features and physico-chemical characteristics of 16 cashew groves on the Makonde plateau and 14 in the Inland plains were investigated. Cashew groves on the Makonde plateau had sandy, deep and well drained soils free from hardpans. *Ferralsols* constituted over 60 % of the soil groupings on the plateau and 30 % in the Inland plains. Besides *Ferralsols*, other soil groupings found in the plains are *Acrisols*, *Alisols*, *Cambisols*, *Phaeozems* and *Plinthosols*. These soils are generally clayey, less weathered and are often shallow.

The relationship of 19 soil properties and 20 cashew tree parameters from thirty cashew groves were examined by means of multivariate analysis. Cashew trees were found to have larger dimensions and yield on deep, strongly weathered soils on the Makonde plateau. The cashew tree prefers loose and porous nature of the soil medium found on the plateau. In the Inland plains, shallow, less weathered soils had trees of small dimensions and low yield. The fact that the plant grew favourably on the plateau, regardless of the low chemical fertility, showed that the cashew tree was more sensitive to physical than to chemical limitations of the terrain. It was concluded that soil profile depth and weathering status were important determinants for future cashew planting schemes. Since canopy size, soil type and nut yield are strongly correlated it is felt that spacing configuration for high yielding tree types which maximises canopy size is likely to offer increased nut yield.

To test the hypothesis that cashew growing soils in southern Tanzania are poorly buffered against soil acidification, a buffering capacity experiment involving soils from 35 groves was conducted. Buffering capacity of the cashew growing soils in the study area correlated strongly with clay content and weakly with organic carbon content. In addition, it was only weakly correlated with total exchangeable bases and available P of the surface horizon, but strongly with soil pH, base saturation and cation exchange capacity of the clay fraction of the subsurface horizon. The buffering capacity of soils on the Makonde plateau was comparable to that of soils in the Inpland plains. However, due to their lower initial pH, they have a higher risk for acidifying upto critical levels. Due to a deep rooting system for cashew trees there was no immediate threat to the cashew trees. It is the annual crops with shallow rooting systems that are vulnerable.

To investigate if prolonged sulphur dusting of cashew trees has lead to soil acidification in farmers cashew groves, pH of topsoil (0-20 cm) and subsoil (20-40 cm) of 70 cashew groves, where fanners had used sulphur for 0-12 years was compared with pH of non S dusted cashew groves. There was a significant decline in pH of soils on the plateau. This was not the case for soils in the plains. This is explained by the sandy character and the strong weathering status of the *Xanthic Ferralsols* and *Haplic Ferralsols* on the plateau. Soils in the plains are less weathered, clayey and have a high initial soil pH. Soil pH in the plains is between 5.5 to 6.5 which is within the suitable range for the growth of most annual crops. The situation on the plateau where soil pH ranges between 4.2 and 5.5 requires special remedial measures such as application of locally available liming materials. The optimum pH range for the cashew tree is between 4.5 and 6.5 and as expected the effects on cashew nut production were not noticeable.

Twelve field experiments located at three sites tested the hypothesis that application of sulphur on soils has negative effects on soils and cashew intercrops. Sulphur treatments consisted of 0, 60, 90, 120, 180 and 240 kg per hectare. Negative effects on germination and yield of sorghum and maize were observed beginning from the second growing season onwards at rates above 120 kg S/ha for sorghum and 180 kg S/ha for maize. Reduction of seed germination and yield was more pronounced for sorghum than for maize indicating that sorghum was more sensitive than maize. Effect of sulphur on crops in the plains was less pronounced due to soils of high chemical fertility offering high buffering against sulphur. Cowpeas had a high tolerance to sulphur use. Research is needed to find alternative practices to either reduce the amount of sulphur use or to replace it. This study confirmed that sulphur acidifies soils and resulting acidity has negative effects on intercrop production.

To demonstrate that soil amendments can effectively be utilised to manage acid affected soils an incubation experiment was conducted to evaluate effectiveness of three locally available soil amendments. Varying levels of Mikindani lime, ash from cashew leaves and Minjingu rock phosphate were incubated with acidified soils for 4 months in plastic containers. Mikindani lime was found to be the most suitable material since it attained the target pH at the rate of 0.3 ton ha^{-1} costing US$ 10 per hectare. Minjingu rock phosphate and ash from cashew leaves required US$ 79 and 185 per ha, respectively.

Results of effects of sulphur dusting on soil pH and annual crops lead to following practical recommendations:

(a) pH of soils in cashew groves with a history of sulphur dusting of 10 or more years on the Makonde plateau should be assessed and those found to have a pH less than 4.5 should be limed. This was particularly important if sorghum and/or maize are to be intercropped.

(b) Deliberate efforts should be made to reduce quantity of sulphur being used on the Makonde plateau. This can take different approaches e.g. promotion of crop sanitary measures (like pruning, removal and subsequent destruction of diseased plant parts) already recommended by Naliendele Research Institute; adhere to scouting of mildew infection and adopt sulphur dusting only when infection reaches critical levels; removal of pathogens on plant parts providing survival points during off-season periods, use of organic fungicides fungicides for cashew groves accessible to water supplies

(c) As risk for soil acidification is less pronounced in the in Inland plains, sulphur use can be continued, however, periodic monitoring of soil pH is recommended.

Implications for research

Several issues still require attention by the research establishment in South Eastern Tanzania. Available literature indicates that promising alternatives to sulphur use such as organo-fungicides are toxic. There is a need to assess residual quantities of these fungicides in nuts and apples as well as drinks (derived from apples). Research is required to find out if lime can have beneficial effect on the growth and yield of cashew as well as annual crops intercrops. Positive outcome of such studies will provide additional advantage so that farmers do not consider liming as an added burden to the already high costs of using sulphur. Research aimed at reducing the quantity of sulphur use on soils of the Makonde plateau is of paramount importance. Although a clear relationship was found between soils and cashew nut yields, soil factors that determine quality of cashew nuts are not known.

An integrated approach to address the mildew problem should also involve a long-term strategy to evaluate/breed for disease resistant tree types. The high heterogeneity of the local cashew tree population in South Eastern Tanzania pointed out in the study should encourage plant breeders to find breeding material resistant to powdery mildew disease among the already established trees in the groves. This study has shown that Mikindani lime (burned coral lime) is suitable for neutralising soil acidity. Further research is required to determine an economic rate for its application.

References

Abo-Rady MDK, Duheash O, Khalil M and Turjaman AM (1988) Effect of elemental sulphur on some properties of calcareous soil and growth of date palm seedling. *Arid Soils Research and Rehabilitation* 2 (2):121-130

Agrawal M, Nandi PK and Rao DN (1985) Effects of sulphur dioxide fumigations on soil system and growth behaviour of Vicia faba plants. *Plant and Soil* 1:69-78

Agrios GN (1988) *Plant Pathology* 3rd Edition. Academic Press. Publishers London UK

Aitken WG (1961) Geology and paleontology of the Jurassic and Cretaceous of Southern Tanganyika. Ministry of Energy and Minerals Dar Es Salaam Tanzania

Alexander M (1965) Nitrification. In: *Soil Nitrogen*. Bartholomew WV and Clark FE (Eds). American Society of Agronomy. Inc. Publisher. Madson Wisconsin USA.300-303.

Allen RG, Pereira LS, Raes D and Smith M (1999) *Crop evapotranspiration. Guidelines for computing crop water requirements*. FAO Irrigation and Drainage paper. 56 Rome.

Alva AK, Edwards DG, Asher CJ and Blamey FPC (1986) Effect of phosphorus/aluminium molar ratio and calcium concentration on plant response to aluminium toxicity. *Soil Science Society of America Journal* 50:133-137

Anderson B (1957) A survey of soils of Kongwa and Nachingwea Districts of Tanganyika. University of Reading in conjuction with Tanganyika Agriculture Corporation. Mimeograph. Ministry of Agriculture Dar Es Salaam Tanzania

Aulakh MS and Chihbba IM (1992) Sulphur in soils and response of crops to its application in Punjab. *Fertiliser News* 37(9):33-41

Bank of Tanzania (1999) Economic Bulletin for the Quarter ended 31st March 1999. Published by the Central Bank of Tanzania 89 pp

Beaton JD, Tisdale SL and Platou J (1971) Crop responses to sulphur in North America. Technical Bulletin 18. The sulphur Institute Washington DC

Behrens R (1996) Cashew as an agroforestry crop: prospects and potentials.Tropical Agriculture 9. Dissertation published by Maargraf Verlag Weikersheim Germany

Beniamino F, Ponge JF and Arpin P (1991) Soil acidification under the crown of oak trees I. Spatial distribution. *Journal Forest Ecology and Management* 4:221-232

Bennett JG. Brown LC. Geddes AMW. Hendy CRC, Lavelle AM, Sewell LG and Rose Innes R (1979) Report of the Zonal Survey Team in Phase 2. Volume I The physical environment and Vol.II The farming systems and development prospects. Mtwara and Lindi Regional Integrated Development Programme. Ministry of Overseas Development Land Resources Development Centre Surrey England 242 pp

Beverly RB and Anderson DL (1987) Effect of acid source on soil pH. *Soil Science* 143 (4):301-303

Binkley D and Richter D (1987) Nutrient cycles and H^+ budgets of forest ecosystems. *Advances in Ecological Research* 16:1-51

Blair JG (1988) Chemistry of S and S cycle in the tropics. In TSI-FAI Symposium Sulphur in Indian Agriculture 9-11th March 1988 New Delhi

Bloom PR and Grigal DF (1985) Modelling soils response to acid deposition in non sulphate adsorbing soils. *Journal of Environmental Quality* 14:489-495.

Bold HC, Alexopoulos CJ and Delevoryas (1987) *Morphology of Plants and Fungi*. 5th Edition. Harper & Row Publishers New York

Boma F. Topper CP and Anthony J (1998) Evaluation of various sulphur formulations for the control ofpowdery mildew (*Oidium anacardii* Noack) on cashew in Tanzania. In: *Proceedings of the International Cashew and Coconut Conference. Trees for life the key to development*. Topper CP. Calligari D S, Kullaya AK, Shomari SH, Kasuga LJ, Massawe PAL and Mpunami AA (Eds.) BioHybrids International 71-75.

Brady NC (1990) *The nature and properties of soils*. Macmillan Publishing Company Inc New York

Bray RH and Kurtz LT (1945) Determiation of total nitrogen and available forms of phosphorus in soils. *Soil Science* 59: 39-45.

Breedemeier M. Matzner M and Ulrich B (1990) Internal and external proton load to forest soils in northern Germany. *J. Environmental Quality* 19: 467-477

Bremner JM and Mulvaney CS (1982) Total nitrogen. In: *Methods of Soil Analysis Part 2*. 2nd edition (Page AL. Miller RH and Keeney DR Eds) 595-624. SSSA Monograph no 9 Madison. Wisconsin

Brenes E. and Pearson RW (1973) Root responses of three gramineae species to soil acidity in an oxisol and ultisol. *Soil Science* 116:295-302.

Brown LC. Minja E and Hamad AS (1984) Cashew production in East Africa. Paper presented at the conference. Advancing Agriculture Production in Africa, Arusha, Tanzania.

Cameron RS, Ritchie GSP and Robson AD (1986) Relative toxicities of inorganic aluminium complexes to barley. *Soil Science Society of America Journal* 50: 1231-1236

Cashew Research Report (1992/93) Annual Report of Cashew Research Programme for 1992/1993. Naliendele Agricultural Research Institute Ministry of Agriculture Mtwara Tanzania

Cashew Research Report (1997/98) Annual Report of Cashew Research Programme for 1998/1999. Naliendele Agricultural Research Institute Ministry of Agriculture Mtwara Tanzania.

Cashew Research Report (1998/99) Annual Report of Cashew Research Programme for 1998/1999. Naliendele Agricultural Research Institute Ministry of Agriculture Mtwara Tanzania

Cashew Research Report (1999/00) Annual Report of Cashew Research Programme for 1999/2000. Naliendele Agricultural Research Institute Ministry of Agriculture Mtwara Tanzania.

Cashewnut Board of Tanzania (1999) Annual report for the year 1999. Ministry of Agriculture and Cooperatives Tanzania

Casulli F (1981) Prove di lotte chimica sull' anacardio (*Anacardium occidentale* L) in Tanzania. *Rivista di Agricoltura Subtropicale e Tropicale* 75:256-266.

Castellani E and Casulli F (1981) Osservationi preliminari su *Oidium anacardii* Noack agent del mal bianco dell anacardio. *Rivista di Agricoltura Subtropicale e Tropicale* 75:211-222

Castellano SD and Dick RP (1988) Distribution of S fractions in soil as influenced by management of organic residues. *Soil Science Society of Am Journal* 4:283-285

Chapman SJ (1989) Oxidation of micronised elemental sulphur in soils. *Plant and Soil* 116:69-76

Charter CF (1957) Report on the environmental conditions prevailing in Block "A", Southern Province, Tanganyika Territory, with special reference to the large-scale mechanised production of grroundnuts Occassional paper Ghana No 1

Coleman ET. Kamprath EJ and Weed SB (1958) Liming. *Advances in Agronomy* 10:475-522

Cools N (1998) Geographical analysis for soil acidification due to sulphur dusting on cashew trees in Tanzania's Southern Zone MSc dissertation Faculty of Agricultural and Applied Biological Sciences, Katholieke Universiteit Leuven, Belgium

Cumbi S (1998) Cashew production in Mozambique. Country paper In: *Proceedings of the international cashew and Coconut Conference Trees for life, the key to development.* (Topper CP. Calligari DS, Kullaya AK, Shomari SH, Kasuga LJ, Massawe PAL and Mpunami AA Eds) BioHybrids International 14-15.

Curtin D. Campbell C and Meer D (1996) Prediction of titratable and soil sensitivity to pH change. *Journal of Environmental Quality* 25:1280-1284.

Dagg M (1972) Water requirement of crops In: *East Africa its people and resources*. Morgan WTW (Ed). Oxford University Press London UK

Dagg M. Woodhead T and Rijks DA (1970) Evaporation in East Africa *Bulletin of the International Association of Scientific Hydrology* 15(1):61-67.

Day PR (1965) Particle fractiotion and particle size analysis. In: *Methods of Soil Analysis part 1.* (Eds) Black CA. Evans DD, White JL, Ensminger LE and Clark FE) 545-566 ASA Madison Wisconsin

De Pauw E (1984) Consultants Final Report on soils, physiography and Agro-ecological Zones of Tanzania. Ministry of Agriculture Dar Es Salaam Tanzania

Dederen M (1998) Land evaluation for irrigation in south East Tanzania. Case study of the Kitere zone Msc dissertation Inter-university programme in Water Resources Engineering Katholieke Universiteit Leuven and Vrije Universiteit Brussel.

Dondeyne S, Emmanuel LB, Mugogo SE, Majule AE and Deckers JA (2001) Landscape units of Tunduru district: digital elevation model as a mapping tool. Accepted for publication in the *Tanzanian Journal of Agricultural Sciences*.

Driessen PM and Dudal R (Eds) (1991) *The Major Soils of the World. Lecture Notes on their Geography Formation Properties and Use*. Published by Agricultural University Wageningen and Catholic University of Louvain, Leuven.

Duke JA (1983) Anacardium Occidentale. Handbook of Energy Crops. Unpublished Report

Dytham C (1999) *Choosing and using statistics: a biologist's guide*. Blackwell Science Oxford UK

Eriksen J (1997) Sulphur cycling in Danish agricultural soils: inorganic sulphate dynamics and plant uptake. *Soil biol biochem*. 29 (10):1379-1385

Falade JA (1977) Cashew growing soils in Nigeria. *East African Agriculturure and Forestry Journal* 43(2) 100-105

Falade JA (1984) Variability in soils and cashew tree size. *Journal of Plantation Crops* 12(1):30-37

FAO (1990a) FAO-Unesco Soil Map of the World. Revised Legend. World Resources Report 60 FAO Rome

FAO (1990b) Guidelines for soil description 3rd Edition (Revised). Soil Resources Management and Conservation Service. Land and Water Development Division Rome

FAO (1993) FESLM: An international framework for evaluating sustainable land management. World Resources Report 73 Rome

FAO (1994) Ecocrop 1 The adaptability level of the FAO crop environmental requirements database Version 1. Land Resources Management and Conservation Service FAO Rome

FAO (2000) FAO Statistical Database http://www.fao.org

FAO-ISRIC-ISSS (1998) World Reference Base for Soil Resources. World Soil Resources Reports No 8 FAO Rome.

FAO-UNESCO-ISRIC (1988) FAO/Unesco Soil Map of the World Revised Legend. World Resources Report 60 FAO Rome

Finck A (1982) *Fertilizers and fertilization: Introduction and Guide to crop fertilization*. Verlag chemie Publication. Weinheim Germany

Floate MJS and Enright PD (1991) Effect of lime and 5 years sulphur and phosphorus applications on soil pH sulphur and phosphorus status of tussock grassland soils on East Otago uplands. *New Zealand Journal of Agric Research* 34(4):453-465

Foster HL (1970) Liming continuously cultivated soils in Uganda. *East African Agricultural and Forest Journal* 36:58-69

Fox R, Atesolp HM, Kambell DH and Rhodes HF (1964) Factors influencing the availability of sulphur fertilisers to alfalfa and corn. *Soil Science Society of America Proceedings* 28:406-408

Fox RL, Kang BT and Nangju D (1977) Sulphur requirement of cowpeas and implications for production in the tropics. *Agronomy Journal* 69:201-205.

Ghani A, Watkinson JH and Upsdell PM (1997) Modelling the oxidation of elemental S in New Zealand pastoral soils. *Sulphur in Agriculture* 20:3-9

Godefroy J and Dormoy M (1990) Stimulation de l'action du chaulage sur le pH et les teneurs en aluminium et en manganese dans un ferrisol de Martinique. *Fruits* 45:219-222.

Gower C, Rowell LD, Norticliff S and Wild A (1995) Soil acidification: comparison of acid deposition from the atmosphere and inputs from the litter/soil organic layer. *Geoderma* 66:85-98

Grantham DR (1949) Recoinnaissance to find 60,000 acres of agricultural soil in the vicinity of Nachingwea. Report by the Forward Report Party (Mimeo Report)

Gregan PD, Hirth JR and Conyers MK (1989) Amerilioration of soil acidity by liming and other amendments. In: *Soil Acidity and Plant Growth Robson* AD(Ed) 206-264 Academic Press Sydney Australia

Griffiths JF (1972) Climate. In: *East Africa: Its people and resources*. Morgan WTW (Ed). Oxford University Press London UK

Gower C, Rowell DL, Northcliff S and Wild A (1995) Soil acidification: Comparison of acid deposition from the atmosphere with inputs from litter/soil organic layer. *Geoderma* 66:85-98

Hassett JJ and Banwart WL (1992) *Soils and their environment*. Prentice-Hall Englewood Cliffs New Jersey

Helyar KR (1976) Nitrogen cycling and soil acidification. *Journal of Australian Institute of Agricultural Science* 43:217-221

Hilal MH, Abdel FA and Korkor SA (Eds) (1992) Effect of fine and granular sulphur application on root depth and yield of Lupinus in sandy soils. Proceedings of Middle East sulphur symposium 12-16th Feb 1992 Cairo Egypt. The sulphur Institute Washington USA

Hill J (1989) Cashew based farming systems research and development in southern Tanzania. An overview of activities and results. Cashew Production Improvement Pilot Project technical Mtwara Tanzania

Intini M (1987) Phytopathologycal aspects of cashew (*Anacardium occidentale* L.) in Tanzania. *International Journal of Tropical Plant Diseases* 5:115-130

Intini M and Sijaona MER (1983) Calender of disease control with reference to phenological phase of cashew (*Anarcadium occidentale* L.) in Tanzania. *Rivista di Agricoltura Subtropicale e Tropicale* 76.419-422.

Italo-Tanzania Cashew Research Programme (1981) Reconnaissance soil map (first approach) Ruvuma region Tunduru district Map No 2. Ministero degli affari esteri dipartimento per la cooperazione allo sviluppo. Istituto Agronomico per l'otremare Firenz

Jaffee S (1995) Private trader response to market liberalization in Tanzania's cahsew nut industry. Policy Research working Papers. World Bank No WPS1277 Washington DC USA

Janzen HH and Bettany JR (1987) The effect of temperature and water potential on sulphur oxidation in soils. *Soil Science* 144:81-89.

Johnson D (1973a) Cashew cultivation in Brazil. *Agron Mocamb Lourenco Marques* 7(3):119–129

Johnson D (1973b) The botany origin and spread of Cashew (*Anacardium occidentale* L). *Journal of Plantation Crops* 1:1-7

Kaihura FBS, Floor J.and Ikerra ST(Eds) (1988) .Proceedings of Tanzanian National Workshop on Phosphate Rock Research 1-3rd August 1988 Tanga. National Soil Service Misc Publication No F9

Kamprath EJ (1970) Exchangeable aluminium as a criterion for liming leached mineral soils. *Soil Science Society of America Proceedings* 34:252-254.

Kamprath EJ (1984) Crop response to lime on soils in the tropics. In: *Soil acidity and Liming* 2nd edition. Adams F (Ed) 349-368. CSSA, SSSA, and ASA, Agronomy Monograph 12.

Kasuga LJ. Topper C P. Martin PJ, Boma F. de Waal D and Bakari JJ (1998) Integrated cashew management: appropriate strategies for increasing the productivity of smallholder cashew. In: *Proceedings of the International Cashew and Coconut Conference. Trees for life the key to development.* Topper CP, Calligari D.S, Kullaya AK, Shomari SH. Kasuga LJ, Massawe PAL and Mpunami AA (Eds.) BioHybrids International 71-75.

Kayonde GO (1990) Sulphur nutrition of cowpea in the rainforest and savannah regions of Nigeria. *Fertilizer Research* 29 (1):1-6.

Kemmler G and Hobt H (1987) Potash: A product of Nature. *International Fertilizer Correspondent* 29 (4):112-116

Kennedy IR (1992) *Acid Soils and Acid Rain*. John Wiley & Sons Inc New York

Kent PE. Hunt JA and Johnstone DW (1971) The geology and geophysics of coastal Tanzania Natural environment research council. Geographical Paper No 6 Institute of Geological Sciences London

Kenworthy J (1975) Climatology In: *An advanced geography of Africa*. Clarke JI (Ed) Hulton Educational Publications

Kips Ph A and Kimaro RK (1993) Soil conditions and land suitability for irrigated agriculture of Kitere scheme (Mtwara Region). Soil evaluation Report S19 National Soil Service Agricultural Research Institute Mlingano. Ministry of Agriculture and Cooperative Development

Konopka AE, Miller RH and Sommers LE (1986) Microbiology of sulphur cycles. In: Sulphur in Agriculture. Tabatabai MA (Ed) Agronomy 27:23-55

Krug EC and Frink CR (1983) Acid rain on acid soil: a new perspective. *Science* 22 (1):520-525

Laurence RCN. Gibbons RW and Young CT 1976 Changes in yield protein oil and maturity of groundnut cultivars with the application of sulphur fertilizers and fungicides. *Journal of Agricultural Science* 86:245-250

Lawrence JR and Germida JJ (1991) Enumeration of sulphur oxidising micro-organisms in Saskatchewan agricultural soils. *Canadian Journal of Soil Science* 71:127-36

Lee A. Watkinson HJ and Lauren DR (1988) Factors affecting oxidation rate of elemental sulphur in soils under rye grass dominated by sward. *Soil Biology and Biochemistry* 20:809-816

Li P and Caldwell AC (1966) The oxidation of elemental sulfur in soil. *Soil Science Society of America Proceeding* 30:370-372

Littell R.C. Milliken GA. Stroup WW and Wolfinger RD 1996 SAS for Mixed Models. Cary North Carolina SAS Institute Inc

Magdoff FR and Bartlett JR (1985) Soil pH buffering revisited. *Soil Science Society of America Journal* 49:145-148

Majule AE (1999) The effects of organic residues and elemental sulphur additions to soils of Southern Tanzania. PhD thesis Reading University UK.

Majule AE, Topper CP and Nortcliff S (1997) The environmental effects of dusting cashew (*Anacardium occidentale* L) trees with sulphur in southern Tanzania. *Tropical agriculture (Trinidad)* 74 (1):25-33

Martin PJ and Kasuga LJ (1995) Variation in cashew tree yields in south east Tanzania and the implication for management of cashew small holdings. *Tropical Agriculture. Trinidad* 72:261-268

Martin PJ and Kasuga LJ (1998) Cashew farm upgrading: Agronomic options for increasing cashew production by smallholder farmers in Tanzania. *Experimental Agriculture* 34:137-152

Martin PJ, Topper CP, Bashiru RA, Boma F, De Waal D, Haries H, Kasuga LJ, Katanila N, Kikoka LP, Lamboll R, Maddison A, Majule AE, Masawe PA, Millanzi KJ, Nathaniels NQ, Shomari SH, Sijoana ME and Stathers T (1997) Cashew nut production in Tanzania: Constraints and progress through integrated crop management. *Crop Protection* 16:6-14

Martinez F and Estrella H (1996) Advances in the understanding of aluminium toxicity and the development of aluminium-tolerant transgenic plants. *Advances in Agronomy* 66:103-120

Masawe PAL (1994) Aspects of Breeding and Selecting Improved Cashew Genotype (*Anacardium occidentale* L.). PhD thesis The University of Reading UK

Masawe PAL, Cundall EP and Caligari PDS (1999a) Observations on progenies in a crossing scheme between cashew clones: Establishment characters. *Tanzania Journal of Agricultural Sciences* 2(1):1-6

Masawe PAL, Cundall EP and Caligari PDS (1999b) Studies on Genotype-Environment interaction (GXE) in half-sib Progenies of cashew (*Anacardium occidentale* L) in Tanzania. *Tanzania Journal of Agricultural Sciences* 2(1):53-62

Maynard DG, Germida JJ and Addison PA (1986) The effect of elemental sulphur on certain chemical and biological of surface organic horizons of a forest soil. *Canadian Journal of Forest Research* 16(5):1050-1054

McFee WW (1983) Sensitivity ratings of soils to acid deposition. *Environmental Experimental Botany* 23:203-210

Mishra DP (1984) Land Suitability Classification for Cashew I The Criteria. *Cashew Causerie* 6 (4):12-20

Mitchell JD and Mori SA (1987) The cashew and its relatives (Anacardium; Anacardiaceae). Memoirs of the New York Botanical Gardens 42:1-76

Morton J (1987) Cashew Apple. *In*: Fruits of warm climates (Morton JF Ed). Miami Florida USA 239–240

Mponda OKK. Mkamilo GS, Kafiriti EN and Mpiri MG 1993 Oilseeds Research Programme Annual Report Naliendele Agricultural Research Institute, Mtwara. Ministry of Agriculture Tanzania

Murdock GP (1959) *Africa: Its Peoples and Their cultural history* New York McGraw-Hill

Nathaniels N (1998) Self help, cashew trees and learning in rural primary schools in Nachingwea district Tanzania. *Forest Trees and People Newsletter* 35:9-13.

Nathaniels NQR and Kennedy R (1996) Variation in severity of cashew powdery mildew (*Oidium anacardii* Noack) disease in Tanzania: implications for research and extension. *International Journal of Pest Management* 42 (3) 171-182

National Soil Service (1987) Soils of the Kikwetu estate (Lindi) and their potential for sisal and other alternative crops. Reconnaissance Soil Survey report No 4 National Soil Service Agricultural Research Institute Mlingano. Ministry of Agriculture Tanzania

Nayar MNC. George TE and Mathew L (1981) The Relationship Between Height Girth and Spread with Yield in Cashew (*Anacardium Occidentale* L). *Cashew Causerie* 3 (2):13-14.

Neale SP. Shah Z and Adams WA (1997) Changes in microbial biomass and nitrogen turnover in acidic organic soils following liming. *Soil Biology and Biochemistry* 29:1463-1474

Nelson DW and Sommers LE (1982) Total carbon organic carbon and organic matter. *In Methods of Soil Analysis part II*, 2nd edition (Page AL, Miller RH and Keeney DR Eds) 595-624 ASA SSSA Monograph no 9 Madison Wisconsin

Ngailo JA and Kips PhA (1991) Soils of Mikindani estate and their suitability for cashew mango lime hybrid sisal and teak. Semi-detailed soil survey Report D32. National Soil Servive. Agricultural Research Institute Mlingano Ministry of Agriculture Tanzania

Ngatunga EL. Dondeyne S and Deckers JA (1998) One decade of sulphur dusting in South Eastern Tanzanian: effects on soil pH. *In*: *Proceedings of the international cashew and*

Coconut Conference. Trees for life the key to development (Topper CP, Calligari D.S, Kullaya AK. Shomari SH. Kasuga LJ. Massawe PAL and Mpunami AA Eds) BioHybrids International 64-70

Ngatunga EL, Cools N, Dondeyne S and Deckers JA (2001) Soil suitability for cashew production in South Eastern Tanzania. Accepted for publication in the journal "The Land" (In press)

Ngongi AGN, Howeler R and MacDonald HA (1977) Effect of potassium and sulphur on the growth, yield and composition. *In: Proceedings of the fourth symposium of the International Society for Tropical Root Crops.* Cornell University. Ithaca New York USA. 107-113

Nielsen D. Hoyt PB. Parchomchuk P, Nielsen G and Hogue EJ (1995) Measurements of the sensitivity of orchard soil to acidification. *Canadian Journal of Soil Science* 75:391-395

NOMISMA (1994) The World Cashew Economy. Bologna Italy

Nortcliff S and Wong M (1995) A review of the effects of sulphur additions on acid tropical soils. with particular emphasis on the soils of the ODA Cashew Research Project. University of Reading UK 17 pp.

Northwood PJ (1967) The variation in cashew yields in Southern Tanzania. *East African Agriculture and Forestry Journal* 32:237-239

Northwood PJ and Kayumbo HY 1970 Cashew production in Tanzania. World Crops 22:88-91.

Nyborg M and Malhi SS (1991) Acidification of forestry by elemental sulphur dust. *In: Proceedings of the International Symposium on Plant-Soil Interactions at low pH* 24-29th June 1990 Beckley West Virginia USA

Ohler JG (1979) *Cashew*. Communication No 71. Department of Agricultural Research of the Royal Tropical Institute Amsterdam The Netherlands

Partel L (1988) Programma anacardio: un contributo italiano al rilancio della coltura in Tanzania. *Rivista di Agricoltura Subtropicale e Tropicale.* Instituto Agronomico per l'Ontremare Firenze 4:631-645

Pasricha NS and Fox RL (1993) Plant nutrient sulphur in the tropics. *Advances in Agronomy* 10:209-267

PC-SAS (1988) *The GLM Procedure. SAS/STAT Users Guide*. SAS Institute Incorporation Carry North Carolina USA

Poulton C, Katinila N and Gongwe A (1997) The cashew sector in Tanzania: Overcoming problems of input supply. Research Report submitted to Policy Research Programme Natural Resources Policy and Advisory Department ODA UK

Purseglove JW (1968) *Tropical Crops: Dicotyledons*. Longmans London.

Raikes P (1986) The agricultural sector. In Tanzania-crisis and struggle for survival (Boesen J, Havenevik K., Koponen J and Odgaard R Eds). Scandinavian Institute of African Studies Uppsla Sweden 105-141

Randall PJ and Wrigley CW (1992) Effects of sulphur supply on the yield composition and quality of grain from cereals, oilseeds, and legumes. *Advances in Cereal Science and Technology* 8:171-205

Reuss JO and Johnson DW (1986) Acid Deposition and the Acidification of Soils and waters. *Ecological Studies* 59 25-31

Robarge WP and Johnson DW (1992) The effects of acidic deposition on forested soils. *Advances in Agronomy* 47:1-83

Robson AD (1989) *Soil Acidity and Plant Growth*. Academic Press Sydney Australia

Rowell DL (1981) *Oxidation and Reduction*. *In:* Greenland DJ and Hayes MHB (Eds) The Chemistry of Soil Processes. John Wiley and Sons Chichester New York 101-462

Rowell DL (1994) *Soil science: Methods and Applications* Longman Scientific and Techincal Harlow England

Sakala MG (1998) The effect of incorporating plant residues on soil acidity in the management of tropical soils. PhD thesis Reading University UK 192 p.

Sanchez PA and Salinas JG (1981) Low input technology for managing oxisols and ultisols in tropical America. *Advances in Agronomy* 34:280-406

Sanchez PA and Uehara G (1980) The role of phosphorus in Agriculture. *In: "The role of phosphorus in Agriculture"* (Khasawneh FE, Sample EC and Kamprah EJ Eds) pp 263-310. American Society of Agronomy Madison Wisconsin

Sastry LVL. Setty L. Satyavathi VK. Pruthi JS and Siddappa GS (1962) Polyphenol constituents in cashew apple juice as influenced by region; strain and selection. *Indian Journal for Applied Chemistry* 25:4-7

Schlüter Th. Kohring R and Wipki M (*in press*) Genesis and depositional facies of the continental phosphorites of Minjingu (Lake Manyara, N Tanzania), *Journal of African Earth Sciences*. http://userpage.fu-berlin.de/~palaeont/MINJINGU.HTM

Shadfan H and Hussen AA (1985) Effect of sulphur application on the availability of P Fe Mn Zn and Cu in selected Saudi soils. *In: Proc.of Regional conference on sulphur and its usage in Arab countries*. Riyadh 2-5th March 1985. 1:24.

Shen S, Gary EP, Hassett JJ and Stucki JW (1998) Acidity and aluminium toxicity caused by iron oxidation around anode bars. *Soil Science* 163:657-664

Shomari SH (1996) Studies on the biology and epidemiology of Oidium anacardii (Noack). The powdery mildew pathogen of cashew. PhD Thesis University of Birmingham UK

Shomari SH and Kennedy R (1998) Field and laboratory investigations on the development of oidium anacardii in relaation to environmental factors. *In*: *Proceedings of the international cashew and Coconut Conference. Trees for life, the key to development* (Topper CP. Calligari D.S, Kullaya AK, Shomari SH, Kasuga LJ, Massawe PAL and Mpunami AA Eds) BioHybrids International 260-266

Shomari SH (1999) Potential sources for initial inoculum and dispersal pattern of cashew powdery mildew disease. *Tanzania Journal of Agricultural Sciences* 2(1):63-70

Shrestha AB (1989) Cashew propagation in Tanzania. *A quarterly publication of Agricultural Research and Training Newsletter 4(3):16-19* published by the Ministry of Agriculture Dar Es salaam Tanzania

Sijaona MER and Mansfield JW (1999) Structural resistance of cashew (Anacardium occidentale) against powdery mildew (Oidium anacardii). *Tanzania Journal of Agricultural Sciences* 2:115-125

Sijaona MER (1997) Studies on aspects of cashew resistance to powdery mildew (*Oidium anacardii* Noack) PhD Thesis Wye College University of London UK

Sijaona MER and Shomari SH (1987) The powdery mildew disease of cashew in Tanzania. A quarterly publication of Agricultural Research and Training Newsletter 11 (3):4-5 published by the Ministry of Agriculture Dar Es Salaam Tanzania

Sijaona MER(1984) Investigations into effectiveness of sulphur w.p. against Oidium anacardii Noack on five cashew trees at Naliendele. *Rivista di Agricultura Subtropicale e Tropicale*. 78:199-209.

Singh B. Harris JP and Wilson MJ (1997) Geochemistry of Acid Mine Waters and the Role of Micro-organisms in Such Environments: A Review. *In*: Soils and Environments (Auerswald K, Stanjek H and Bigham JM Eds). *Advances in Geoecology* 30:159-192

Singh BL (1968) *The Mango: Botany Cultivation and Utilization*. World Crops Books Leonard Hill London UK

Smith DN. King WJ . Topper CP. Boma F and Cooper JF (1995) Alternative techniques for the application of sulphur to cashew trees for the control of powdery mildew caused by the fungus *Oidium anacardii* in Tanzania. *Crop Protection* 14 (7):550-560

Smith DN. Topper CP and Cooper JF (1998) Comparison and evaluation of alternative methods for the application of fungicides to cashew trees for the control of powdery mildew disease. *In*: *Proceedings of the international cashew and Coconut Conference - Trees for* *life, the key to development* (Topper CP and Calligari DS *et al.* Eds) BioHybrids International University of Reading UK pp282-285.

Soil Survey Staff (1996) *Keys to Soil Taxonomy*. Seventh Edition. United States Department of Agriculture Washington DC

Sumner ME (1987) Field experimentation: changing to meet current and future needs. *In:* Brown JR (Ed) Soil testing: sampling, correlation, calibration, and interpretation. *Soil Science Society of America*. Special Publication Number 21:119-131

Takkar PN (1988) Sulphur status of Indian soils In Sulphur in Indian Agriculture. Proc TSI FAI Symposium held 9-11th March NewDelhi India

Tanzania Population Census (1988) Population Census. Regional Profile Bureau of Statistics. Planning Commission President's Office Dar es Salaam Tanzania

Thomas GW (1982) Exchangeable cations *In: Methods of Soil Analysis, Part 2*, 2nd edition Page AL. Miller RH and Keeney DR (Eds) 595-624 ASA SSSA Monograph No 9 Madison Wisconsin

Thomas GW and Hargrove WL (1984) Soil Acidity and Liming. *In: The chemistry of Soil Acidity.* Fred Adams (Ed). American Society of Agronomy 12:3-32.

Tisdale SL and Nelson WL (1975) *Soil Fertility and Fertilizers*. Macmillan Company London UK

Tomlin C (ed.) (1994) *The pesticide manual* Incorporating the agrochemical handbook 10th edition. The British Crop Protection Council and the Royal society of Chemistry London UK pp1341

Topper CP, Boma F and Mhando H (1998a) Evaluation of various sulphur formulations for the control of powdery mildew (*Oidium anacardii* Noack) on cashew in Tanzania. A. Fungicide strategy development trials. *In: Proceedings of the international cashew and Coconut Conference. Trees for life, the key to development.* Topper CP, Calligari DS, Kullaya AK. Shomari SH, Kasuga LJ, Massawe PAL and Mpunami AA (Eds.) BioHybrids International 254-259

Topper CP, Boma F and Mhando H (1998b) Evaluation of various sulphur formulations for the control of powdery mildew (*Oidium anacardii* Noack) on cashew in Tanzania. B. On farm testing of fungicide control strategies. *In: Proceedings of the international cashew and Coconut Conference. Trees for life, the key to development.* Topper CP, Calligari DS, Kullaya AK, Shomari SH, Kasuga LJ, Massawe PAL and Mpunami AA (Eds) BioHybrids International 270-276

Topper CP. Martin PJ, Katinila N, Kikoka LP, Lamboll R, Masawe PAL and Shomari SH (1998c) The historical and institutional background of the Tanzanian cashew industry 76-83 *In: Proceedings of the international cashew and Coconut Conference. Trees for life, the key to development*. Topper CP. Calligari DS, Kullaya AK, Shomari SH, Kasuga LJ. Massawe PAL and Mpunami AA (Eds.) BioHybrids International 76-83

Trudinger PA (1986) Chemistry in the sulphur cycle. *In: Sulphur in Agriculture* (Tabatabai MA Ed) Agronomy series 27 American Society of Agronomy Madison USA

Tsakiris A and Northwood PJ (1967) Cashew nut production in Tanzania. IV The root system of the cashew nut tree. *East African Agricultural and Forestry Journal* 33:83-87

Tsakiris A and Northwood PJ (1971) Cashew nut production in southern Tanzania. IV. The root system of the cashew tree *East African Agricultural and Forestry Journal* 33:83-87

Van Breemen N. Dricoll TC and Mulder J (1984) Acid deposition and internal proton sources in acidification of soils and water *Nature* 307:599-604

Van Reuler H (1996) Nutrient management over extended cropping periods in shifting cultivation systems of south-west Côte d'Ivoire. Doctoral Thesis Wageningen Agricultural University The Netherlands

Van Reuler H and Jansen BH (1993) Nutrient fluxes in the shifting cultivation system of south-west Cote d'Ivoire I. Dry matter production, nutrient content and nutrient release after slash and burn for two fallow vegetations. *Plant and Soil* 154:169-177

Verwilghen F (1996) Geomorphology, soil patterns and local land classification in Mtwara region Southern Tanzania MSc dissertation Faculty of Agricultural and Applied Biological Sciences Catholic University of Louvain Belgium

Wainwright M (1984) Sulphur oxidation in soils. Advances in Agronomy 37:349-396

Wait AJ and Jamieson GI (1986) The cashew: its botany and cultivation. *Queeensland Agricultural Journal* 112:253-257

Walworth JL. Letzsch WS and Sumner ME (1986) Use of boundary line in establishing diagnostic norms *Soil Science Soc Am Journal* 50:123-128

Watkinson HJ (1989) Measurement of the oxidation rate of elemental sulfur in soil. *Australian Journal of Soil Research* 27:365-375

Watkinson HJ and Bolan SN (1997) Modelling the rate of elemental sulfur oxidation in soils. In: *Sulphur in the Environment* 135-172 (Maynard DG Ed). Marcel Dekker Inc New York

Weir RG. Garkus B and tkison WT (1963) The effect of particle size on the availability of brimstone sulphur to white clover. *Australian Journal of Experimental Agriculture and Animal Husbandry* 3:314-318

Wembah-Rashid JAR (1975) *The Ethnohistory of the Matrilineal Peoples of southeastern Tanzania* Wien Acta Ethnologica et Linguistica series Africana 9

Wijffels A (1997) Development of a participatory approach in land evaluation for forestry: the case of Angai forest Tanzania. MSc dissertation Faculty of Agricultural and Applied Biological Sciences Catholic University of Louvain Belgium

World Bank (1989) Cashew and Coconut Treecrops Project. Staff Appraisal Report No 7681-TA Southern Africa Department Agriculture Operations Division Nairobi Kenya

Xu S. Harsh JB and Boyle JS (1991) Solid phase control of aluminum acivity in an artificial plant growth medium containing hydroxly-Al-montmorillonite. In *Plant Soil Interaction at Low pH*. Wright R J *et al* (Ed) Kluwer Academic Publishers Dordercht The Netherlands 25-34

Zake JYK (1970) The effect of S on the yield and quality of finger millet in Uganda. PhD Thesis Ohio State University.

List of papers published, accepted and submitted

Published in journals

Ngatunga EL. Cools N. Dondeyne S, Deckers JA and Merckx R (2001) Buffer capacity of cashew growing soils of South Eastern Tanzania. Soil Use and Management. 17 (3):155-162

Published in Proceedings

Ngatunga EL . Dondeyne S and Deckers JA (1998) One decade of sulphur dusting in South Eastern Tanzanian: effects on soil pH. In: Proceedings of the international cashew and Coconut Conference - Trees for life, the key to development Topper C. P., D.S. Calligari, A.K. Kullaya, S.H. Shomari, L.J. Kasuga, P.A.L. Massawe and A.A. Mpunami (Eds.) BioHybrids International 64-70

Accepted for publication in journals

Ngatunga EL. Cools N. Dondeyne S and Deckers JA (2001) Soil suitability for cashew production in South Eastern Tanzania. Accepted for publication in the journal "The Land" (In press)

Accepted for publication in a handbook

Ngatunga EL, Dondeyne S, Cools N, Majule A.E, Mugogo S and Deckers JA (2001) Soils and landscapes of the Southern Zone: their suitability for cashew nut production. Accepted for publication in a handbook titled "A case history of the Tanzania Integrated Cashew Management Programme for Southern Tanzania"

Submitted to journals

Ngatunga EL, Dondeyne S and Deckers JA (2001) Is sulphur acidifying the Cashew growing soils of South Eastern Tanzania? Submitted to Agriculture, Ecosystems and Environment in the Netherlands

Ngatunga EL. Dondeyne S and Deckers JA (2001) Effect of sulphur application on seed germination and yield of maize. sorghum and cowpeas in South Eastern Tanzania. Submitted to the "African Crop Science Journal"

E L. Ngatunga. S. Dondeyne and J.A. Deckers (2001) Field and laboratory evaluation of locally available soil amendments for managing soil acidity due to sulphur dusting in cashew groves in South Eastern Tanzania. Submitted to *TROPICULTURA*.

Annex I Soil correlation:FAO (1990), WRB (FAO-ISRIC-ISSS, 1998) and USDA (1996)

(a) Plateau

Location	FAO Revised legend	WRB	USDA
Msijuie	Haplic Ferralsol	Veti-Acric Ferralsol (Rhodic)	Typic Haplustox
Naliendele	Haplic Acrisol	Rhodi-Arenic Acrisol	Rhodic Haplustult
Mbawala	Xanthic Ferralsol	Xanthi-Acric Ferralsol	Xanthic Eutrustox
Nanguruwe	Haplic Luvisol	Albi-Arenic Luvisol	Arenic Haplustalf
Maranje	Xanthic Ferralsol	Veti-Acric Ferralsol (Xanthic)	Xanthic Eutrustox
Kiromba	Xanthic Ferralsol	Veti-Acric Ferralsol (Xanthic)	Xanthic Haplustox
Mtimko	Xanthic Ferralsol	Veti-Acric Ferralsol (Xanthic)	Xanthic Haplustox
Namkuku	Xanthic Ferralsol	Veti-Acric Ferralsol (Xanthic)	Xanthic Haplustox
Kitama	Xanthic Ferralsol	Veti-Arenic Ferralsol (Xanthic)	Xanthic Haplustox
Madaba	Haplic Alisol	Ochri-Profondic Alisol	Typic Paleustult
Miule	Haplic Ferralsol	Veti-Acric Ferralsol (Haplic)	Typic Kandiustox
Nanyanga	Xanthic Ferralsol	Veti-Acric Ferralsol (Xanthic)	Typic Eutrustox
Chikwaya	Chromic Luvisol	Hapli-Rhodic Luvisol	Typic Rhodustalf
Makonga	Haplic Alisol	Profondi-Arenic Alisol (Dystric)	Typic Paleustult
Mtopwa	Haplic Ferralsol	Veti-Acric Ferralsol (Hyperdystric)	Typic Haplustox
Kitangari	Haplic Alisol	Profondi-Arenic Alisol (Hyperdystric)	Typic Paleustult

(b) Plains

Mlundelunde 1	Haplic Phaeozem	Endolepti-Arenic Phaeozem	Entic Haplustoll
Mlundelunde 2	Chromic Luvisol	Cutani-Rhodic Luvisol	Typic Rhodustalf
Chikukwe	Plinthic Ferralsol	Areni-Plinthic Ferralsol	Plinthic Eutrustox
Chikundi	Haplic Acrisol	Ochri-Profondic Acrisol	Typic Paleustult
Mnanje	Haplic Acrisol	Rhodi-Profondic Acrisol	Typic Paleustult
Mwenge	Humic Cambisol	Hapli-Eutric Cambisol	Typic Ustropept
Temeke Chini	Albic Plinthosol	Ferri-Endocutric Plinthosol	Typic Plinthaqualf
Mraushi	Rhodic Ferralsol	Rhodi-Acric Ferralsol	Kandiustalfic Eustrustox
Chemchem	Eutric Plinthosol	Endo-Petric Plinthosol	Lithic Quartpsisamment
Namatula	Rhodic Ferralsol	Rhodi-Acric Ferralsol (Rhodic)	Rhodic Eutrustox
Nampemba	Haplic Alisol	Profondi-Chromic Alisol	Typic Paleustult
Mandai	Rhodic Ferralsol	Veti-Acric Ferralsol (Rhodic)	Rhodic Eutrustox
Mkumba	Rhodic Ferralsol	Veti-Acric Ferralsol (Rhodic)	Rhodic Eutrustox
Libea	Gleyic Luvisol	Dystri-Gleyic Luvisol	Aquic Kandiustalf

Annex II Cashew nut production costs for a 1 ha and 5 ha producing groves

Cost Item	Cost Item	1 ha ($)	1 ha ($)	5 ha ($)	5 ha ($)
Hired labour	Own labour	Hired labour	Own labour	Hired labour	Own labour
70 trees per ha					
Weeding	0	4.38	0.00	21.88	0.00
Pruning	0	8.75	0.00	43.75	0.00
Sulphur (1.75 bags)	Y	21.88	21.88	109.38	109.38
Nut collection	0	17.50	0.00	87.50	0.00
Spraying	Y	8.75	8.75	43.75	43.75
Bags	Y	7.50	7.50	37.50	37.50
Transport	0	2.50	0.00	12.50	0.00
Subtotal		71.25	38.13	356.25	190.63
50 trees per ha					
Weeding	0	3.13	0.00	15.63	0.00
Pruning	0	6.25	0.00	31.25	0.00
Sulphur	Y	15.63	15.63	78.13	78.13
Nut collection	0	12.50	0.00	62.50	0.00
Spraying	Y	6.25	6.25	31.25	31.25
Bags	Y	6.25	6.25	31.25	31.25
Transport	0	2.50	0.00	12.50	0.00
Subtotal		52.50	28.13	262.50	140.63

* price of 1 ton of cashew nut = US$ 437.50
Y = cost item included
0 = cost item not included
1 US$ = 800 Tanzanian Shillings (Tsh

Annex III Cost of producing annual crops (per ha) in a cashew mixed cropping system*

		Input requirement					
Crop	Target production (ton/ha)	Seed	Fertiliser	Pesticide	Labour	Harvesting bags	Total cost
		US$/ha					
Maize	0.5	3.75	12.50	0.00	0.00	3.13	19.38
Sorghum	0.5	2.50	12.50	0.00	0.00	3.13	18.13
Cassava	25.0	0.00	0.00	0.00	6.25	13.75	20.00
Cowpea	0.5	3.00	6.25	0.00	0.00	3.13	12.38
Pigeon pea	0.5	1.88	6.25	0.00	0.00	3.13	11.25
Total cost							81.13

* 2800 square meters of area per hectare will be used to grow intercrops while the remaining 7200 square meters per hectare will be used to grow cashew

Annex II Cashew nut production costs for a 1 ha and 5 ha producing groves

Cost Item	Cost Item	1 ha ($)	1 ha ($)	5 ha ($)	5 ha ($)
Hired labour	Own labour	Hired labour	Own labour	Hired labour	Own labour
70 trees per ha					
Weeding	0	4.38	0.00	21.88	0.00
Pruning	0	8.75	0.00	43.75	0.00
Sulphur (1.75 bags)	Y	21.88	21.88	109.38	109.38
Nut collection	0	17.50	0.00	87.50	0.00
Spraying	Y	8.75	8.75	43.75	43.75
Bags	Y	7.50	7.50	37.50	37.50
Transport	0	2.50	0.00	12.50	0.00
Subtotal		71.25	38.13	356.25	190.63
50 trees per ha					
Weeding	0	3.13	0.00	15.63	0.00
Pruning	0	6.25	0.00	31.25	0.00
Sulphur	Y	15.63	15.63	78.13	78.13
Nut collection	0	12.50	0.00	62.50	0.00
Spraying	Y	6.25	6.25	31.25	31.25
Bags	Y	6.25	6.25	31.25	31.25
Transport	0	2.50	0.00	12.50	0.00
Subtotal		52.50	28.13	262.50	140.63

* price of 1 ton of cashew nut = US$ 437.50
Y = cost item included
0 = cost item not included
1 US$ = 800 Tanzanian Shillings (Tsh

2 Naliendele

Location	Mtwara region, Mtwara district 3 km south of Naliendele ARI which is 13 km from Mtwara, along the Mtwara-Newala road. The profile is located 1 km from the road to Mbawala village and lays within the CDC experimental farm
UTM Coordinates:	zone 37: 627.3 km E, 8852.1 km S
Authors:	Ngatunga E., Mapua, M.
Date:	11 December 1996
Landform and relief:	landscape unit: Makonde Dissected Plateau, 120 M, site is sloping gently towards east to a broad valley almost 1 km away
Slope of site:	2 - 5 %
Vegetation and land use:	Large portions of the CDC farm are planted with cashew. Other experimental plots with cassava, maize, cowpeas and sorghum. The nearby bush is covered with Makonde thicket.
Soil parent material:	sandstone
Drainage class:	well drained
Rock outcrop:	nil
Surface stones:	nil
Signs of erosion:	nil

Ap 0 - 15 cm: dark brown (7.5 YR 3/ 4) when moist and brown (7.5 YR 4/4) when dry; loamy sand; soft when dry, friable when moist, non sticky and non plastic; weak fine to medium sub-angular blocky structure, patchy medium thick cutans clay and organic matter in nature; few medium to coarse tubular pores, size > 2 mm; few fine to medium roots, sizes 1 - 5 mm; smooth (2 - 5 cm) boundary

AB 15 - 47 cm: brown (7.5 YR 4/6) when moist and brown (7.5 YR 4/6) when dry; loamy sand; slightly hard when dry, friable when moist; slightly sticky and non plastic; moderate fine to medium sub-angular blocky, patchy thin cutans clay and organic matter in nature; few fine tubular pores, size 1 - 2 mm, few fine tubular pores, size 1 - 2 mm; few fine to medium roots, size 1 - 5 mm; smooth (2 - 5 cm) boundary

BA 47 - 108 cm: reddish brown (2.5 YR 4/6) when moist and reddish brown (2.5 YR 4/6) when dry; sandy loam; slightly hard when dry, friable when moist; slightly sticky and slightly plastic; moderate fine to medium sub-angular blocky; patchy thin cutans clay and organic matter in nature; few fine tubular pores size 1 - 2 mm; few common very fine to fine roots, size < 2 mm; smooth (5 - 12 cm) boundary

B 108 - 200+ cm: dark reddish brown (2.5 YR 3/6) when moist and reddish brown (2.5 YR 4/8) when dry; sandy loam; slightly hard when dry, friable when moist; slightly sticky to sticky and slightly plastic; weak fine to medium sub-angular blocky structure; patchy thin cutans clay and organic matter in nature; few fine tubular pores, size ≤ 1 mm; few fine to medium roots, size < 2 mm

A. Physico-chemical characteristics*

Horiz	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Text	pH (H2O)	pH (KCl)	OC (%)	av. P (mg kg^{-1})	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	TEB	CEC soil	CEC clay	BS (%)
Ap	0-15	87	2	11	LS	5.4	4.6	0.51	1.53	0.94	0.17	0.44	0.12	1.668	4	36.4	42
AB	15-47	85	1	14	LS	5.5	4.5	0.24	0.53	0.71	0.33	0.29	0.09	1.416	2.2	15.7	64
BA	47-108	80	2	18	SL	5.0	4.2	0.03	0.70	0.60	0.16	0.37	0.08	1.214	4	22.2	30
B	108-200+	71	3	26	SCL	4.9	4.3	0.20	0.73	0.51	0.57	0.37	0.17	1.607	7	26.9	23

B. Diagnostic horizons, soil classification and correlation

Horiz.	Diagnostic horizon		Classification		
	Revised legend	WRB	Revised Legend	WRB	Soil Taxonomy
Ap	Ochric A-horizon		Haplic Acrisol	Rhodi-Arenic Acrisol (Rhodic)	Rhodic Haplustult
AB					
BA	Argic B-horizon	Argic horizon			
B	Argic B-horizon	Argic horizon			

* Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}, TEB, CEC soil and CEC clay are expressed in $cmol_c\ kg^{-1}$

3 Mbawala

Location:	Mtwara region. Mtwara district, 1 km south of Mbawala village which is located 12 km from Mtwara along the main road Mtwara-Newala. The profile is located on the left of a road to Rudipe settlement.
UTM Coordinates:	zone 37: 621.6 km E, 8843.7 km S
Authors:	Ngatunga E., Dondeyne S., Mapua
Date:	11 December 1996
Landform and relief:	landscape unit. Makonde Dissected Plateau, site is sloping gently towards west to a broad valley almost 400 m away
Slope of site:	2 - 5 %
Vegetation and land use:	Mainly cashew. however, nearby cassava is cultivated. The nearby bush is covered with Makonde thicket.
Soil parent material:	sandstone
Drainage class:	well drained
Rock outcrop:	nil
Surface stones:	nil
Signs of erosion:	nil

Ap 0 - 20 cm. brown (7.5 YR 4/4) when moist and brown (7.5 YR 4/4) when dry; loamy sand; soft when dry. friable when moist, non sticky and non plastic. weak fine sub-angular blocky structure; patchy medium thick clay and organic matter in nature; common fine to medium tubular pores, size > 2 mm. common fine to medium roots. sizes 1 - 5 mm; wavy (2 - 5 cm) boundary

AB 20 - 40 cm. bright brown (7.5 YR 5/6) when moist and bright brown (7.5 YR 5/6) when dry, loamy sand: soft when dry. friable when moist; slightly sticky and slightly plastic; weak fine to medium sub-angular blocky: patchy medium thick cutans clay and organic matter in nature; common fine to medium tubular pores, size > 2 mm; common fine to medium roots, size 1 - 5 mm; irregular (5 - 12 cm) boundary

BA 40 - 88 cm: bright brown (7.5 YR 5/6) when moist and bright brown (7.5 YR 5/6) when dry; sandy loam: slightly hard when dry. friable when moist; slightly sticky and plastic; moderate fine to medium sub-angular blocky: patchy medium thick cutans clay and organic matter in nature; common fine to medium tubular pores. size 2 - 5 mm. few fine to medium roots, size 2 - 5 mm. smooth (5 - 12 cm) boundary

Bw 88 - 200+ cm: bright brown (7.5 YR 5/8) when moist and bright brown (7.5 YR 5/8) when dry; sandy loam: soft when dry. friable when moist; slightly sticky to sticky and plastic; weak fine to medium sub-angular blocky structure: patchy thin clay in nature; few fine tubular pores, size < 1 mm; few fine roots. size 1 - 2 mm

A. Physico-chemical characteristics*

Horiz	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Text	PH (H2O)	pH (KCl)	OC (%)	av. P (mg kg^{-1})	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	TEB	CEC soil	CEC clay	BS (%)
Ap	0-20	81	1	18	SL	5.1	4.4	0.46	3.27	0.90	0.34	0.56	2.62	4.412	2.2	12.2	100
AB	20-40	75	1	24	SCL	5.1	4.4	0.20	0.43	0.63	0.42	0.33	2.59	3.98	4.4	18.3	90
BA	40-88	73	1	26	SCL	5.1	4.2	0.16	0.07	0.50	0.22	0.34	0.15	1.211	4.2	16.2	29
Bw	88-200+	69	2	29	SCL	5.05	4.2	0.03	4.83	0.65	0.49	0.30	0.11	1.55	4.8	16.6	32

B. Diagnostic horizons, soil classification and correlation

Horiz	Diagnostic horizon		Classification		
	Revised legend	WRB	Revised Legend	WRB	Soil Taxonomy
Ap	Ochric A-horizon	Ochric horizon	Xanthic Ferralsol	Xanthi-Acric Ferralsol	Xanthic Eutrustox
AB	Argic B-horizon	Argic horizon			
BA	Ferralic B-horizon	Ferralic horizon			
Bw	Ferralic B-horizon	Ferralic horizon			

* Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}, TEB, CEC soil and CEC clay are expressed in $cmol_c\ kg^{-1}$

4 Nanguruwe

Location	Mtwara region. Mtwara district, 20 km from Mtwara, on the left side of the Mtwara-Newala road
UTM Coordinates	Zone 37: 613.5 km E, 8839.5 km S
Authors	Ngatunga E., Dondeyne S., Mapua
Date	10 December 1996
Landform and relief:	landscape unit: Makonde Dissected Plateau, site is sloping north-northwestwards
Slope of site:	5 %
Vegetation and land use:	Mainly cashew. The nearby bush is covered with Makonde tichet.
Soil parent material	sandstone
Drainage class:	well drained
Rock outcrop	nil
Surface stones	nil
Signs of erosion	nil

Ap 0 - 39 cm greyish yellow brown (10 YR 4/2) when moist and greyish yellow brown (10 YR 5/2) when dry; loamy sand; soft when dry, very friable when moist; non sticky and non plastic; weak fine to medium sub-angular blocky structure; patchy and medium thick cutans clay and organic matter in nature; few to common tubular pores, all sizes; many fine to coarse roots, all sizes; smooth (< 2 cm) boundary

A 39 - 65 dull yellowish brown (10 YR 4/3) when moist and dull yellow brown (10 YR 5/3) when dry: loamy sand: slightly hard when dry, very friable when moist; non sticky and non plastic; moderate medium sub-angular blocky structure; patchy and medium thick cutans mainly clay and organic matter in nature: few tubular pores, size > 5 mm and common tubular pores, size 1 - 2 mm; common fine to medium roots. all sizes, smooth (5 - 12 cm) boundary

AB 65 - 143 cm: dull yellowish brown (10 YR 4/3) when moist and dull yellow orange (10 YR 6/3) when dry, loamy sand, slightly hard when dry, very friable when moist; slightly sticky and slightly plastic, moderate medium sub-angular structure; patchy and medium thick cutans mainly clay in nature; common tubular pores, size 1 -2 mm; few fine to coarse roots, all sizes; smooth (5 - 12 cm) boundary

Bt 143 - 200+ cm bright brown (7.5 YR 5/6) when moist and dull yellow orange (10 YR 6/4) when dry, sandy clay loam, slightly hard when dry, friable when moist; slightly sticky and slightly plastic; moderate medium to coarse sub-angular blocky structure; patchy and thin cutans mainly clay in nature; common tubular pores, size 1 - 2 mm; few fine roots size < 1 mm

A. Physico-chemical characteristics*

Horiz	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Text	pH (H2O)	pH (KCl)	OC (%)	av. P ($mg\ kg^{-1}$)	Ca^{2+}	Mg^{2+}	K^{2+}	Na^{+}	TEB	CEC soil	CEC clay	BS (%)
Ap	0-39	87	5	8	LS	5.6	4.5	0.42	3.27	0.81	0.94	0.33	2.08	4.159	1.8	22.5	100
A	39-65	83	2	15	SL	5.4	4.15	0.20	2.10	0.65	0.31	0.17	2.49	3.622	3.2	21.3	100
AB	65-143	76	3	21	SCL	5.3	4.0	0.18	0.83	1.68	0.45	0.27	2.52	4.917	4.8	22.9	100
Bt	143-200+	71	3	26	SCL	5.2	4.0	0.22	0.80	0.71	0.34	0.25	2.66	3.959	5.6	21.5	71

B. Diagnostic horizons, soil classification and correlation

Horiz	Diagnostic horizon		Classification		
	Revised legend	WRB	Revised Legend	WRB	Soil Taxonomy
Ap	Ochric A-horizon	Ochric horizon	Haplic Luvisol	Albi-Arenic Luvisol	Arenic Haplustalf
A	Argic B-horizon	Argic horizon			
AB	Argic B-horizon				
Bt	Argic B-horizon				

* Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}, TEB, CEC soil and CEC clay are expressed in $cmol_c\ kg^{-1}$

5 Maranje

Location:	Mtwara region, Mtwara district, along the main road Mtwara-Newala; profile is located on the left of a road to Rudipe settlement
UTM Coordinates:	Zone 37: 621.6 km E, 8843.7 km S
Authors:	Ngatunga E., Dondeyne S., Mapua
Date:	11 December 1996
Landform and relief:	landscape unit: Makonde Dissected Plateau, site is sloping gently towards southwest
Slope of site:	5 %
Vegetation and land use:	Mainly cashew, however, nearby cassava is cultivated. The nearby bush is covered with Makonde thicket.
Soil parent material:	sandstone
Drainage class:	well drained
Rock outcrop:	nil
Surface stones:	nil Signs of erosion: nil

Ap 0 - 14 cm: brown (7.5 YR 4/3) when moist and brown (7.5 YR 4/4) when dry; loamy sand; soft whendry, very friable when moist; slightly sticky and non plastic; weak medium to coarse sub-angular blocky structure; patchy and medium thick cutans clay and organic matter in nature; few tubular pores, size > 2 mm; common fine to medium roots, size > 1 mm; wavy (< 2 cm) boundary

AB 14 - 33 cm: brown (7.5 YR 4/4) when moist and brown (7.5 YR 4/4) when dry; loamy sand; slightly hard when dry, friable when moist, slightly sticky and slightly plastic; weak to moderate medium sub-angular blocky structure; patchy and medium thick cutans mainly clay and organic matter in nature; common tubular pores, size > 2 mm, common fine to medium roots, all sizes; smooth (2 - 5 cm) boundary

Bt_1 33 - 60 cm: brown (7.5 YR 4/6) when moist and bright brown (7.5 YR 5/6) when dry; sandy clay loam; slightly hard when dry, friable when moist; slightly sticky and slightly plastic; weak to moderate medium sub-angular blocky structure; patchy and medium thick cutans mainly clay and organic matter in nature; common tubular pores, size > 2 mm; few fine to coarse roots, all sizes; smooth (5 - 12 cm) boundary

Bt_2 60 - 100 cm: bright brown (7.5 YR 5/6) when moist and orange (7.5 YR 6/6) when dry; sandy clay loam; slightly hard when dry, friable when moist, slightly sticky and slightly plastic; moderate medium sub-angular blocky structure; patchy and thin to medium thick cutans mainly clay in nature; common tubular pores, size > 1 mm; few fine to medium roots, size < 5 mm; smooth (5 - 12 cm) boundary

Bt_3 100 - 200+ cm: bright brown (7.5 YR 5/8) when moist and bright brown (7.5 YR 5/8) when dry; sandy clay loam; soft when dry, friable when moist; slightly sticky and plastic; weak fine to medium sub-angular blocky structure; patchy and thin cutans mainly clay in nature; common tubular pores, size < 1 mm; few fine roots, size < 2 mm

A. Physico-chemical characteristics*

Horiz.	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Text.	pH (H2O)	pH (KCl)	OC (%)	av. P (mg kg^{-1})	Ca^{2+}	Mg^{2+}	K^{2+}	Na^{+}	TEB	CEC soil	CEC clay	BS (%)
Ap	0-14	85	3	12	LS	5.3	4.2	0.46	4.63	1.30	0.39	0.24	0.20	2 127	5.2	43 3	41
AB	14-33	76	3	21	SCL	5.1	4.2	0.55	1.80	0.62	0.47	0.29	0.34	1.726	4.8	22.9	36
Bt_1	33-60	75	0	25	SCL	5.0	4.0	0 22	1.30	1.11	0.26	0.34	0.75	2.456	6.0	24	41
Bt_2	60-100	74	1	25	SCL	5.4	4.1	0.10	1.03	0.56	0.51	0.24	1.47	2.787	2.2	8.8	100

B. Diagnostic horizons, soil classification and correlation

Horiz	Diagnostic horizon		Classification		
	Revised legend	WRB	Revised Legend	WRB	Soil Taxonomy
Ap	Ochric A-horizon	Ochric horizon	Xanthic Ferralsol	Veti-Acric Ferralsol (Xanthic)	Xanthic Eutrustox
AB	Argic B-horizon	Argic horiozon			
Bt_1	Argic B-horizon	Argic horiozon			
Bt_2	Ferralic B-horizon	Ferralic horizon			

* Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}, TEB, CEC soil and CEC clay are expressed in $cmol_c\ kg^{-1}$

6 Kiromba

Location:	Mtwara region, Mtwara district, 12km south of Maranje village which is 40 km from Mtwara along the Mtwara-Newala road. The profile is located 2 km north before reaching Kiromba village
UTM Coordinates	Zone 37: 613 3 km E, 8820.1 km S
Authors:	Ngatunga E., Mapua
Date	30 December 1996
Landform and relief	landscape unit: Makonde Dissected Plateau, site is sloping southwards (123 m)
Slope of site:	4 - 6 %
Vegetation and land use	mainly cashew, nearby farms have been planted with cassava; the nearby bush is covered with Makonde ticket
Soil parent material:	sandstone
Drainage class:	well drained
Rock outcrop	nil
Surface stones	nil
Signs of erosion	nil

Ap 0 - 17 cm greyish yellow brown (10 YR 6/2) when moist and greyish yellow brown (10 YR 5/2) when dry: loamy sand. soft when dry, very friable when moist; non sticky and non plastic; weak fine granular structure. no cutans; few fine to medium tubular pores, size 1 - 5 mm; common fine roots, size < 5 mm, smooth (< 2 cm) boundary

E 17 - 38 cm: dull yellow orange (10 YR 6/3) when moist and dull yellowish brown (10 YR 5/3) when dry; loamy sand; slightly hard when dry, friable when moist; slightly sticky and slightly plastic; weak to moderate medium sub-angular blocky; no cutans; no pores; few fine to medium roots, size 1 - 5 mm. smooth (< 2 cm) boundary

B_1 38 - 85 cm dull yellow orange (10 YR 6/3) when moist and dull yellowish brown (10 YR 5/3) when dry: sandy loam slightly hard when dry, friable when moist, slightly sticky and slightly plastic; weak to moderate medium sub-angular blocky, no cutans; no pores, very few fine to medium roots, size 1 - 5 mm smooth (< 2 cm) boundary

B_2 85 - 200+ cm: dull yellow orange (10 YR 7/3) when moist and dull yellow orange (10 YR 6/3) when dry. sandy loam; hard when dry, friable when moist; sticky and plastic; moderate medium to coarse sub-angular blocky structure; no pores; very few fine roots, size 2 - 5 mm

A. Physico-chemical characteristics*

Horiz.	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Text.	pH (H_2O)	pH (KCl)	OC (%)	N (%)	Av. P (mg kg^{-1})	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	CEC soil	CEC clay	BS (%)
Ap	0-17	89	2	9	S	5.1	4.2	0.40	0.05	3.06	0.30	0.12	0.11	0.01	0.54	1.38	15.3	39
E	17-38	84	5	11	LS	4.4	4.0	0.3	0	3.42	0.20	0.10	0.10	0	0.42	2.1	19.1	20
B_1	38-85	81	2	17	SL	4.7	3.9	0.13	0.04	0.72	0.03	0.03	0.11	0.01	0.18	0.69	4.1	26
B_2	85-200+	78	3	19	SL	4.7	3.8	0.14	0.02	0.49	0.13	0.02	0.11	0.01	0.27	0.93	4.9	29

B Diagnostic horizons, soil classification and correlation

Horiz.	Diagnostic horizon		Classification		
	Revised Legend	WRB	Revised Legend	WRB	Soil Taxonomy
Ap	Ochric A-horizon	Ochric horizon	Xanthic Ferralsol	Veti-Acric Ferralsol (Xanthic)	Xanthic Haplustox
E					
B_1	Ferralic B-Horizon	Ferralic horizon			
B_2	Ferralic B-Horizon	Ferralic horizon			

* Ca^{2+}, Mg^{2+}, K^+, Na^+, TEB, CEC soil and CEC clay are expressed in $cmol_c\ kg^{-1}$

7 Mtiniko

Location:	Mtwara region, Mtwara district, Along the Mtwara-Newala road about 50 km from Mtwara. The profile is on the left side of the road.
UTM Coordinates:	Zone 37: 605.2 km E, 8829.5 km S
Authors:	Ngatunga E., Dondeyne S., Mapua
Date:	10 December 1996
Landform and relief:	landscape unit: Makonde Dissected Plateau site is sloping southwestwards
Slope of site:	5 - 10 %
Vegetation and land use:	mainly cashew, intercropped on nearby farms with cassava. The nearby bush is covered with Makonde ticket.
Soil parent material:	sandstone
Drainage class:	well drained
Rock outcrop:	nil
Surface stones:	nil
Signs of erosion:	nil

Ap 0 - 8 cm: greyish yellow brown (10 YR 5/2) when moist and greyish yellow brown (1O YR 4/2)when dry: loamy sand: soft when dry, friable when moist; non sticky and non plastic; weak fine granular structure; no cutans; few fine tubular pores, size 1 - 2 mm; common fine to medium roots, size 1 - 5 mm. smooth (2 - 5 cm) boundary

AB 8 - 40 cm: dull yellowish brown (10 YR 5/3) when moist and dull yellowish brown (1O YR 4/3) when dry; loamy sand; soft to slightly hard when dry, friable when moist; slightly sticky and non plastic; weak to moderate fine to medium sub-angular blocky structure; patchy and thin cutans mainly clay and organic matter in nature; few fine tubular pores, size 1 -2 mm; common fine to medium roots, size 1 - 5 mm; smooth (2 - 5 cm) boundary

Bt_1 40 - 141 cm: dull yellowish orange (10 YR 6/4) when moist and dull yellowish brown (10 YR 5/4) when dry: sandy loam: soft to slightly hard when dry, friable when moist; sticky and plastic; moderate fine to medium sub-angular blocky structure; patchy and thin cutans which are clay and organic in nature; common tubular pores, size 1 - 2 mm; few fine roots, size < 1 mm; smooth (2 - 5 cm) boundary

Bt_2 141 - 200+ cm: bright yellowish brown (10 YR 6/6) when moist and yellowish brown (10 YR 5/6) when dry: sandy clay, soft to slightly hard when dry, friable to firm when moist; sticky and plastic; weak to moderate fine to medium sub-angular blocky structure; patchy and thin cutans mainly clay in nature; few tubular pores, size 1 - 2 mm, very few very fine roots, size < 1mm

A. Physico-chemical characteristics*

Horiz	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Text.	pH (H_2O)	pH (KCl)	OC (%)	N (%)	Av. P (mg kg^{-1})	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	CEC soil	CEC clay	BS (%)
Ap	0-8	85	5	10	LS	5.6	4.4	1.03	0.11	16.40	0.73	0.30	0.16	0.01	1.20	2.14	21.4	56
AB	8-40	84	3	13	LS	4.9	4.0	0.41	0.03	1.94	0.15	0.15	0.14	0.05	0.49	1.16	8.9	38
Bt_1	40-141	81	3	16	SL	5.5	4.0	0.28	0.02	0.85	0.18	0.15	0.14	0.02	0.49	0.96	6.0	49
Bt_2	141-200+	72	4	14	SL	4.8	3.9	0.15	0.01	0.56	0.40	0.11	0.11	0.05	0.67	2.09	14.9	32

B. Diagnostic horizons, soil classification and correlation

Horiz	Diagnostic horizon		Classification		
	Revised Legend	WRB	Revised Legend	WRB	Soil Taxonomy
Ap	Ochric A-horizon	Ochric horizon	Xanthic Ferralsol	Veti-AcricFerralsol (Xanthic)	Xanthic Haplustox
AB					
Bt_1	Ferralic B-Horizon	Ferralic horizon			
Bt_2		Ferralic horizon			

* Ca^{2+}, Mg^{2+}, K^+, Na^+, TEB, CEC soil and CEC clay are expressed in $cmol_c\ kg^{-1}$

8 Namkuku

Location:	Mtwara region, Mtwara district 7 km north of Nanyamba village which is 70 km from Mtwara along the Mtwara-Newala road; profile is 200 m from house of Mr. Mawji
UTM Coordinates:	Zone 37: 587.4 km E, 8822.8 km S
Authors:	Ngatunga E., Mapua
Date:	21 December 1996
Landform and relief:	landscape unit: Makonde Dissected Plateau, site is very gently sloping towards the north-west
Slope of site	2 -3 %
Vegetation and land use:	mainly cashew, intercropped with cassava on some parts of the field. The nearby bush is covered with Makonde thicket.
Soil parent material:	sandstone
Drainage class:	well drained
Rock outcrop:	nil
Surface stones:	nil
Signs of erosion:	nil

Ap 0 - 8 cm dull yellowish brown (10 YR 5/4) when moist and dull yellowish brown (10 YR 5/3) when dry: loamy sand; loose when dry, loose when moist; non sticky and non plastic; very weak very fine to fine granular structure; few patchy cutans which are organic matter in nature; few medium tubular pores, size 2 - 5 mm, common fine roots, size 1 - 2 mm; wavy (2 - 5 cm) boundary

AB 8 - 31 cm yellowish brown (10 YR 5/6) when moist and yellowish brown (10 YR 5/6) when dry; loamy sand; soft when dry, friable when moist; slightly sticky and non plastic; weak and very fine to fine granular structure; few granules of high clay concentrations; patchy thin cutans mainly clay and organic matter in nature; common medium tubular pores, size 2 - 5 mm; common medium to coarse roots, size > 2 mm; smooth (2 - 5 cm) boundary

BA 31 - 87 cm: brown (10 YR 4/6) when moist and brown (10 YR 4/6) when dry; loamy sand; soft when dry, friable when moist; slightly sticky and slightly plastic; weak fine granular and weak fine sub-angular blocky structure; patchy and thin cutans and few small granules of high clay concentrations; few very fine tubular pores, size < 1 mm; few fine to medium roots, size 1 - 5 mm; smooth (2 - 5 cm) boundary

B 87 - 200+ cm: brown (10 YR 4/6) when moist and brown (10 YR 4/6) when dry; sandy loam; soft to slightly hard when dry, friable when moist; slightly sticky and slightly plastic; moderate fine to medium sub-angular blocky structure; no cutans; few very fine tubular pores, size < 1 mm; few fine roots, size 1 - 2 mm

A. Physico-chemical characteristics*

Horiz	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Text.	pH (H_2O)	pH (KCl)	OC (%)	N (%)	Av. P (mg kg^{-1})	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	CEC soil	CEC clay	BS (%)
Ap	0-8	89	1	10	S	4.4	3.2	0.53	0.07	5.53	0.09	0.06	0.09	0.01	0.25	1.56	15.6	16
AB	8-31	86	1	13	LS	4.2	3.8	0.68	0.07	1.64	0.06	0.03	0.05	0.05	0.19	1.27	9.8	15
BA	31-87	82	1	17	SL	4.4	3.9	0.26	0.02	1.61	0.07	0.04	0.03	0.03	0.17	1.11	6.5	18
B	87-200+	73	3	24	SCL	4.6	4.0	0.10	0.01	2.16	0.03	0.02	0.02	0.05	0.12	0.55	2.3	22

B. Diagnostic horizons, soil classification and correlation

Horiz.	Diagnostic horizon: Revised Legend	Diagnostic horizon: WRB	Classification: Revised Legend	Classification: WRB	Classification: Soil Taxonomy
Ap	Ochric A-horizon	Ochric horizon	Xanthic Ferralsol	Veti-Acric Ferralsol (Xanthic)	Xanthic Haplustox
AB					
BA	Ferralic B-Horizon	Ferralic horizon			
B	Ferralic B-Horizon	Ferralic horizon			

* Ca^{2+}, Mg^{2+}, K^+, Na^+, TEB, CEC soil and CEC clay are expressed in $cmol_c\ kg^{-1}$

9 Kitama

Location:	Mtwara region, Tandahimba district 1km north of Kitama village, 80 km from Mtwara, along Mtwara-Newala road; profile is on the right side of the road to Mkonjowano village
UTM Coordinates:	Zone 579.3 km E, 8811.9 km S
Authors:	Ngatunga E., Mapua
Date:	21 December 1996
Landform and relief:	landscape unit: Makonde Dissected Plateau, sloping gently northwards
Slope of site:	1 - 2 %
Vegetation and land use:	mainly cashew, also cassava and sorghum; the nearby bush is covered with Makonde ticket
Soil parent material:	sandstone
Drainage class:	well drained
Rock outcrop:	nil
Surface stones:	nil
Signs of erosion:	nil

Ap 0 - 10 cm brown (10 YR 4/4) when moist and dull yellowish brown (10 YR 5/4) when dry; loamy sand, soft when dry, very friable when moist; non sticky and non plastic; weak very fine to fine granular structure; no cutans; common fine to medium tubular pores, size 1 - 5 mm; common fine roots, size < 2 mm; smooth (< 2 cm) boundary

AB 10 - 37 cm brown (10 YR 4/6) when moist and yellowish brown (10 YR 5/6) when dry; loamy sand; very soft when dry, very friable when moist; slightly sticky and non plastic; very weak and very fine to fine granular structure; patchy and thin mainly clay and organic matter in nature; common fine to medium tubular pores, size 1 - 5 mm; few fine to medium roots, size < 2 mm; smooth (2 - 5 cm) boundary

B_1 37 - 127 cm brown (10 YR 4/6) when moist and yellowish brown (10 YR 5/6) when dry; loamy sand; slightly hard when dry, friable when moist; slightly sticky and slightly plastic; moderate medium sub-angular blocky structure, patchy and thin cutans mainly organic matter in nature; few fine tubular pores, size 1 - 2 mm; very few fine roots, size ≤ 1 mm; smooth (2 - 5 cm) boundary

B_2 127 - 200+ cm: brown (10 YR 4/6) when moist and brown (10 YR 4/6) when dry; loamy sand; slightly hard when dry, friable when moist; sticky and plastic; weak to moderate medium sub-angular blocky structure; patchy and thin to medium thick cutans mainly clay in nature; common tubular pores, size 1 - 2 mm to > 5 mm, few fine to medium roots, size < 5 mm;

A. Physico-chemical characteristics*

Horiz.	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Text	pH (H_2O)	pH (KCl)	OC (%)	N (%)	Av. P (mg kg^{-1})	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	CEC soil	CEC clay	BS (%)
Ap	0-10	85	3	12	LS	4.8	4.0	0.52	0.06	6.82	0.12	0.07	0.03	0.02	0.24	3.66	30.5	29
AB	10-37	83	1	16	SL	4.5	4.0	0.34	0.04	2.25	0.05	0.03	0.06	0.02	0.16	0.89	5.6	18
B_1	37-127	80	2	18	SL	5.0	4.1	0.18	0.02	3.85	0.09	0.06	0.02	0.01	0.18	0.47	2.6	38
B_2	127-200+	75	3	22	SCL	5.2	4.2	0.10	0.01	3.48	0.35	0.03	0.03	0.02	0.43	1.00	4.5	43

B. Diagnostic horizons, soil classification and correlation

Horiz.	Diagnostic horizon		Classification		
	Revised Legend	WRB	Revised Legend	WRB	Soil Taxonomy
Ap	Ochric A-horizon	Ochric horizon	Xanthic Ferralsol	Veti-Arenic Ferralsol (Xanthic)	Xanthic Haplustox
AB					
B_1	Ferralic B-Horizon	Ferralic horizon			
B_2	Ferralic B-Horizon	Ferralic horizon			

* Ca^{2+}, Mg^{2+}, K^+, Na^+, TEB, CEC soil and CEC clay are expressed in $cmol_c\ kg^{-1}$

10 Madaba

Location	Mtwara region, Tandahimba district, 1 km east of Madaba village which is 70 from Mtwara. The profile is on the right side of the Mtwara-Newala road before reaching the village.
UTM Coordinates:	Zone 37: 575 km E. 8810.7 km S
Authors	Ngatunga E., Dondeyne S
Date	4 April 1997
Landform and relief:	landscape unit: Makonde Dissected Plateau, site is sloping southwestwards
Slope of site	8 %
Vegetation and land use	Mainly cashew. The nearby bush is Makonde thicket
Soil parent material	sandstone
Drainage class:	well drained, moist conditions when described
Rock outcrop	nil
Surface stones	nil
Signs of erosion:	nil

Ap 0 - 36 cm: greyish yellow brown (10 YR 5/2) when moist; loamy sand; very friable when moist; non sticky to non plastic; weak fine to medium sub-angular blocky structure; no cutans; common fine to medium tubular pores, size 1 -2 mm; many very fine to coarse roots, all sizes; clear and smooth (< 2 cm) boundary

AB 36 - 78 cm: greyish yellow brown (10 YR 5/2) when moist; sandy loam; very friable when moist; no sticky and non plastic; very weak medium sub-angular blocky structure; patchy and thin cutans seen on voids and pedfaces mainly clay in nature, few fine to coarse tubular pores, size 1 - 5 mm; few fine to coarse roots, all sizes; smooth (2 - 5 cm) boundary;

Bt_1 78 - 113 cm: greyish yellow brown (10 YR 5/2) when moist; sandy clay loam; friable when moist; slightly sticky and slightly plastic, weak medium sub-angular blocky structure; patchy and thin cutans mainly organic matter in nature, few fine to coarse tubular pores, size 1 - 5 mm; very few fine roots, size ≤ 1 mm; smooth (2 - 5 cm) boundary

Bt_2 113 - 200+ cm; greyish yellow brown (10 YR 5/2) when moist; sandy clay loam; friable when moist; slightly sticky and plastic; moderate medium sub-angular blocky structure; broken and medium thick cutans mainly clay in nature; few fine to coarse tubular pores, size 1 - 5 mm; few fine to medium roots, size < 5 mm

A Physico-chemical characteristics*

Horiz	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Text	pH (H_2O)	pH (KCl)	OC (%)	N (%)	Av P (mg kg^{-1})	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	CEC soil	CEC clay	BS (%)
Ap	0-36	87	3	10	LS	5.4	4.0	0.25	0.02	8.64	0.70	0.30	0.20	0.02	1.22	2.54	25.4	48
AB	36-78	82	3	15	LS	5.1	4.0	0.13	0.01	7.99	0.90	0.40	0.13	0.02	1.45	3.72	24.8	39
Bt_1	78-113	73	3	24	SCL	4.9	3.9	0.12	0.01	4.43	1.20	0.60	0.13	0.02	1.95	6.09	25.4	32
Bt_2	113-200+	66	2	32	SCL	4.8	3.8	0.20	0.03	4.37	1.30	0.90	0.11	0.04	2.35	8.10	25.3	29

B Diagnostic horizons, soil classification and correlation

Horiz	Diagnostic horizon		Classification		
	Revised Legend	WRB	Revised Legend	WRB	Soil Taxonomy
Ap	Ochric A-horizon	Ochric horizon	Haplic Alisol	Ochri-Profondic Alisol	Typic Paleustult
AB					
Bt_1	Argic B-horizon	Argic horizon			
Bt_2	Argic B-horizon	Argic horizon			

* Ca^{2+}, Mg^{2+}, K^+, Na^+, TEB, CEC soil and CEC clay are expressed in $cmol_c\ kg^{-1}$

11 Miule

Location:	Mtwara region, Tandahimba district, 2 km west of Miule village which is on the road Mtwara - Newala
UTM Coordinates	Zone 37: 573.7 km E, 8812.4 km S
Authors:	Ngatunga E., Mapua
Date	20 December 1996
Landform and relief	landscape unit Makonde Dissected Plateau, sloping gently westwards
Slope of site:	1-2 %
Vegetation and land use	mainly cashew, nearby land is covered with Makonde ticket
Soil parent material:	sandstone
Drainage class:	well drained
Rock outcrop.	nil
Surface stones	nil
Signs of erosion:	slight sheet erosion

Ap 0 - 17 cm: very dark brown (7.5 YR 2/3) when moist and dark brown (7.5 YR 3/ 4) when dry; sandy loam: soft to slightly hard when dry, friable when moist; sticky and plastic; weak fine to medium sub-angular blocky structure; no cutans; common fine tubular pores, size 1 - 2 mm; common fine to medium roots, size 1 - 5 mm; smooth (2 -5 cm) boundary

E 17 -47 cm: brown (7.5 YR 4/6) when moist and brown (7.5 YR 4/6) when dry; sandy clay loam; slightly hard when dry, friable when moist; sticky and plastic; moderate fine to medium sub-angular blocky; few patchy cutans clay and organic matter in nature; common tubular pores, size 1 - 2 mm; common to medium coarse roots, size > 1 mm, smooth (2 -5 cm) boundary

Bt_1 47 - 100 cm. brown (7.5 YR 4/4) when moist and brown (7.5 YR 4/4) when dry; sandy clay; slightly hard when dry, friable when moist, sticky and plastic; moderate medium to coarse sub-angular blocky structure: few patchy thin cutans which are clay and organic matter in nature; common medium tubular pores, size 2 - 5 mm; common fine to medium roots, size 1 - 5 mm; smooth (2 - 5 cm) boundary

Bt_2 100 - 200+ cm: reddish brown (5 YR 4/8) when moist and reddish brown (5 YR 4/8) when dry; sandy clay; slightly hard when dry, friable to firm when moist; sticky and plastic; moderate fine to medium sub-angular blocky structure; few patchy and thin cutans organic matter in nature; few very fine tubular pores, size < 1 mm; few very fine roots, size < 1 mm

A Physico-chemical characteristics*

Horiz	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Text	pH (H_2O)	pH (KCl)	OC (%)	N (%)	Av. P (mg kg^{-1})	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	CEC soil	CEC clay	BS (%)
Ap	0-17	80	3	17	SL	5.2	4.2	0.91	0.10	2.60	0.81	0.48	0.11	0.02	1.42	3.64	21.4	39
E	17-47	75	3	22	SCL	4.7	3.9	0.42	0.05	0.95	0.20	0.16	0.03	0.01	0.40	1.54	7.0	26
Bt_1	47-100	67	2	31	SCL	4.3	3.8	0.43	0.03	0.40	0.25	0.10	0.02	0.01	0.38	2.71	8.7	14
Bt_2	100-200+	60	2	38	SC	4.9	3.9	0.29	0.03	0.39	0.18	0.12	0.01	0.01	0.32	1.00	2.6	32

B Diagnostic horizons, soil classification and correlation

Horiz	Diagnostic horizon		Classification		
	Revised Legend	WRB	Revised Legend	WRB	Soil Taxonomy
Ap	Ochric A-horizon	Ochric horizon	Haplic Ferralsol	Veti-Acric Ferralsol (Haplic)	Typic Kandiustox
E					
Bt_1	Ferralic B-Horizon	Ferralic horizon			
Bt_2	Ferralic B-Horizon	Ferralic horizon			

* Ca^{2+}, Mg^{2+}, K^+, Na^+, TEB, CEC soil and CEC clay are expressed in $cmol_c\ kg^{-1}$

12 Nanyanga

Location	Mtwara region. Tandahimba district, 4 km east of Nanyanga village which is on the road Mtwara - Newala
UTM Coordinates	Zone 37. 556.8 km E, 8807.1 km S
Authors	Ngatunga E., Mapua
Date	20 December 1996
Landform and relief	landscape unit. Makonde Dissected Plateau, site is sloping northwards
Slope of site	2 %
Vegetation and land use:	mainly cashew, intercropped with cowpeas and bambaranuts at some parts of the farm
Soil parent material	sandstone
Drainage class	well drained
Rock outcrop	nil
Surface stones	nil
Signs of erosion	slight

Ap 0 - 18 cm: dark brown (7.5 YR 3/3) when moist and dark brown (7.5 YR 3/3) when dry; sandy loam. soft to slightly hard when dry, friable when moist; sticky and plastic; weak fine granular structure. no cutans, common tubular pores, size 1 - 2 mm; common fine to medium roots, size 1 - 5 mm; smooth (2 - 5 cm) boundary

E 18 - 51 cm: brown (7.5 YR 4/4) when moist and brown (7.5 YR 4/4) when dry; sandy loam; slightly hard when dry, friablewhen moist; sticky and plastic to very plastic; moderate fine to medium sub-angular blocky structure ; few patchy cutans clay and organic matter in nature; common tubular pores. size 1 - 2 mm. few to common coarse roots. size > 2 mm; wavy (2 - 5 cm) boundary

Bt_1 51 - 132 cm: brown (7.5 YR 4/6) when moist and brown (7.5 YR 4/6) when dry; sandy clay; hard when dry. friable to firm when moist; sticky and plastic, moderate medium to coarse sub-angular blocky structure. no cutans, common tubular pores, size 2 - 5 mm; few roots, size 1 - 2 mm; smooth (2 - 5 cm) boundary

Bt_2 132 - 200+ cm: bright brown (7.5 YR 5/6) when moist and bright brown (7.5 YR 5/8) when dry; sandy clay loam; slightly hard when dry, friable when moist; sticky and plastic; weak medium to coarse sub-angular blocky structure; few patchy and thin cutans organic matter in nature; few tubular pores, size < 1 mm; few roots, size < 1mm

A Physico-chemical characteristics*

Horiz	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Text	pH (H_2O)	pH (KCl)	OC (%)	N (%)	Av. P (mg kg^{-1})	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	CEC soil	CEC clay	BS (%)
Ap	0-18	75	5	20	SL	4.6	3.6	1.12	0.10	3.11	0.55	0.32	0.05	0.05	0.97	3.88	19.4	25
E	18-51	69	4	27	SCL	4.5	3.6	0.66	0.06	1.07	0.33	0.12	0.01	0.02	0.48	2.18	8.1	22
Bt_1	51-132	61	3	36	SC	4.7	3.9	0.71	0.06	0.56	0.16	0.07	0.01	0.01	0.25	0.93	2.6	27
Bt_2	132-200+	58	4	38	SC	4.8	4.0	0.30	0.04	0.30	0.21	0.12	0.01	0.05	0.39	1.34	3.5	29

B Diagnostic horizons, soil classification and correlation

Horiz	Diagnostic horizon		Classification		
	Revised Legend	WRB	Revised Legend	WRB	Soil Taxonomy
Ap	Ochric A-horizon	Ochric horizon	Xanthic Ferralsol	Veti-Acric Ferralsol (Xanthic)	Typic Eutrustox
E					
Bt_1	Ferralic B-Horizon	Ferralic horizon			
Bt_2	Ferralic B-Horizon	Ferralic horizon			

* Ca^{2+}, Mg^{2+}, K^+, Na^+, TEB, CEC soil and CEC clay are expressed in $cmol_c\ kg^{-1}$

13 Chikwaya

Location:	Mtwara region, Newala district, 3 km south of Mahumbika village which is 6 km from Newala town along the Mtwara-Newala road
UTM Coordinates:	Zone 37: 538.7 km E, 8892.6 km S
Authors:	Ngatunga E., Dondeyne S. and Wieland
Date:	4 April 1997
Landform and relief:	landscape unit: Makonde Plateau, site is sloping southwards
Slope of site:	5 %
Vegetation and land use:	cashew; maize, pigeon peas and cassava and pumkins on neighbouring plots
Soil parent material:	sandstone
Drainage class:	well drained, moist conditions when described
Rock outcrop:	nil
Surface stones:	nil — Signs of erosion: slight

Ah_1 0 - 6 cm: very dark reddish brown (2.5 YR 2/2) when moist; sandy loam; very friable when moist; slightly sticky and non plastic. weak fine granular structure. no cutans; few very fine tubular and interstitial pores, size < 1 mm; common fine roots, size 1 - 2 mm; smooth (2 - 5 cm) boundary

Ah_2 6 - 30 cm: very dark reddish brown (2.5 YR 2/3) when moist; sandy loam; very friable when moist: slightly sticky and slightly plastic; moderate fine to medium sub-angular blocky structure; patchy and thin cutans which are mainly clay and organic matter in nature and are seen on voids; common fine to medium tubular pores, size 1 - 2 mm; few to common fine to coarse roots, size 1 - 5 mm; smooth (2 - 5 cm) boundary

AB 30 - 62 cm: dark reddish brown (2.5 YR 3/ 4) when moist; sandy clay loam; friable when moist; sticky and slightly plastic. moderate fine to medium sub-angular blocky structure, patchy and medium thick cutans which are clay and organic matter in nature and found on voids; common fine tubular pores, size 1 - 2 mm; few to common fine to coarse roots, size 1 - 5 mm, smooth (2 - 5 cm) boundary

Bt_1 62 - 99 cm: dark reddish brown (2.5 YR 3/6) when moist; sandy clay loam; friable when moist; sticky and plastic; weak to moderate fine to medium sub-angular blocky structure; patchy and thin cutans which are clay in nature and located in voids and on pedfaces; common fine tubular pores, size 1 - 2 mm; very few very fine to coarse roots, size < 5 mm; smooth (2 - 5 cm) boundary

Bt_2 99 - 200+ cm: reddish brown (2.5 YR 4/6) when moist, sandy clay; friable when moist, sticky and plastic; moderate fine to medium sub-angular blocky structure, broken and thick cutans which are clay in nature and located in voids and on pedfaces, common fine tubular pores, size 1 - 2 mm; very few fine to medium roots, size 1 - 2 mm

A Physico-chemical characteristics*

Horiz	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Text	pH (H_2O)	pH (KCl)	OC (%)	N (%)	Av. P (mg kg^{-1})	Ca^{++}	Mg^{++}	K^+	Na^+	TEB	CEC soil	CEC clay	BS (%)
Ah_1	0-6	77	5	18	SL	6.5	6.0	0.77	0.07	28.41	2.40	0.90	0.45	0.02	3.77	4.49	24.9	84
Ah_2	6-30	75	3	22	SCL	6.0	5.0	0.98	0.06	6.00	2.80	1.20	0.15	0.02	4.17	6.13	27.9	68
AB	30-62	57	3	40	SC	6.1	5.0	0.46	0.03	7.79	4.90	2.20	0.10	0.02	7.22	10.03	25.1	72
Bt_1	62-99	79	8	13	SL	6.0	5.1	0.32	0.03	6.34	1.20	0.80	0.09	0.02	2.11	3.20	24.6	66
Bt_2	99-200+	83	8	9	LS	6.5	5.7	0.16	0.02	3.89	1.30	0.50	0.04	0.02	1.86	2.21	24.6	84

B Diagnostic horizons, soil classification and correlation

Horiz	Diagnostic horizon		Classification		
	Revised Legend	WRB	Revised Legend	WRB	Soil Taxonomy
Ah_1	Ochric A-horizon	Ochric horizon	Chromic Luvisol	Hapli-Rhodic Luvisol	Typic Rhodustalf
Ah_2	Ochric A-horizon	Ochric horizon			
AB	Argic B-horizon	Argic horizon			
Bt_1					
Bt_2					

* Ca^{++}, Mg^{++}, K^+, Na^+, TEB, CEC soil and CEC clay are expressed in $cmol_c$ kg^{-1}

14 Makonga

Location	Mtwara region, Newala district, along the Newala-Kitangari road at Makonga village about 8 km from Newala; on the left side of the road about 2 km northeast of the village
UTM Coordinates	Zone 531.7 km E, 8800.4 km S
Authors	Ngatunga E., Dondeyne S., Mapua
Date	3 April 1997
Landform and relief:	landscape unit: Makonde Plateau, site is gently sloping northwards
Slope of site	2 %
Vegetation and land use:	mainly cashew, nearby farms have been planted with upland rice, cassava; nearby land has been cleared for cashew and other crops; the nearby bush is covered with Makonde ticket
Soil parent material:	sandstone
Drainage class:	well drained, moist conditions when described
Rock outcrop	nil
Surface stones	nil Signs of erosion: nil

Ap 0 - 32 cm: dark brown (7.5 YR 3/3) when moist; sandy loam; loose to very friable when moist; non sticky and non plastic, weak medium sub-angular blocky structure; no cutans; very few fine tubular pores, size 1 - 2 mm, common very fine to coarse roots, all sizes; smooth (2 - 5 cm) boundary

AB 32 - 70 cm: dark brown (7.5 YR 3/ 4) when moist; sandy loam; friable when moist; slightly sticky and non plastic; weak medium sub-angular blocky;; no cutans; few fine tubular pores, size & - 2 mm; common fine to coarse roots, size > 1 mm, smooth (2 - 5 cm) boundary

BA 70 - 105 cm: brown (7.5 YR 4/4) when moist; sandy loam; friable when moist; slightly sticky and slightly plastic, weak to moderate medium sub-angular blocky; broken thin cutans mainly clay and on pedfaces; few fine tubular pores, size 1 - 2 mm; few fine to coarse roots, all sizes; smooth (2-5 cm) boundary

Bt_1 105 - 145 cm: brown (7.5 YR 4/6) when moist; sandy clay loam; friable when moist; sticky and plastic; moderate medium sub-angular blocky structure; continuous and thin cutans mainly clay and on pedfaces, few fine tubular pores, size 1 - 2 mm; very few fine roots, size < 1 mm; smooth (2 - 5 cm) boundary

Bt_2 145 - 200+ cm: bright brown (7.5 YR 5/8) when moist; sandy clay loam; friable when moist; sticky and plastic; moderate medium to coarse sub-angular blocky structure; continuous tin cutans mainly clay in nature and on pedfaces; few fine tubular pores, size < 1 mm; very few and fine roots, size < 1 mm

A. Physico-chemical characteristics*

Horiz	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Text.	pH (H_2O)	pH (KCl)	OC (%)	N (%)	Av. P (mg kg^{-1})	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	CEC soil	CEC clay	BS (%)
Ap	0-32	87	2	11	LS	5.4	4.3	0.92	0.06	4.96	1.00	0.30	0.04	0.02	1.36	2.83	25.7	48
AB	32-70	81	1	8	LS	5.3	4.3	0.26	0.04	4.31	1.30	0.70	0.01	0.02	2.03	4.61	57.6	44
BA	70-105	77	2	21	SCL	4.8	4.1	0.25	0.04	5.44	1.10	0.40	0.01	0.02	1.53	5.28	25.1	29
Bt_1	105-145	69	2	29	SCL	4.7	4.1	0.30	0.03	3.94	1.20	0.40	0.01	0.02	1.63	7.08	24.4	23
Bt_2	145-200	61	4	35	SCL	4.6	4.0	0.17	0.02	3.38	1.20	0.70	0.01	0.02	1.93	8.77	25.1	22

B. Diagnostic horizons, soil classification and correlation

Horiz	Diagnostic horizon		Classification		
	Revised Legend	WRB	Revised Legend	WRB	Soil Taxonomy
Ap	Ochric A-horizon	Ochric horizon	Haplic Alisol	Profondi-Arenic Alisol(Dystric)	Typic Paleustult
AB					
BA	Argic B-horizon	Argic horizon			
Bt_1	Argic B-horizon	Argic horizon			
Bt_2	Argic B-horizon	Argic horizon			

* Ca^{2+}, Mg^{2+}, K^+, Na^+, TEB, CEC soil and CEC clay are expressed in $cmol_c\ kg^{-1}$

15 Mtopwa

Location:	Mtwara region, Newala district, 2 km northeast of Mtopwa Experimental Substation of NARI
UTM Coordinates:	Zone 37: 542.2 km E, 8818.6 km S
Authors:	Ngatunga E., Mapua
Date:	20 December 1996
Landform and relief:	landscape unit: Makonde Plateau, sloping slightly eastwards (456 m asl)
Slope of site:	2 %
Vegetation and land use:	Cashew, maize, cowpeas, cassava and sorghum on experimental, plots belonging to the station
Soil parent material:	sandstone
Drainage class:	well drained
Rock outcrop:	nil
Surface stones:	nil
Signs of erosion:	slight sheet erosion

Ap 0 - 28 cm brown (7.5 YR 4/4) when moist and brown (7.5 YR 4/4) when dry; loamy sand; soft when dry, friable when moist; slightly sticky and slightly plastic; weak very fine to fine sub-angular blocky structure; patchy thin cutans organic matter in nature; few tubular pores, size 1 -2 mm; common fine to medium roots, size 1 - 5 mm; smooth (2 - 5 cm) boundary

AB 28 - 58 cm: brown (7.5 YR 4/6) when moist and brown (7.5 YR 4/6) when dry; loamy sand; slightly hard when dry, friable when moist; slightly sticky and slightly plastic; weak very fine to fine sub-angular blocky structure; patchy thin cutans organic matter in nature; few tubular pores, size < 2 mm; common to many fine to medium roots, size 1 - 5 mm, smooth (2 - 5 cm) boundary

B_1 58 - 116 cm: bright brown (7.5 YR 4/6) when moist and bright brown (7.5 YR 5/6) when dry; sandy loam; slightly hard when dry, friable when moist; sticky and plastic; moderate fine to medium sub-angular blocky structure; patchy thin cutans clay in nature; common tubular pores, size < 2 mm; common to many fine roots, size 1 - 2 mm; smooth (2 -5 cm) boundary

B_2 116 - 200+ cm: bright reddish brown (5 YR 5/6) when moist and bright reddish brown (5 YR 5/6) when dry; sandy clay loam; slightly hard when dry, friable when moist; sticky to very sticky and plastic; moderate fine to medium sub-angular blocky structure; patchy thin cutans clay in nature; few tubular pores, size < 2 mm; few fine roots, size 1 - 2 mm

A. Physico-chemical characteristics*

Horiz.	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Text.	pH (H_2O)	pH (KCl)	OC (%)	N (%)	Av. P (mg kg^{-1})	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	CEC soil	CEC clay	BS (%)
Ap	0-28	85	2	13	LS	4.2	3.9	0.74	0.09	9.08	0.25	0.15	0.07	0.02	0.49	3.27	25.2	15
AB	28-58	76	2	22	SCL	4.3	3.9	0.39	0.04	1.47	0.03	0.02	0.01	0.01	0.07	2.00	9.1	17
B_1	58-116	76	2	22	SCL	4.3	3.9	0.20	0.02	1.38	0.02	0.01	0.01	0.01	0.05	0.33	1.5	15
B_2	116-200+	73	2	25	SCL	4.3	3.9	0.13	0.01	0.83	0.03	0.02	0.02	0.01	0.08	0.44	1.8	18

B. Diagnostic horizons, soil classification and correlation

Horiz	Diagnostic horizon		Classification		
	Revised Legend	WRB	Revised Legend	WRB	Soil Taxonomy
Ap	Ochric A-horizon	Ochric horizon	Haplic Ferralsol	Veti-Acric Ferralsol	Typic Haplustox
AB	Ferralic B-Horizon	Ferralic horizon		(Hyperdystric)	
B_1	Ferralic B-Horizon	Ferralic horizon			
B_2	Ferralic B-Horizon	Ferralic horizon			

* Ca^{2+}, Mg^{2+}, K^+, Na^+, TEB, CEC soil and CEC clay are expressed in $cmol_c$ kg^{-1}

16 Kitangari

Location	Mtwara region. Newala district. km northeast of Kitangari village which is on the road Mtwara-Newala
UTM Coordinates	Zone 37: 536.9 km E, 8824.8 km S
Authors	Ngatunga E., Mapua
Date	20 December 1996
Landform and relief	landscape unit Makonde Plateau, site is sloping northwards
Slope of site	10 %
Vegetation and land use	mainly cashew
Soil parent material	sandstone
Drainage class	well drained
Rock outcrop	nil
Surface stones	nil
Signs of erosion	slight

Ap 0 - 5 cm brownish grey (7.5 YR 4/1) when moist and brownish grey (7.5 YR 4/1) when dry; loamy sand; loose sand, loose when dry, loose when moist; slightly sticky and non plastic; very weak very fine to fine crumb to weak sub-angular blocky structure; no cutans; few tubular pores, size 1 - 2 mm; few fine to medium roots, size 1 - 2 mm; wavy (2 - 5 mm) boundary

AE 5 - 30 cm dull brown (7.5 YR 5/3) when moist and dull brown (7.5 YR 5/3) when dry; sandy loam, soft when dry, friable when moist; slightly sticky and slightly plastic; weak fine to medium sub-angular blocky; no cutans, few tubular pores, size < 2 mm; few to common roots, size 1 - 5 mm; irregular (2 - 5 cm) boundary

Bt_1 30 - 72 cm bright yellowish brown (10 YR 6/6) when moist and bright yellowish brown (10 YR 6/6) when dry; sandy loam; loose to soft when dry, very friable when moist; slightly sticky and slightly plastic; very weak very fine granular structure; no cutans, common tubular pores, size ≤ 1 mm; few roots, size 1 - 2 mm; smooth (2 - 5 cm) boundary

Bt_2 72 - 200+ cm: yellowish brown (10 YR 5/6) when moist and bright yellowish brown (10 YR 5/6) when dry; sandy clay loam; soft when dry, friable when moist; slightly sticky and slightly plastic; weak very fine sub-angular blocky structure; no cutans, common tubular pores, size ≤ 1 mm; few roots, size 1 - 2 mm, smooth (2 - 5 cm) boundary

A. Physico-chemical characteristics*

Horiz.	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Text.	pH (H_2O)	pH (KCl)	OC (%)	N (%)	Av. P (mg kg^{-1})	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	CEC soil	CEC clay	BS (%)
Ah	0 - 5	91	1	8	S	5.3	4.1	1.04	0.11	16.68	0.60	0.30	0.08	0.08	1.06	2.30	28.8	47
AE	5-30	91	0	9	S	5.3	4.1	1.02	0.11	15.46	0.60	0.30	0.08	0.08	1.06	2.30	25.6	45
Bt_1	30-72	85	1	14	LS	4.9	4.0	0.56	0.04	5.60	0.60	0.20	0.03	0.03	0.86	2.97	21.2	29
Bt_2	72-200+	83	1	16	SL	4.8	4.0	0.35	0.03	14.16	0.40	0.20	0.01	0.03	0.64	4.27	26.7	15

B. Diagnostic horizons, soil classification and correlation

Horiz.	Diagnostic horizon		Classification		
	Revised Legend	WRB	Revised Legend	WRB	Soil Taxonomy
Ah	Ochric A-horizon		Haplic Alisol	Profondi-Arenic	Typic Paleustult
AE				Alisol (Hyperdystric)	
Bt_1					
Bt_2	Argic B-horizon	Argic horizon			

* Ca^{2+}, Mg^{2+}, K^+, Na^+, TEB, CEC soil and CEC clay are expressed in $cmol_c\ kg^{-1}$

17 Mlundelunde 1

Location	Mtwara region, Masasi district, 1 km southwest of Mlundelunde village, which is 12 km from Masasi town, the profile is on the left side of the Newala-Masasi road on a distance of 100 m
UTM Coordinates	Zone 37: 491.4 km E, 8801.1 km S
Authors	Ngatunga E., Dondeyne S.
Date:	2 April 1997
Landform and relief:	landscape unit: Lulindi Plain, site is sloping eastwards to a river 300 m away
Slope of site:	4 - 6 %
Vegetation and land use:	mainly cashew
Soil parent material:	gneiss
Drainage class:	no data, moist conditions when described
Rock outcrop:	nil
Surface stones.	nil
Signs of erosion:	sheet wash

Ah 0 - 21 cm: brownish black (7.5 YR 2/2) when moist; sandy loam; very friable when moist; non sticky, and non plastic: moderate tot medium granular and sub-angular blocky structure; no cutans; very few fine tubular pores, size 1 - 2 mm; common very fine to coarse roots, size < 5 mm; smooth (2 - 5 cm) boundary

AB 21 - 37 cm: very dark brown (7.5 YR 2/3) when moist; sandy loam; very friable when moist; non sticky and non plastic: weak medium sub-angular blocky structure; no cutans; very few fine tubular pores, size ≤ 1 mm: few very fine to medium roots, size < 1 and 2 - 5 mm, smooth (2 - 5 cm) boundary

BA 37 - 60 cm: dark brown (7.5 YR 3/ 4) when moist; sandy loam; very friable when moist; non sticky and non plastic; weak medium sub-angular blocky structure; no cutans; very few fine tubular pores, size 1 - 2 mm; few very fine to medium roots, size < 5 mm, smooth (< 2 cm) boundary)

C 60 - 95 cm: brown (7.5 YR 4/4) when moist; 20 % sandy loam while 80 % gravel; the soils part is friable when moist; non sticky and non plastic, weak medium sub-angular blocky structure; no cutans; no pores; very few very fine to medium roots, size < 5 mm; abrupt and smooth (< 2 cm) boundary;

C_g 95+ cm: 80% gravel and very coarse sand, roots cannot penetrate the compact gravel layer (was not sampled)

A Physico-chemical characteristics*

Horiz	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Text.	pH (H_2O)	pH (KCl)	OC (%)	N (%)	Av. P (mg kg^{-1})	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	CEC soil	CEC clay	BS (%)
Ah	0-21	83	8	9	LS	6.2	5.2	1.08	0.09	2.91	0.80	0.50	0.30	0.02	1.62	2.19	24.3	74
AB	21-37	80	8	12	SL	6.5	5.2	0.51	0.03	2.59	1.40	0.80	0.21	0.04	2.45	2.99	24.9	82
BA	37-60	83	6	11	LS	6.7	5.2	0.22	0.03	2.59	1.20	1.00	0.22	0.02	2.44	2.71	24.6	90
C	60-95+	84	5	11	LS	6.8	5.0	0.13	0.02	2.17	1.50	0.90	0.11	0.04	2.55	2.72	24.7	94

B Diagnostic horizons, soil classification and correlation

Horiz	Diagnostic horizon: Revised Legend	Diagnostic horizon: WRB	Classification: Revised Legend	Classification: WRB	Classification: Soil Taxonomy
Ap	Mollic A-horizon	Mollic horizon	Haplic Phaeozem	Endolepti-Arenic Phaeozem	Entic Haplustoll
AB					
BA					
C					

* Ca^{2+}, Mg^{2+}, K^+, Na^+, TEB, CEC soil and CEC clay are expressed in $cmol_c\ kg^{-1}$

18 Mlundelunde 2

Location	Mtwara region. Masasi district. 1 km southwest of Mlundelunde village, which is 12 km from Masasi town, the profile is on the left side of the Newala-Masasi road on a distance of 100 m
UTM Coordinates	zone 37: 491.3 km E. 8801.1 km S
Authors	Ngatunga E., Dondeyne S.
Date	2 April 1997
Landform and relief:	landscape unit: Lulindi Plain, site is sloping eastwards to a river valley 400 m away
Slope of site:	6 %
Vegetation and land use	cashew intercropped with groundnuts, pigeon peas and bulrush, millet. The nearby bush is thicket and unattended cashew trees.
Soil parent material	gneiss
Drainage class	well drained, moist conditions when described
Rock outcrop	nil
Surface stones	nil Signs of erosion: nil

Ap 0 - 20 cm: very dark reddish brown (2.5 YR 2/3) when moist, sandy loam: very friable when moist: non sticky and non plastic; weak to moderate fine crumb and sub-angular blocky structure; no cutans. few fine tubular pores, size 1 - 2 mm; common fine roots and few medium roots, size 1 - 5 mm; smooth (2 - 5 cm) boundary

AB 20 - 40 cm: dark reddish brown (2.5 YR 3/ 4) when moist; sandy loam; very friable when moist; non sticky and non plastic: weak to moderate fine to medium sub-angular blocky; no cutans; common fine tubular pores. size 1 - 2 mm. common fine roots, size 1 - 2 mm. smooth (2 - 5 cm) boundary

Bt_1 40 -80 cm: dark reddish brown (2.5 YR 3/6) when moist; sandy clay loam: very friable when moist: slightly sticky and slightly plastic, weak to moderate fine to medium sub-angular blocky; no cutans. common fine to medium tubular pores, size 1 - 5 mm; common fine roots, size < 1 mm; smooth (5 - 12 cm) boundary

Bt_2 80 - 130 cm dark red (10 R 3/6) when moist; sandy clay loam; friable when moist; sticky and plastic: moderate medium sub-angular blocky structure; patchy thin cutans clay in nature and located in voids. many fine to medium tubular pores. size 1 - 5 mm; few coarse roots and few fine roots, size 1 - 5 mm. smooth (2 - 5 cm) boundary

Bt_3 130 - 200+ cm: dark red (10 R 3/6) when moist. sandy clay loam; friable when moist; sticky and plastic: moderate medium sub-angular blocky structure. broken thick cutans clay in nature and located in voids. common fine to medium tubular pores, size 1 - 5 mm; few fine roots, size 1 - 2 mm

A Physico-chemical characteristics*

Horiz	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Text	pH (H_2O)	pH (KCl)	OC (%)	N (%)	Av. P (mg kg^{-1})	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	CEC soil	CEC clay	BS (%)
Ap	0-20	82	8	10	LS	6.9	6.0	0.33	0.02	1.54	1.70	0.50	0.19	0.02	2.41	2.46	24.6	98
AB	20-40	82	7	11	LS	7.2	5.9	0.18	0.02	10.87	2.00	0.60	0.15	0.02	2.77	2.77	25.2	100
Bt_1	40-80	69	6	25	SCL	7.4	5.8	0.25	0.03	2.59	4.40	2.40	0.28	0.02	7.10	6.28	25.1	100
Bt_2	80-130	61	4	35	SCL	7.4	5.7	0.24	0.03	0.69	7.00	2.80	0.18	0.05	10.03	8.72	24.9	100
Bt_3	130-200+	82	3	15	SL	5.3	4.1	0.17	0.02	1.17	0.80	0.50	0.20	0.02	1.52	3.78	25.2	45

B Diagnostic horizons, soil classification and correlation

Horiz	Diagnostic horizon		Classification		
	Revised Legend	WRB	Revised Legend	WRB	Soil Taxonomy
Ap	Ochric A-horizon	Ochric horizon	Chromic Luvisol	Cutani-Rhodic Luvisol	Typic Rhodustalf
AB					
Bt_1	Argic B-horizon	Argic horizon			
Bt_2	Argic B-horizon	Argic horizon			
Bt_3	Argic B-horizon	Argic horizon			

* Ca^{2+}, Mg^{2+}, K^+, Na^+, TEB, CEC soil and CEC clay are expressed in $cmol_c\ kg^{-1}$

19 Chikukwe

Location:	Mtwara region, Masasi district, 1 km southwest of Chikukwe village which is 22 km from Masasi town along the main road Masasi-Lindi. The profile is located on the left side of an old road to the south of the village.
UTM Coordinates:	zone 37: 488.2 km E. 8827.5 km S
Authors:	Ngatunga E., Deckers S., Mapua
Date:	17 December 1996
Landform and relief:	landscape unit: Nachingwea-Masasi Plain, site is sloping gently northwards to the river Lukuledi about 5 km, away (281m asl)
Slope of site:	2 - 4 %
Vegetation and land use:	mainly cashew intercropped with cassava and groundnuts; nearby areas are covered with thin ticket or/and unattended cashew trees
Soil parent material:	sandstone
Drainage class:	poorly drained
Rock outcrop:	nil
Surface stones:	nil
Signs of erosion:	nil

Ap 0 - 16 cm: very dark brown (7.5 YR 2/3) when moist and very dark brown (7.5 YR 2/3) when dry; loamy sand; soft when dry, very friable when moist; non sticky and non plastic; weak very fine to fine crumb and granular structure; no cutans; few fine interstitial pores, size 1 - 2 mm; common fine to medium roots, size > 1 mm; wavy (2 - 5 cm) boundary

E 16 - 45 cm: dark brown (7.5 YR 3/3) when moist and dark brown (7.5 YR 3/3) when dry; loamy sand: soft when dry, very friable when moist: non sticky and non plastic; weak very fine to fine crumb and granular structure: no cutans: few fine interstitial pores, size 1 - 2 mm; common fine to medium roots size 1 - 5 mm: smooth (2 - 5 cm) boundary

Bt_1 45 - 90 cm: dull brown (7.5 YR 5/4) when moist and brown (7.5 YR 4/4) when dry; sandy clay loam; soft when dry, friable when moist; slightly sticky and non plastic; weak very fine to fine crumb and granular structure; no cutans; few fine tubular pores, size 1 - 2 mm; common very fine to fine roots, size < 5 mm; smooth (2 - 5 cm) boundary

Bt_2 90 - 120 cm: dull orange (7.5 YR 7/4) when moist and dull orange (7.5 YR 7/4) when dry; sandy loam: common distinct clear mottles which are dark reddish brown (5 YR 3/6), brownish black (5 YR 3/1) and others are reddish brown (5 YR 4/6), size 5 - 15 mm common distinct clear mottles which are dark reddish brown (5 YR 3/6). brownish black (5 YR 3/1) and others are reddish brown (5 YR 4/6), size 5 - 15 mm: soft to slightly hard when dry, friable when moist; sticky and plastic; moderate fine to medium coarse sub-angular blocky structure, patchy thin cutans which are silky in nature; few very fine to fine tubular pores, size < 2mm; few fine roots, size < 2 mm; wavy (2 - 5 cm) boundary

Bt_3 120 - 145+: light grey (7.5 YR 8/2) when moist and light grey (7.5 YR 8/2) when dry; sandy loam; common prominent sharp mottles which are dark reddish brown (5 YR 3/6), brownish black (5 YR 3/1) and others are reddish brown (5 YR 4/6), size 5 - 15 mm; hard when dry, firm when moist; sticky to very sticky and plastic; moderate to strong fine to medium coarse sub-angular blocky structure; patchy thin cutans which are silky in nature; common very fine to fine tubular pores, size < 2 mm; few very fine to fine roots, size < 2 mm

A. Physico-chemical characteristics*

Horiz	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Text	pH (H_2O)	pH (KCl)	OC (%)	N (%)	Av. P (mg kg^{-1})	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	CEC soil	CEC clay	BS (%)
Ap	0-16	93	3	4	S	5.9	5.2	0.33	0.03	2.54	0.70	0.30	0.06	0.08	1.14	1.75	43.8	65
E	16-45	91	1	8	S	5.8	4.9	0.10	0.01	1.40	0.40	0.20	0.05	0.08	0.73	1.18	14.8	62
Bt_1	45-90	90	2	8	S	6.3	4.8	0.10	0.01	1.38	0.40	0.20	0.08	0.02	0.70	0.92	11.5	76
Bt_2	90-120	83	2	15	SL	6.5	4.8	0.11	0.01	1.27	0.40	0.20	0.13	0.01	0.74	0.84	5.6	88
Bt_3	120-145+	80	4	16	SL	6.5	4.6	0.10	0.01	1.14	0.30	0.30	0.14	0.10	0.84	0.99	6.2	85

B. Diagnostic horizons, soil classification and correlation

Horiz	Diagnostic horizon		Classification		
	Revised Legend	WRB	Revised Legend	WRB	Soil Taxonomy
Ap	Ochric A-horizon	Ochric horizon	Plinthic Ferralsol	Areni-Plinthic Ferralsol	*Plinthic Eutrustox*
E					
Bt_1					
Bt_2	Ferralic B-Horizon	Ferralic horizon			
Bt_3		Ferralic horizon			

* Ca^{2+}, Mg^{2+}, K^+, Na^+, TEB, CEC soil and CEC clay are expressed in $cmol_c\ kg^{-1}$

20 Chikundi

Location:	Mtwara region, Masasi district, 1 km northwest of Chikundi village (8 km west of Ndanda Mission) which is on the main road Lindi-Masasi
UTM Coordinates:	zone 37: 495.5 km E, 8836.9 km S
Authors:	Ngatunga E., Dondeyne S., Mapua
Date:	17 December 1996
Landform and relief:	landscape unit: Nachingwea-Masasi Plain. The site is located on the lower slopes of the Lukuledi Plain and is almost 1 km away from the Lukuledi river. (285 m asl)
Slope of site:	5 %
Vegetation and land use:	mainly cashew, intercropped with bananas, coconuts, fruit trees, sesame and lablab beans (Sw.: mucuna)
Soil parent material:	gneiss
Drainage class:	well drained upper horizon (0 - 145 cm), beyond 145 mottles and nodules are observed

Ap 0 - 24 cm: brownish black (7.5 YR 3/1) when moist and brownish black (7.5 YR 3/1) when dry; loamy sand; soft to slightly hard when dry, friable when moist; slightly sticky and slightly plastic; weak very fine to fine sub-angular blocky, granular and crumb structure; patchy to broken medium thick cutans lay and organic matter in nature; common tubular pores, size < 5 mm; few fine roots, size < 2 mm; smooth (< 2 cm) boundary

BA 24 - 50 cm: brown (7.5 YR 4/4) when moist and brown (7.5 YR 4/4) when dry; sandy clay loam; hard to very hard when dry, firm to very firm when moist; very sticky to very plastic; moderate to strong medium to coarse sub-angular blocky structure; patchy to broken and thin cutans clay and organic matter in nature; common tubular pores, size < 2 mm; few fine roots, size < 1 mm; wavy (2 - 5 cm) boundary

Bt_1 50 - 97 cm: brown (7.5 YR 4/4) when moist and brown (7.5 YR 4/4) when dry; sandy clay loam; slightly hard to hard when dry, firm to very firm when moist; sticky and plastic, moderate fine to medium sub-angular blocky structure; patchy thin cutans mainly clay in nature; few tubular pores, size 1 - 2 mm; few fine roots, size < 1 mm; wavy (2 - 5 cm) boundary

Bt_2 97 - 144 cm: bright brown (7.5 YR 5/8) when moist and bright brown (7.5 YR 5/8) when dry; sandy clay, common faint and diffuse mottles which are bright reddish brown (5 YR 5/6), size < 5 mm; slightly hard to hard when dry, friable to firm when moist; sticky and plastic; moderate fine to coarse sub-angular blocky structure, patchy and thin cutans clay and organic matter in nature; few tubular pores, size < 1mm; few fine roots, size < 1 mm; wavy (2 - 5 cm) boundary

BC 144 - 200+ cm: bright brown (7.5 YR 5/8) when moist and bright brown (7.5 YR 5/8) when dry; sandy clay; common to abundant distinct and clear mottles which are reddish (5 YR 4/8), common to abundant distinct and clear mottles which are brown (7.5 YR 4/4) and others are bright brown (7.5 YR 5/6), sizes 5 - 15 mm and > 15 mm; soft when dry, friable when moist; sticky and plastic; weak fine to medium sub-angular blocky structure; patchy and thin cutans which are clay in nature; few fine interstitial and tubular pores, size < 1mm; many roundish gravels, 1 - 2 cm; few nodules with reddish colour inside (5 YR 4/8); very few fine roots size < 2 mm

A. Physico chemical characteristics*

Horiz	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Text.	pH (H_2O)	pH (KCl)	OC (%)	N (%)	Av. P (mg kg^{-1})	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	CEC soil	CEC clay	BS (%)
Ap	0-24	80	11	11	SL	5.9	4.9	0.84	0.10	7.15	2.70	1.26	0.30	0.02	4.28	6.48	58.9	66
BA	24-50	56	8	36	SC	5.3	4.2	0.55	0.06	1.95	2.58	2.42	0.14	0.04	5.18	11.51	32.0	45
Bt_1	50-97	41	8	57	C	4.9	3.8	0.43	0.05	0.35	2.00	1.15	0.09	0.02	3.26	9.31	16.3	35
Bt_2	97-144	39	7	54	C	4.8	3.8	0.40	0.03	0.26	2.14	1.32	0.08	0.03	3.57	12.75	23.6	28
BC	144-200+	40	7	53	C	5.0	4.1	0.25	0.02	0.15	2.82	1.95	0.08	0.04	4.89	13.22	24.9	37

B. Diagnostic horizons, soil classification and correlation

Horiz	Diagnostic horizon		Classification		
	Revised Legend	WRB	Revised Legend	WRB	Soil Taxonomy
Ap	Ochric A-horizon	Ochric horizon	Haplic Acrisol	Ochri-Profondic Acrisol	Typic Paleustult
E					
Bt_1	Argic B-horizon	Argic horizon			
Bt_2	Argic B-horizon	Argic horizon			
BC	Argic B-horizon	Argic horizon			

* Ca^{2+}, Mg^{2+}, K^+, Na^+, TEB, CEC soil and CEC clay are expressed in $cmol_c\ kg^{-1}$

21 Mnanje

Location:	Mtwara region, Masasi district, 2 km east of Mnanje A village, 5 km from Namatumbusi village along the Masasi-Tunduru road, 15 km southwest of Masasi
UTM Coordinates:	zone 37: 468.5 km E, 8798.9 km S
Authors.	Ngatunga E., Mapua
Date.	19 December 1996
Landform and relief	landscape unit Southern Masasi Plain site is sloping towards the north
Slope of site:	6 %
Vegetation and land use:	mainly cashew. intercropped with cassava, groundnuts, sorghum and bambaranuts
Soil parent material:	sandstone
Drainage class:	well drained
Rock outcrop:	nil
Surface stones:	nil
Signs of erosion:	slight

Ap 0 -19 cm: dark reddish brown (5 YR 3/2) when moist and dark reddish brown (5 YR 3/2) when dry: loamy sand: soft when dry, friable when moist; non sticky and non plastic; weak very fine to fine granular and sub-angular blocky structure: no cutans: common very fine to fine tubular pores, size 1 - 2 mm: common fine to medium roots, size 1 - 5 mm, smooth (2 - 5 cm) boundary

E 19 - 30 cm: dark reddish brown (2.5 YR 3/ 4) when moist and dark reddish brown (2.5 YR 3/ 4) when dry: loamy sand. soft when dry. friable when moist, slightly sticky and slightly plastic, very weak very fine to fine granular and sub-angular blocky structure, patchy thin cutans which are clay and organic matter in nature. common fine tubular pores, size 1 - 2 mm; many fine to medium roots, size 2 - 5 mm: irregular (5 - 12 cm) boundary

Bt_1 30 - 120 cm: dark reddish brown (2.5 YR 3/6) when moist and dark reddish brown (2.5 YR 3/6) when dry: sandy loam; slightly hard when dry, friable to firm when moist; slightly sticky to sticky and slightly plastic to plastic: moderate fine to medium sub-angular blocky structure; patchy thin cutans which are clay and organic matter in nature: common fine tubular pores, size 1 -2 mm; few fine roots, size 1 - 2 mm: wavy (5 - 12 cm) boundary

Bt_2 120 - 150 cm: dark reddish brown (2.5 YR 3/6) when moist and reddish brown (2.5 YR 4/6) when dry: loamy sand: soft to slightly hard when dry, friable when moist; slightly sticky to sticky and slightly plastic: weak to moderate fine to medium sub-angular blocky structure; patchy thin cutans which are clay in nature: common fine tubular pores, size 1 -2 mm; few very fine roots, size < 1mm

C 150 - 200+ cm: There is an irregular hardpan (of cemented basement rocks) beyond in between 150-200 cm which is overlain by gravel layer. dark reddish brown (2.5 YR 3/6) when moist and reddish brown (2.5 YR 4/6) when dry. loamy sand; slightly hard to hard when dry, friable to firm when moist; slightly sticky and slightly plastic, moderate medium to coarse sub-angular blocky structure; many coarse gravels: few very fine tubular pores, size < 1 mm; no roots

A Physico-chemical characteristics*

Horiz	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Text	pH (H_2O)	pH (KCl)	OC (%)	N (%)	Av. P (mg kg^{-1})	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	CEC soil	CEC clay	BS (%)
Ap	0-19	84	9	7	LS	5.8	5.1	0.70	0.06	2.30	0.75	0.57	0.21	0.03	1.56	2.52	36.0	62
E	19-30	79	7	14	SL	6.1	5.2	0.34	0.03	0.96	1.35	0.40	0.15	0.02	1.92	2.59	18.5	74
Bt_1	30-120	72	5	23	SCL	6.2	4.8	0.29	0.02	3.48	1.24	0.84	0.25	0.02	2.35	3.09	13.4	76
Bt_2	120-150	65	5	30	SCL	5.1	4.1	0.22	0.02	1.39	2.34	0.65	0.55	0.10	3.64	10.40	34.7	35
C	150-200+	67	8	26	SCL	6.0	4.5	0.15	0.02	0.51	2.21	1.00	0.16	0.06	3.43	5.04	19.4	68

B Diagnostic horizons, soil classification and correlation

Horiz	Diagnostic horizon		Classification		
	Revised Legend	WRB	Revised Legend	WRB	Soil Taxonomy
Ap	Ochric A-horizon	Ochric horizon	Haplic Acrisol	Rhodi-Profondic Acrisol	Typic Paleustult
E					
Bt_1	Argic B-horizon	Ferralic horizon			
Bt_2	Argic B-horizon	Argic horizon			
C					

* Ca^{2+}, Mg^{2+}, K^+, Na^+, TEB, CEC soil and CEC clay are expressed in $cmol_c\ kg^{-1}$

22 Mwenge

Location:	Mtwara region, Masasi district, 3 km southwest of Masasi, the profile is located 2 km to the left left side of the Masasi-Tunduru road
UTM Coordinates:	Zone 37: 475.7 km E, 8811.1 km S
Authors:	Ngatunga E., Dondeyne S. and Rogg H.
Date:	1 April 1997
Landform and relief:	landscape unit: Masasi Plains the site is sloping gently towards the northeast to a broad valley almost 400 m away
Slope of site:	4 - 5 %
Vegetation and land use:	Mainly cashew, the nearby uncleared land is covered with thin ticket. The lower slopes are planted with lowland rice.
Soil parent material:	gneiss
Drainage class:	well drained, moist conditions when described
Rock outcrop:	nil
Surface stones:	nil
Signs of erosion:	nil

Ap 0 - 20 cm: brownish black (5 YR 2/2) when moist; sandy loam, friable when moist; non sticky and non plastic; moderate medium sub-angular blocky structure; no cutans; common very fine to fine tubular pores, size < 2 mm; many fine to coarse roots, size > 1 mm; abrupt and smooth (2 - 5 cm) boundary

AB 20 - 48 cm: dark reddish brown (5 YR 3/4) when moist; sandy loam; friable when moist; slightly sticky and slightly plastic; moderate medium sub-angular blocky structure; common distinct cutans which are clay and organic matter in nature and located in voids; common very fine to fine tubular pores, size < 2 mm; common fine to coarse roots, size > 1 mm; clear and smooth (2 - 5 cm) boundary

Bt_1 48 - 75 cm: reddish brown (5 YR 4/6) when moist, sandy loam; very friable when moist; slightly sticky and slightly plastic; weak fine to medium sub-angular blocky structure, patchy and thin cutans which are clay and organic matter in nature and located in voids; common fine tubular pores, size 1 - 2 mm; common fine to coarse roots, size > 1 mm, abrupt and wavy (2 - 5 cm) boundary

Bt_2 75 - 130 cm: bright reddish brown (5 YR 5/6) when moist and reddish brown (5 YR 4/6) when dry; coarse sandy loam; very hard when dry, friable when moist; slightly sticky and slightly plastic; moderate fine to medium sub-angular blocky structure; very patchy and thin cutans mainly clay in nature; few fine and distinct sharp reddish mottles observed at the horizontal boundary, common fine tubular pores, size 1 - 2 mm; few fine roots, size 1 - 2 mm; abrupt and wavy (2 - 5 cm) boundary;

R 130+ cm: hard gravelly layer prevents further digging; manganese concretions, Mn brought in by slow movement of water, stagnic properties on top of gneiss

A. Physico-chemical characteristics*

Horiz	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Text	pH (H_2O)	pH (KCl)	OC (%)	N (%)	Av. P (mg kg^{-1})	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	CEC soil	CEC clay	BS (%)
Ap	0-20	81	12	7	LS	6.3	5.4	0.75	0.06	4.12	0.70	0.30	0.28	0.02	1.30	1.71	24.4	76
AB	20-48	77	12	11	SL	6.4	5.3	0.25	0.03	2.41	1.70	0.40	0.15	0.02	2.27	2.73	24.8	83
Bt_1	48-75	76	11	13	SL	6.5	5.0	0.16	0.02	2.26	2.00	0.60	0.11	0.04	2.75	3.27	25.2	84
Bt	75-130	79	10	11	SL	6.6	5.0	0.12	0.01	3.03	1.70	0.60	0.11	0.02	2.43	2.83	25.7	86

B. Diagnostic horizons, soil classification and correlation

Horiz.	Diagnostic horizon: Revised Legend	Diagnostic horizon: WRB	Classification: Revised Legend	Classification: WRB	Classification: Soil Taxonomy
Ap	Mollic A-horizon	Mollic horizon	Humic Cambisol	Hapli-Eutric Cambisol	Typic Ustropept
AB	Cambic B-horizon	Cambic horizon			
Bt_1					
Bt_2					

* Ca^{2+}, Mg^{2+}, K^+, Na^+, TEB, CEC soil and CEC clay are expressed in $cmol_c\ kg^{-1}$

23 Temeke Chini

Location	Lindi region, Nachingwea district, 2 km west of Temeke Chini village, 3 km from Masasi-Nachingwea road, about 8 km from Masasi
UTM Coordinates	zone 37: 475.8 km E, 8820.9 km S
Authors	Ngatunga E., Dondeyne S.
Date	1 April 1997
Landform and relief	landscape unit: Nachingwea-Masasi Plain site is gently sloping eastwards to a small streamlet 40 m away
Slope of site	5 %
Vegetation and land use	Mainly cashew. The nearby uncleared land is covered by thin thicket. The lower slopes are planted with lowland rice.
Soil parent material	sandstone
Drainage class:	poorly drained,clear hydromorphic properties below 90 cm
Rock outcrop:	nil
Signs of erosion	nil

Ap 0 - 14 cm dark reddish brown (5 YR 3/2) when moist; loamy sand; very friable when moist; non sticky and non plastic; moderate fine to medium sub-angular blocky structure; no cutans; very few fine tubular pores, size 1 - 2 mm; many very fine to medium roots, size 1 - 5 mm; clear and smooth (2 -5 cm) boundary

E 14 - 40 cm dull reddish brown (5 YR 4/3) when moist; sandy loam; very friable to friable when moist, non sticky and non plastic; weak fine to medium sub-angular blocky; no cutans; few fine to medium tubular pores, size 1 - 2 mm, common very fine to medium roots, size < 5 mm; abrupt and smooth (2 -5 cm) boundary

Bv_1 40 - 91 cm: dull reddish brown (5 YR 5/3) when moist; sandy clay loam; friable when moist; sticky and slightly plastic; moderate medium to coarse angular blocky; no cutans; many (30 %) medium prominent and sharp mottles which are dark red (10 R 3/ 4); common fine to medium tubular pores, size 1 - 2 mm; very few very fine roots, size ≤ 1 mm; gradual and smooth (2 - 5 cm) boundary

Bv_2 91 - 140 cm greyish brown (5 YR 6/2) when moist; sandy clay loam; friable when moist; sticky and plastic; moderate medium to coarse angular blocky structure; no cutans; many (30 %) medium prominent and sharp mottles which are reddish brown (2.5 YR 4/6); common fine to medium tubular pores, size 1 - 2 mm; very few and very fine to fine roots, size ≤ 1 mm

Cg 140+ cm more hydromorphic characteristics observed, water made further profile description impossible

A Physico-chemical characteristics*

Horiz	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Text.	pH (H_2O)	pH (KCl)	OC (%)	N (%)	Av. P (mg kg^{-1})	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	CEC soil	CEC clay	BS (%)
Ap	0-14	85			LS	5.6	4.6	0.35	0.04	4.66	0.70	0.40	0.13	0.02	1.25	2.31	25.7	54
E	14-40	79	7	14	SL	5.4	3.9	0.26	0.04	2.09	1.00	0.60	0.09	0.02	1.71	3.49	24.9	49
Bv_1	40-91	53	6	42	SC	5.5	3.7	0.44	0.03	1.89	3.60	1.70	0.05	0.07	5.42	10.42	24.8	52
Bv_2	91-140	51	6	43	SC	5.8	3.8	0.28	0.03	1.85	2.00	1.10	0.05	0.21	3.36	5.42	12.6	62

B. Diagnostic horizons, soil classification and correlation

Horiz	Diagnostic horizon		Classification		
	Revised Legend	WRB	Revised Legend	WRB	Soil Taxonomy
Ap	Ochric A-horizon	Ochric horizon	Albic Plinthosol	Ferri-Endoeutric Plinthosol	Typic Plinthaqualf
E	Albic E-horizon	Albic horizon			
Bv_1	Argic B-horizon	Argic horizon			
Bv_2	Ferralic B-Horizon	Plinthic horizon			

* Ca^{2+}, Mg^{2+}, K^+, Na^+, TEB, CEC soil and CEC clay are expressed in $cmol_c\ kg^{-1}$

24 Mraushi

Location:	Mtwara region, Masasi district, 8 km northwest of Temeke Juu village, along Masasi-Nachingwea road 8 km from Masasi. The profile is located in the cashew farm 200 m before reaching the farmer's house
UTM Coordinates:	Zone 37: 475.8 km E, 8824.9 km S
Authors:	Ngatunga E., Mapua
Date:	18 December 1996
Landform and relief:	landscape unit: Nachingwea-Masasi Plain, on the upper slopes of the Lukuledi valley and is almost 6 km away from the Lukuledi river (260 m asl)
Slope of site:	1 - 2 %
Vegetation and land use:	mainly cashew intercropped with maize
Soil parent material:	gneiss
Drainage class:	well drained
Rock outcrop:	nil
Surface stones:	nil
Signs of erosion:	sheet erosion. The profile is located at a point where the plough has scrapped a part of the top layer

Ap 0 - 17 cm brownish black (7.5 YR 3/1) when moist and brownish black (7.5 YR 3/2) when dry; sandy loam; soft when dry, friable when moist; sticky and plastic; weak very fine to fine sub-angular blocky and granular structure; patchy thin to medium tick cutans clay and organic matter in nature; common fine to medium tubular pores, size 1 - 5 mm; common fine roots, size < 2 mm; smooth (< 2 cm) boundary

BA 17 - 36 cm: dark reddish brown (2.5 YR 3/3) when moist and dark reddish brown (2.5 YR 3/3) when dry; sandy clay loam; slightly hard to hard when dry, friable when moist; sticky to very sticky and plastic; moderate fine to medium sub-angular blocky structure; patchy to broken thin cutans which are clay and organic matter in nature; common fine tubular pores, size < 2 mm; common fine roots, size < 2 mm, wavy (2 - 5 cm) boundary

Bt_1 36 - 70 cm: dull reddish brown (2.5 YR 4/4) when moist and dull reddish brown (2.5 YR 4/4) when dry; clay, hard when dry, firm when moist; sticky to very sticky and plastic to very plastic; strong medium to coarse sub-angular blocky structure; patchy thin to medium thick cutans mainly clay and organic matter in nature; common fine tubular pores, size 1 - 2 mm; few to common fine roots, size < 2 mm; wavy (2 - 5 cm) boundary

Bt_2 70 - 125 cm: dark reddish brown (2.5 YR 3/6) when moist and reddish brown (2.5 YR 4/6) when dry; clay; soft to slightly hard when dry, friable when moist, sticky and plastic; moderate fine to medium sub-angular blocky structure; patchy to broken thin cutans which are clay and organic matter in nature; common fine tubular pores, size < 1 mm; few to common fine roots, size < 2 mm; smooth (2 - 5 cm) boundary

Bt_3 125 - 200+ cm: dark reddish brown (2.5 YR 3/6) when moist and reddish brown (2.5 YR 4/6) when dry; clay; slightly hard when dry, friable when moist, sticky and plastic; moderate fine to medium sub-angular blocky structure; patchy to broken thin cutans which are clay and organic matter in nature; common fine tubular pores, size < 1 mm; few to common fine roots size <2 mm

A. Physico-chemical characteristics*

Horiz.	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Text.	pH (H_2O)	pH (KCl)	OC (%)	N (%)	Av. P (mg kg^{-1})	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	CEC soil	CEC clay	BS (%)
Ap	0-17	75	2	23	SCL	5.0	4.2	1.22	0.12	1.89	2.15	1.18	0.44	0.03	3.80	10.56	45.9	36
AB	17-36	45	5	50	SC	5.3	4.0	0.98	0.07	0.53	2.00	1.73	0.30	0.02	4.05	8.80	17.6	46
Bt_1	36-70	38	2	60	C	5.2	4.0	0.62	0.05	0.13	2.16	1.82	0.12	0.02	4.12	9.58	16.0	43
Bt_2	70-125	30	5	65	C	5.9	5.1	0.23	0.02	0.40	2.55	1.84	0.03	0.02	4.44	7.16	11.0	62
Bt_3	125-200+	36	6	58	C	6.2	5.4	0.1	0.01	0.31	7.70	2.80	0.04	0.05	10.59	15.15	26.1	73

B. Diagnostic horizons, soil classification and correlation

Horiz.	Diagnostic horizon		Classification		
	Revised Legend	WRB	Revised Legend	WRB	Soil Taxonomy
Ap	Ochric A-horizon	Ochric horizon	Rhodic Ferralsol	Rhodi-Acric Ferralsol	Kandiustalfic Eutrustox
AB					
Bt_1	Ferralic B-Horizon	Ferralic horizon			
Bt_2	Ferralic B-Horizon	Ferralic horizon			
Bt_3					

* Ca^{2+}, Mg^{2+}, K^+, Na^+, TEB, CEC soil and CEC clay are expressed in $cmol_c\ kg^{-1}$

25 Chemchem

Location:	Lindi region, Nachingwea district, 1 km northwest of Chemchem village which is 1 km from Nachingwea Prison Farm
UTM Coordinates:	Zone 37, 474.4 km E, 8846.7 km S
Authors:	Ngatunga E., Dondeyne S., Emmanuel L.B.
Date:	13 December 1996
Landform and relief:	landscape unit: Nachingwea - Masasi Plain, site is sloping towards east and northeast
Slope of site:	7 %
Vegetation and land use:	mainly cashew; in the neighbourhood coconuts, banana, pigeon peas, cassava and cow peas
Soil parent material:	sandstone
Drainage class:	well drained
Rock outcrop:	nil
Surface stones:	nil
Signs of erosion:	slight

Ap 0 - 10 cm: brown black (7.5 YR 3/2) when moist and brown (7.5 YR 4/3) when dry; loamy sand; soft when dry, very friable when moist; non sticky and non plastic; weak fine to medium sub-angular blocky structure, no cutans, few fine to medium tubular pores, size 1 - 2 mm; common very fine to medium roots, size < 5 mm; wavy (2 - 5 cm) boundary

Ah 10 - 20 cm: brown black (7.5 YR 3/2) when moist and greyish brown (7.5 YR 4/2) when dry; loamy sand; soft to slightly hard when dry, very friable when moist; non sticky and non plastic; moderate medium sub-angular blocky structure; no cutans; few fine tubular pores, size 1 - 2 mm; common very fine to medium roots, size < 5 mm; smooth (2 - 5 cm) boundary

AB_1 20 - 29 cm: very dark brown (7.5 YR 2/3) when moist and dark brown (7.5 YR 3 / 4) when dry; loamy sand; soft when dry, very friable when moist; non sticky and non plastic, weak fine sub-angular blocky; no cutans, common fine tubular pores, size 1 - 2 mm; common very fine to fine and coarse roots, size < 1, 1 - 2 to > 5 mm; smooth (2 - 5 cm) boundary

AB_2 29 - 45 cm: dark brown (7.5 YR 3 /4) when moist and dull brown (7.5 YR 5/4) when dry; sandy loam; slightly hard when dry, very friable when moist; slightly sticky and non plastic; moderate medium to coarse sub-angular blocky structure; no cutans; few gravels seen; common fine to medium tubular pores, size 1 - 5 mm; common very fine and coarse roots, size <1 and >5 mm; wavy (<2cm) boundary;

R Petroferric phase with > 80 % petroferric gravels, roots can not penetrate the petroferric gravel layer

A. Physico-chemical characteristics*

Horiz.	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Text.	pH (H_2O)	pH (KCl)	OC (%)	N (%)	Av. P (mg kg^{-1})	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	CEC soil	CEC clay	BS (%)
Ap	0-10	92	3	5	S	6.4	5.4	0.42	0.03	4.71	1.80	0.50	0.13	0.08	2.51	3.77	75.4	82
Ah	10-20	91	4	5	S	7.2	5.8	0.38	0.03	2.58	1.10	0.60	0.15	0.06	1.91	1.87	37.4	100
AB_1	20-29	89	5	6	S	6.6	5.3	0.37	0.02	3.42	0.70	0.30	0.20	0.10	1.30	1.46	24.3	89
AB_2	29-45	88	5	7	S	6.4	4.3	0.25	0.02	0.96	0.70	0.40	0.20	0.03	1.33	1.56	22.3	85

B. Diagnostic horizons, soil classification and correlation

Horizon	Diagnostic horizon		Classification		
	Revised Legend	WRB	Revised Legend	WRB	Soil Taxonomy
Ap	Ochric A horizon	Ochric horizon	Eutric Plinthosol	Endo-Petric Plinthosol	Lithic Quartsipsamment
Ah	Ochric A horizon	Ochric horizon			
AB_1					
AB_2					
R		Petroplintic horizon			

* Ca^{2+}, Mg^{2+}, K^+, Na^+, TEB, CEC soil and CEC clay are expressed in $cmol_c\ kg^{-1}$

26 Namatula

Location:	Lindi region, Nachingwea district, 7 km southwest of Stesheni Village, along the Masasi-Nachingwea road,
UTM Coordinates:	Zone 37. 471.6 E, 8849.7 S
Authors:	Ngatunga E., Mapua
Date	15 December 1996
Landform and relief:	landscape unit Nachingwea-Masasi Plain. The profile is located on the middle of a slope towards the south (425 m asl)
Slope of site:	6 %
Vegetation and land use:	cashew intercropped with cassava on some parts of the field
Soil parent material:	gneiss and sandstone
Drainage class:	well drained
Rock outcrop:	nil
Surface stones:	nil
Signs of erosion:	sheet and rill erosion common

Ap 0 - 25 cm: dark reddish brown (2.5 YR 3/2) when moist and dark reddish brown (2.5 YR 3/3) when dry; sandy clay loam; slightly hard to hard when dry, friable to firm when moist; sticky to very sticky and plastic to very plastic; moderate medium to coarse sub-angular blocky structure; patchy and thin to medium thin cutans mainly clay and organic matter in nature; common tubular pores, size 1 - 5 mm; common fine to medium roots, size 1 - 2 mm; wavy (2 - 5 cm) boundary

AB 25 - 43 cm: dark reddish brown (2.5 YR 3/6) when moist and dark reddish brown (2.5 YR 3/6) when dry, sandy clay loam, hard to very hard when dry, friable to firm when moist; very sticky and very plastic, moderate to strong fine to medium angular blocky to prism structure; patchy and thin cutans mainly clay and organic matter in nature; common tubular pores, size < 5 mm; few to common fine to medium roots, size 1 - 5 mm; smooth (2 - 5 cm) boundary; compact horizon which could have developed from use of heavy machinery four decades ago

Bs_1 43 - 134 cm: dark reddish brown (2.5 YR 3/6) when moist and dark reddish brown (2.5 YR 3/6) when dry: clay, hard to very hard when dry, friable to firm when moist; very sticky and very plastic; moderate to strong medium to coarse sub-angular blocky and angular blocky structure; broken and thin cutans mainly clay and organic matter in nature, few tubular pores, size < 2 mm; few fine roots, size 1 - 2 mm, smooth (2 - 5 cm) boundary

Bs_2 134 - 200+ cm: dark reddish brown (2.5 YR 3/6) when moist and dark reddish brown (2.5 YR 3/6) when dry: clay. soft to slightly hard when dry, friable when moist; sticky and plastic; moderate fine to medium sub-angular blocky structure; very patchy and thin cutans mainly clay and organic matter in nature. few interstitial and tubular pores, size < 2 mm; few fine roots, size 1 - 2 mm

A. Physico-chemical characteristics*

Horiz.	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Text.	pH (H_2O)	pH (KCl)	OC (%)	N (%)	Av. P (mg kg^{-1})	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	CEC soil	CEC clay	BS (%)
Ap	0-25	64	7	29	SCL	5.5	4.6	0.88	0.08	1.99	1.19	1.08	0.18	0.03	2.48	4.77	16.4	52
AB	25-43	33	5	62	C	5.2	4.5	0.87	0.07	0.14	3.95	1.58	0.04	0.04	5.61	13.05	21.0	43
Bs_1	43-134	31	8	61	C	5.9	4.7	0.11	0.01	0.65	4.53	1.36	0.04	0.02	5.95	9.30	15.2	64
Bs_2	134-200+	27	13	60	C	5.8	4.6	0.11	0.01	0.67	4.70	1.46	0.04	0.02	6.22	9.24	15.4	65

B. Diagnostic horizons, soil classification and correlation

Horiz.	Diagnostic horizon		Classification		
	Revised Legend	WRB	Revised Legend	WRB	Soil Taxonomy
Ap	Ochric A-horizon	Ochric horizon	Rhodic Ferralsol	Rhodi-Acric Ferralsol (Rhodic)	Rhodic Eutrustox
AB	Argic B-horizon	Argic horizon			
Bs_1	Ferralic B-Horizon	Ferralic horizon			
Bs_2		Ferralic horizon			

* Ca^{2+}, Mg^{2+}, K^+, Na^+, TEB, CEC soil and CEC clay are expressed in $cmol_c\ kg^{-1}$

27 Nampemba

Location:	Lindi region. Nachingwea district. located at Nampemba village which is 11 km from Nachingwea eastwards along the road Nachingwea-Lindi. The profile is located 1 km north of the road.
UTM Coordinates:	Zone 37: 483.6 km E. 8852.9 km S
Authors:	Ngatunga E., Mapua
Date:	18 April 1997
Landform and relief:	landscape unit: Nachingwea-Masasi Plains, profile is located on the lower slopes of the Mandai Hills, site is sloping towards a valley in the west
Slope of site:	2 - 5 %
Vegetation and land use:	Mainly cashew, but nearby also maize, bambaranuts, pigeon peas and cassava are grown
Soil parent material:	gneiss
Drainage class:	well drained
Rock outcrop:	nil
Surface stones:	nil
Signs of erosion:	sheet and rill erosion common

Ap 0 - 18 cm: very reddish brown (5 YR 4/6) when moist and dark reddish brown (5 YR 3/6) when dry; sandy loam; soft when dry, friable when moist; slightly sticky and slightly plastic; weak fine to medium sub-angular blocky structure; patchy and thin cutans mainly clay in nature; common fine to medium tubular pores, size 1 - 5 mm; common fine to coarse roots, size > 1mm; smooth (2 - 5 cm) boundary

AB 18 - 43 cm: reddish brown (2.5 YR 4/6) when moist and dark reddish brown (2.5 YR 3/6) when dry; sandy clay loam; slightly hard when dry, friable when moist; slightly sticky and slightly plastic; weak to moderate fine to medium sub-angular blocky structure; broken and thin to medium thick cutans which are mainly clay in nature; common fine to medium tubular pores, size 1 - 5 mm; common fine to coarse roots, size 1 - 5 mm; smooth (2 - 5 cm) boundary

BA 43 - 77 cm: reddish brown (2.5 YR 4/8) when moist and reddish brown (2.5 YR 3/6) when dry; sandy clay loam; slightly hard when dry, friable when moist; sticky and plastic; weak to moderate fine to medium sub-angular blocky structure; patchy and thin cutans mainly clay in nature; few fine tubular pores, size 1 - 2 mm; few fine to medium roots, size 1 - 2 mm; smooth (2 - 5 cm) boundary

Bt_1 77 - 143 cm: reddish brown (2.5 YR 4/8) when moist and reddish brown (2.5 YR 4/8) when dry; sandy clay; slightly hard when dry, friable when moist, sticky and plastic; weak to moderate fine to medium sub-angular blocky structure; patchy and thin cutans mainly clay in nature; few fine tubular pores, size 1 - 2 mm; few fine roots, size 1 - 2 mm; smooth (2 - 5 cm) boundary

Bt_2 143 - 200+ cm: reddish brown (2.5 YR 4/8) when moist and reddish brown (2.5 YR 4/6) when dry; sandy clay; firm when dry, friable when moist, sticky and plastic; moderate medium sub-angular blocky structure; patchy and thin cutans which are mainly clay in nature; few fine tubular pores, size 1 - 2 mm; few fine roots, size 1-2 mm

A. Physico-chemical characteristics*

Horiz	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Text	pH (H_2O)	pH (KCl)	OC (%)	N (%)	Av. P (mg kg^{-1})	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	CEC soil	CEC clay	BS (%)
Ap	0-18	77	4	19	SL	5.2	4.0	0.65	0.05	7.51	0.80	0.80	0.15	0.02	1.77	4.43	23.3	40
AB	18-43	45	3	32	SCL	4.8	3.8	0.34	0.04	4.88	1.70	0.50	0.04	0.04	2.28	8.14	25.4	28
BA	43-77	59	2	39	SC	4.8	3.8	0.45	0.04	10.28	1.60	0.80	0.04	0.02	2.46	9.92	25.4	25
Bt_1	77-143	59	3	38	SC	5.0	3.9	0.76	0.50	1.86	2.00	1.20	0.08	0.02	3.30	9.43	33.7	35
Bt_2	143-200+	56	5	39	SC	4.8	5.9	0.57	0.03	1.89	1.60	0.70	0.01	0.02	2.33	9.71	24.9	24

B. Diagnostic horizons, soil classification and correlation

Horiz	Diagnostic horizon		Classification		
	Revised Legend	WRB	Revised Legend	WRB	Soil Taxonomy
Ap	Ochric A-horizon	Ochric horizon	Haplic Alisol	Profondi-chromic Alisol	Typic Paleustult
AB					
BA	Argic B-horizon	Argic horizon			
Bt_1	Argic B-horizon	Argic horizon			
Bt_2	Argic B-horizon	Argic horizon			

* Ca^{2+}, Mg^{2+}, K^+, Na^+, TEB, CEC soil and CEC clay are expressed in $cmol_c\ kg^{-1}$

28 Mandai

Location:	Lindi region, Nachingwea district, 13 km eastwards from Nachingwea town along the road from Nachingwea town to Nanganga on the Lindi-Masasi Main road
UTM Coordinates:	Zone 37: 482.6 km E, 8853.0 km S
Authors:	Ngatunga E., Mapua
Date:	14 December 1996
Landform and relief:	landscape unit: Nachingwea - Masasi Plain profile is located on the middle slope of a crest; site is sloping westwards (425 m asl)
Slope of site:	mainly cashew, nearby maize and cassava
Soil parent material:	granitic gneiss
Drainage class:	well drained
Rock outcrop:	nil
Surface stones:	nil
Signs of erosion:	sheet and rill erosion common

Ap 0 - 11 cm: very dark reddish brown (2.5 YR 2/3) when moist and dark reddish brown (2.5 YR 3/2) when dry; sandy clay loam; slightly hard when dry, friable when moist; sticky and plastic; weak to moderate fine to medium granular to sub-angular blocky structure; patchy and thin cutans mainly clay and organic matter in nature; common tubular pores, size < 5 mm; common fine to medium roots, size 1 - 5 mm; wavy (2 - 5 cm) boundary

AB 11 - 32 cm: very dark reddish brown (2.5 YR 2/4) when moist and dark reddish brown (2.5 YR 3/3) when dry; clay loam; slightly hard when dry, very friable to friable when moist; sticky and plastic; weak to moderate fine to medium sub-angular blocky; patchy and thin cutans mainly clay and organic matter in nature; common tubular pores, size < 5 mm; common fine to medium roots, size 1 - 5 mm; smooth (< 2 cm) boundary

Bs_1 32 - 67 cm: dark reddish brown (2.5 YR 3/ 4) when moist and dark reddish brown (2.5 YR 3/6) when dry; clay loam; hard when dry, firm when moist; sticky and plastic; moderate to strong medium to coarse sub-angular blocky structure; patchy and thin cutans mainly clay and organic matter in nature; few tubular pores, size < 2 mm; few fine roots, size 1 - 2 mm; wavy (2 - 5 cm) boundary

Bs_2 67 - 200+ cm: dark reddish brown (2.5 YR 3/6) when moist and dark reddish brown (2.5 YR 3/6) when dry; clay loam; soft to slightly hard when dry, friable when moist; sticky and plastic; weak to moderate fine to medium sub-angular blocky structure; very patchy and thin cutans mainly clay and organic matter in nature, few interstitial tubular pores, size < 2 mm; few fine roots, size 1 - 2 mm

A. Physico-chemical characteristics*

Horiz	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Text.	pH (H_2O)	pH (KCl)	OC (%)	N (%)	Av. P (mg kg^{-1})	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	CEC soil	CEC clay	BS (%)
Ap	0 - 11	66	6	28	SCL	6.3	4.6	0.10	0.01	0.56	3.50	1.50	0.22	0.09	5.31	6.99	25.0	76
AB	11-32	55	6	39	SC	5.1	4.0	0.96	0.11	0.55	2.50	1.10	0.05	0.03	3.68	5.66	14.5	38
Bs_1	32-67	48	5	47	SC	4.9	3.8	0.47	0.05	0.14	1.09	0.62	0.03	0.08	1.82	5.20	11.1	35
Bs_2	67-200+	43	8	49	C	5.2	4.0	0.25	0.03	0.14	1.21	0.14	0.03	0.05	1.43	3.11	6.3	46

B. Diagnostic horizons, soil classification and correlation

Horiz	Diagnostic horizon		Classification		
	Revised Legend	WRB	Revised Legend	WRB	Soil Taxonomy
Ap	Ochric A-horizon	Ochric horizon	Rhodic Ferralsol	Veti-Acric Ferralsol (Rhodic)	Rhodic Eutrustox
AB					
Bs_1	Ferralic B-Horizon	Ferralic horizon			
Bs_2	Ferralic B-Horizon	Ferralic horizon			

* Ca^{2+}, Mg^{2+}, K^+, Na^+, TEB, CEC soil and CEC clay are expressed in $cmol_c\ kg^{-1}$

29 Mkumba

Location	Lindi region, Nachingwea district, 2 km northeast of Nachingwea Experimental Substation of NARI almost 2 north of Nachingwea township
UTM Coordinates:	Zone 37: 476.0 km E, 8858.4 km S
Authors	Ngatunga E., Mapua
Date	14 December 1996
Landform and relief	landscape unit Nachingwea-Masasi Plains site is sloping towards the north and northeast (381 m asl)
Slope of site:	8 - 10 %
Vegetation and land use	cashew, maize and cowpeas (mainly experimental plots of the station)
Soil parent material:	granitic gneiss
Drainage class:	well drained
Rock outcrop:	nil
Surface stones:	nil
Signs of erosion:	sheet and rill erosion common

Ap 0 - 16 cm: dark reddish brown (2.5 YR 3/3) when moist and dark reddish brown (2.5 YR 3/3) when dry: loamy sand: soft to slightly hard when dry, friable to firm when moist: slightly sticky and slightly plastic. moderate fine to medium sub-angular blocky structure; patchy and thin to medium thin cutans mainly clay and organic matter in nature; few tubular pores, size < 5 mm; common fine to medium roots, size 1 - 2 mm, wavy (2 - 5 cm) boundary

AB 16 - 47 cm: dark reddish brown (2.5 YR 3/6) when moist and dark reddish brown (2.5 YR 3/6) when dry; sandy clay loam; hard to very hard when dry, friable to firm when moist; sticky and plastic; moderate medium to coarse sub-angular blocky and angular blocky structure; patchy and thin cutans mainly clay and organic matter in nature; few tubular pores, size < 5 mm; common fine to medium roots, size 1 - 5 mm, smooth (2 - 5 cm) boundary

Bs_1 47 - 92 cm: dark reddish brown (2.5 YR 3/6) when moist and dark reddish brown (2.5 YR 3/6) when dry: clay. hard to very hard when dry, friable to coarse sub-angular blocky and angular blocky structure. patchy and thin cutans mainly clay and organic matter in nature; few tubular pores, size < 2 mm. few fine roots. size 1 - 2 mm. smooth (2 - 5 cm) boundary

Bs_2 92 - 200+ cm brown (10 YR 4/6) when moist and brown (10 YR 4/6) when dry; clay; soft when dry, very friable to friable when moist; slightly sticky to sticky and plastic; weak to moderate fine to medium sub-angular blocky structure; patchy and thin cutans mainly clay and organic matter in nature; few tubular pores, size < 1 mm; few fine roots, size < 1mm

A. Physico-chemical characteristics*

Horiz.	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Text.	pH (H_2O)	pH (KCl)	OC (%)	N (%)	Av. P (mg kg^{-1})	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	CEC soil	CEC clay	BS (%)
Ap	0-16	85	5	10	LS	5.2	4.3	0.56	0.05	5.03	1.20	0.64	0.18	0.05	2.07	4.81	48.1	43
AB	16-47	61	4	35	SCL	5.3	4.3	0.39	0.04	1.13	1.55	0.93	0.09	0.02	2.59	5.76	16.5	45
Bs_1	47-92	37	4	59	C	5.2	4.6	0.21	0.02	0.56	2.25	0.52	0.03	0.05	2.85	6.79	11.5	42
Bs_2	92-200+	46	7	47	C	5.3	4.2	0.10	0.01	1.55	2.11	0.62	0.02	0.01	2.76	6.00	12.8	46

B. Diagnostic horizons, soil classification and correlation

Horiz.	Diagnostic horizon		Classification		
	Revised Legend	WRB	Revised Legend	WRB	Soil Taxonomy
Ap	Ochric A-horizon	Ochric horizon	Rhodic Ferralsol	Veti-Acric Ferralsol (Rhodic)	Rhodic Eutrustox
AB					
Bs_1	Ferralic B-Horizon	Ferralic horizon			
Bs_2	Ferralic B-Horizon	Ferralic horizon			

* Ca^{2+}, Mg^{2+}, K^+, Na^+, TEB, CEC soil and CEC clay are expressed in $cmol_c\ kg^{-1}$

30 Libea

Location:	Lindi region, Nachingwea district, 3 km northeast of Nachingwea Experimental Substation of NARI
UTM Coordinates:	Zone 37: 476.4 km E, 6660.6 km S
Authors:	Ngatunga E., Dondeyne S., Mapua
Date:	14 December 1996
Landform and relief:	landscape unit: Nachingwea-Masasi Plain site is sloping towards a valley in the south (367 m asl)
Slope of site:	5 - 10 %
Vegetation and land use:	Cashew, maize and sorghum
Soil parent material:	hydromorphic sandstone
Drainage class:	poorly drained subsurface horizons, gleyic properties beyond 145 cm
Rock outcrop:	nil
Surface stones:	nil
Signs of erosion:	sheet and rill erosion

Ap 0 - 16 cm: brownish black (7.5 YR 3/1) when moist and brownish black (7.5 YR 3/2) when dry; loamy sand; soft to slightly hard when dry, very friable when moist; non sticky and non plastic; weak very fine to fine sub-angular blocky and crumb structure; no cutans; common tubular pores, size 1 - 5 mm; few to common fine to medium roots, size 1 - 5 mm; smooth to wavy (2 - 5 cm) boundary

AB 16 - 29 cm: brown (7.5 YR 4/3) when moist and brown (7.5 YR 4/3) when dry; loamy sand; slightly hard when dry, friable when moist, non sticky and non plastic; moderate fine to medium sub-angular blocky structure; patchy and thin cutans clay in nature; common tubular pores of various sizes, size < 5 mm; common fine to medium roots, size 1 - 5 mm; smooth to wavy (2 - 5 cm) boundary

BA 29 - 45 cm: dark brown (7.5 YR 3/ 4) when moist and brown (7.5 YR 4/4) when dry; few distinct diffuse to clear mottles which are bright reddish brown (5 YR 5/6) and others are reddish black (10 R 2/1), size < 15 mm; sandy loam; slightly hard to hard when dry, friable when moist; sticky and plastic; moderate fine to medium sub-angular blocky structure; broken thin to medium thick cutans mainly clay in nature; common tubular pores, size 1 - 5 mm; few fine roots, size 1 - 2 mm; wavy (2 - 5 cm) boundary

Bt_1 42 - 148 cm: yellowish brown (10 YR 5/6) when moist and bright brown (7.5 YR 5/6) when dry; sandy clay; common distinct diffuse to clear mottles which are bright reddish brown (5 YR 5/2) and others are reddish black (10 R 2/1), size < 15 mm; hard to very hard when dry, firm to very firm when moist; very sticky and very plastic; moderate to strong medium to coarse sub-angular blocky structure; patchy to broken and thin to medium thick cutans mainly clay in nature; common tubular pores, size < 2 mm; few fine to medium roots, size < 2 mm; wavy (2 - 5 cm) boundary

Bt_2 148 - 200+ cm: yellowish brown (10 YR 5/6) when moist and light brownish grey (5 YR 7/2) when dry; sandy clay; common to abundant distinct and clear mottles which are greyish brown (5 YR 5/2), common to abundant distinct and clear mottles which are dark reddish brown (5 YR 3/6) and others are bright brown (7.5 YR 5/8), size 5 - 15 mm; very hard when dry, firm to very firm when moist; very sticky to very plastic; moderate to strong medium coarse to very coarse sub-angular blocky structure; few distinct cutans on pedfaces and common distinct cutans on voids; no pores; 1 - 5 roundish gravels, 1 - 5 cm nodules with black colour inside (10 YR 2/1); few fine roots, size < 2 mm

A Physico-chemical characteristics*

Horiz	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Text	pH (H_2O)	pH (KCl)	OC (%)	N (%)	Av P (mg kg^{-1})	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	CEC soil	CEC clay	BS (%)
Ap	0-16	92	4	4	S	6.7	6.1	0.30	0.03	15.57	3.18	1.01	0.12	0.02	4.33	4.71	117.8	92
AB	16-29	90	3	7	S	7.0	6.2	0.16	0.01	2.67	2.12	0.55	0.04	0.02	2.73	0.68	9.7	100
BA	29-45	80	4	16	SL	7.0	6.0	0.19	0.02	1.34	2.73	1.76	0.05	0.01	4.55	4.38	27.4	100
Bt_1	45-148	53	4	43	SC	5.5	3.8	1.11	0.06	2.04	4.99	1.63	0.02	0.03	6.67	13.61	31.7	49
Bt_2	148-200+	57	4	39	SC	5.9	3.8	0.10	0.01	0.95	4.27	1.35	0.01	0.09	5.72	9.53	24.4	60

B Diagnostic horizons, soil classification and correlation

Horiz	Diagnostic horizon		Classification		
	Revised Legend	WRB	Revised Legend	WRB	Soil Taxonomy
Ap	Ochric A-horizon	Ochric horizon	Gleyic Luvisol	Dystiri-Gleyic Luvisol	Aquic Kandiustalf
AB					
BA					
Bt_1	Argic B-horizon	Argic horizon			
Bt_2	Argic B-horizon	Argic horizon			

* Ca^{2+}, Mg^{2+}, K^+, Na^+, TEB, CEC soil and CEC clay are expressed in $cmol_c\ kg^{-1}$